

Distributed Photovoltaic Systems for Sustainable Rural Development

An Assessment Framework Illustrated with a Case Study of Tumaini Open School in Tanzania

Ingvild Oftedal

Renewable Energy Systems

60 ECTS Credits

Department of Technology Systems

Faculty of Mathematics and Natural Sciences



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Abstract

This study develops a comprehensive assessment framework to facilitate a structured comparison of centralized photovoltaic systems (CPVS) and distributed photovoltaic systems (DPVS) in underdeveloped rural areas. The assessment framework considers four perspectives: techno-economic, socio-economic, environmental, and institutional. The study's initial application provides results that lay a foundation for broader evaluations, offering valuable insights for various external stakeholders.

Policymakers can utilize the framework to create evidence-based policies that align national energy goals with local community needs. For investors, the framework provides clear insights into the economic viability and risk factors associated with CPVS and DPVS, assisting investors in making informed decisions. For development organizations, it identifies high-impact initiatives for resource allocation. For researchers, it offers a structured approach to analyzing PV systems in rural areas, enabling the refinement and expansion of the framework based on empirical data.

The research centers around the United Republic of Tanzania (referred to throughout this thesis as Tanzania). It highlights the country's distinct energy challenges, including outdated infrastructure, low rural electrification rates, and political constraints. The study concludes that while CPVS are cost-effective at scale, their dependence on Tanzania's outdated electricity infrastructure means they will not provide reliable electricity in rural areas in the near future. This situation highlights the urgent need for DPVS, which can function independently from the national grid and be deployed rapidly and incrementally by local solar companies.

The case study focuses on the planning, installation, and effects of a hybrid PV system installed at Tumaini Open School's classroom building, situated in the rural outskirts of Tabora, Tanzania. It demonstrates the framework's practical application, highlighting that DPVS not only provided reliable electricity for energy-dependent activities but also increased empowerment, enhanced digital literacy, improved educational environment, new income and employment opportunities, heightened awareness of renewable energy, and increased community engagement.

Keywords: Centralized, Distributed, Photovoltaic, Rural, Development, Aid, Technical, Economic, Social, Environmental, Institutional, Tabora, Tanzania and Sub-Saharan Africa.

Preface

This master's thesis concludes my Master of Science in Renewable Energy Systems at the Department of Technology Systems at the University of Oslo. It is a 60 ECTS credit master's thesis, which corresponds to one year of full-time study and constitutes half of the credits for the master's degree. It results from independently conducted work, with original research and critical analysis.

Sincere acknowledgment to my internal supervisor from the University of Oslo, Professor Josef Noll, for helpful guidance, contributions, and discussions throughout this project. His assistance played a pivotal role in shaping and enriching the content and presentation of my master's thesis.

This master's thesis is also written as a Meaningful Master for Engineers Without Borders Norway (EWB-N). I sincerely appreciate the collaboration with Elise Skattum and EWB-N's invaluable contributions that enabled me to conduct a two-week fieldwork at Tumaini Open School (Tumaini) in March 2024. I am very grateful for the mentorship provided by Trond Øines before and during our collaborative fieldwork experience.

Special thanks to Trainor for their generous and crucial financial contribution to Tumaini's distributed PV system and for gifting the students some iPads, backpacks, and first aid kits. Sincere appreciation is also owed to the Basic Internet Foundation for providing the necessary equipment to establish a wireless network system, called an InfoSpot, consisting of an antenna, a router, a local server, and cables.

Lastly, I would like to recognize the invaluable insights, assistance, and hospitality I received from my hosts and facilitators before, during, and after the fieldwork at Tumaini: Ezekiel, Marius, and John. To process only the minimum amount of personal data necessary, this thesis utilizes only the first names of these local stakeholders.

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Department of Technology Systems, Faculty of Mathematics and Natural Sciences.

University of Oslo, November 2024.

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List of Abbreviations

AC	Alternating current
AGM	Absorbent Glass Mat
BOS	Balance of System
DC	Direct current
DIF	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
CPVS	Centralized Photovoltaic System(s)
DPVS	Distributed Photovoltaic System(s)
EWB-N	Engineers Without Borders Norway
GHI	Global Horizontal Irradiance (DNI)
LCOE	Levelized Cost of Electricity
NGO	Non-governmental Organization
ODA	Official Development Assistance
PPA	Power Purchase Agreement
PV	Photovoltaic
TANESCO	Tanzania Electric Supply Company Limited

1 Introduction

This chapter introduces the study's background, motivation, aim, and scope, effectively setting the stage for subsequent analysis and discussions.

To minimize confusion regarding uncommon or unfamiliar acronyms, two key terms employed in this master's thesis are defined at the outset:

- Distributed photovoltaic system(s) (DPVS) refer to residential-scale solar electricity generation system(s), typically mounted on rooftops and often combined with battery storage. While mini-grids and microgrids are considered distributed solutions, they are not classified as DPVS in this context.
- Centralized photovoltaic system(s) (CPVS) refer to grid-tied, ground-mounted, utility-scale solar electricity generation system(s) without battery storage.

1.1 Background to the Problem

This chapter highlights issues related to electricity access, infrastructure weaknesses, and power outages, establishing the context for the study and emphasizing the importance of exploring innovative energy solutions for rural areas.

1.1.1 Electricity Access and Power Outages in Tanzania

In 2021, about 43% of Africa's population lacked access to electricity, with Sub-Saharan Africa accounting for 98% of this demographic (IEA, 2022). This situation stems from insufficient grid expansion to meet population growth and low household incomes, which hinder both initial access and the maintenance of existing access. Many utilities across Africa struggle with a lack of financial resources, preventing essential investments in the continent's electricity grid. This has resulted in outdated infrastructure and significant network losses. Efforts to electrify rural areas have often been hindered by a reliance on traditional centralized production and the electricity grid (IEA et al., 2024).

In Tanzania, most electricity supply comes from large-scale power projects (EWURA, 2021). In 2021, natural gas contributed the largest share of the electricity generation mix at about 61%,

followed by hydropower at 39%. The grid contributed 97.5% of the total electricity supply, while isolated off-grid generation provided nearly 1%, and cross-border imports accounted for 1.5%. The Tanzania Electric Supply Company Limited (TANESCO), a fully state-owned company, is responsible for most of Tanzania's electricity generation. TANESCO supplied 83% of the grid electricity and 94% of off-grid electricity. The remainder comes from Independent Power Producers (IPP), Small Power Producers (SPP), and neighboring countries. TANESCO is also the only utility responsible for power transmission services in Tanzania, connecting and distributing electricity to customers.

As of 2021, only 23.3% of Tanzania's rural population had access to electricity (World Bank, 2023). This figure is particularly low, given that an estimated 64% of the Tanzanian population lived in rural areas in 2021 (World Bank, 2018). In the Tabora region, only 339 out of 696 rural villages were connected to the electrical grid by 2020 (Mwanri, 2020). Although the national grid serves this region with 40.5 MW, only 14 MW can be utilized due to inadequate electricity infrastructure. Therefore, the issue is not with supply since the region has an additional capacity of 26.5 MW.

From 2016 to 2019, Tanzania experienced an average of 1548 power outages each year, totaling 1407 hours of power interruptions (NAO, 2020). The primary causes of these outages were outdated electricity infrastructure, financial constraints, and inefficiencies within government utilities, which hinder adequate investment in maintenance, upgrades, and expansion (NAO, 2020; EWURA, 2021; RES4Africa, 2023). This situation has resulted in high transmission losses, frequent blackouts, electricity shortages, and unelectrified areas.

Power outages and fluctuations not only affect the daily lives of individuals but can also cause harm to equipment and interrupt manufacturing processes for businesses that rely on national infrastructure for basic energy supplies (Picard & Toulemont, 2022). Power outages cause significant annual business losses, prompting companies to invest heavily in backup power generation systems, typically fossil fuel-based, which are reliable but unsustainable and expensive (RES4Africa, 2023). In 2023, 34.1% of Tanzanian companies faced power outages, averaging 0.7 occurrences per month for a duration of 6 hours each time (Enterprise Surveys, 2023). These outages resulted in an average annual sales loss of 5.3%. Therefore, 38.7% of Tanzanian firms own or share a generator. Using a fossil fuel-based generator increases the carbon footprint and energy costs and reduces profit margins.

Degani (2013) discusses how corruption in the government tendering process for electricity projects and within TANESCO affects Tanzania's capacity to reduce electricity outages. He provides instances of corruption in contracts signed between TANESCO and companies involved in electric power generation and consulting. When these companies fail to meet expectations or leave projects incomplete, TANESCO struggles to take legal action due to the corruption surrounding these agreements, leading to significant financial losses for the government. Degani also highlights the issue of customers hiring part-time TANESCO technicians for illegal connections to the grid. These unauthorized connections can cause overloads and insufficient supply, where demand exceeds available resources. This leads to interruptions and power outages across the grid and results in major revenue losses for TANESCO, further deteriorating service quality and increasing power outages for customers.

During the financial year ending in June 2021, the Energy and Water Utilities Regulatory Authority (EWURA), responsible for regulating the energy and water sector in Tanzania, conducted planned routine inspections of TANESCO's electricity transmission and distribution infrastructure (EWURA, 2021). They identified several shortcomings, including an unreliable power supply, many non-functional energy meters at secondary substations, and an inadequate number of boundary meters to track energy delivery to specific districts or regions. Additional problems included delays in connecting new customers, electricians operating without proper licenses or with expired certifications, the absence of single-line diagrams for the power distribution system, missing data needed for reliability metrics, and a lack of records regarding outages and maintenance for key substations.

The insights from this subsection provided the foundation for the master's thesis and the hypothesis outlined in section 1.3.

1.1.2 Tumaini Open School – Case Study

Since the 1960s, the Tanzanian government has allowed state schools to ban pregnant students and adolescent mothers from continuing their education (Ratcliffe, 2017). In 2017, this discriminatory practice became official when authorities implemented it under the Education Regulations Act of 2002, which allows for the expulsion of students who commit an offense against morality (Amnesty, n.d.). Although the government lifted the ban in 2021, authorities continued to prevent these girls from attending state schools, only permitting education through informal programs. Teenage mothers in Tanzania still face challenges such as social stigma,

limited educational options, and inadequate infrastructure, all of which hinder their ability to empower themselves and provide for their children.

This case study focuses on Tumaini Open School (Tumaini), which offers secondary education and vocational support tailored to teenage mothers (Tumaini Open School, n.d., a). The school was initiated in 2020 by the school director, Ezekiel (Tumaini Open School, n.d., b). Since 2021, Tumaini has been managed by the community-based organization Tumaini Education Initiative.

In July 2023, the school moved from rented rooms to purpose-built classrooms in the rural Isukamahela village, located south of Tabora town in Tanzania (Tumaini Open School, n.d., b). The location was strategically chosen to ensure easy access for teenage mothers from the Tabora region and neighboring areas (Ezekiel, personal communication, August 16, 2023). Adjacent to the classroom building are two separate accommodations for the girls and teachers. As of January 2024, the school's website reports a total of 50 students, with a goal to enroll up to 250 each year (Tumaini Open School, n.d., a).

Tumaini is connected to the national grid, but power outages are common, especially during the rainy season (Ezekiel, personal communication, August 16, 2023). The school experiences daily power outages lasting seven to eight hours. To mitigate the risk of losing electricity, Tumaini is seeking to install a PV system on the roof of the classroom building, which would provide a consistent power supply for essential equipment such as lights, computers, and other electronics (Ezekiel, personal communication, January 8, 2024). This will create a better study environment, enhance the effectiveness of teaching and learning, enable computer-based education, ensure the girls' safety with adequate lighting, and create job opportunities, such as poultry farming with an incubator for chicken eggs.

The insights from this subsection provided the foundation for the case study of this master's thesis, outlined in section 3.5.

1.2 Motivation

This master's thesis was inspired by a strong interest in renewable energy for rural electrification. The author has gained knowledge about the theoretical principles and practical applications of renewable energy, photovoltaic (PV) systems, and power grids by taking courses at the University of Oslo.

The topic of analysis is influenced by Sustainable Development Goal (SDG) 7, set by the United Nations (UN) for the period 2015 to 2030 (IEA, IRENA, UNSD, World Bank & WHO, 2024). This goal aims to “ensure access to affordable, reliable, sustainable, and modern energy for all”. Achieving this goal is crucial for improving nutrition, health, education, jobs, and skills, thereby contributing to other goals, such as good health and well-being (SDG 3), quality education (SDG 4), and gender equality (SDG 5). However, challenges such as the COVID-19 pandemic, the war in Ukraine, rising energy prices since the summer of 2021, and the increasing frequency and intensity of droughts and floods in Sub-Saharan Africa due to climate change have hindered progress, especially in vulnerable and underprivileged countries. Achieving SDG 7 by 2030 necessitates a multi-faceted approach that includes grid, mini-grid, and stand-alone off-grid solutions.

Motivated by a desire to examine the challenges and opportunities of rural electrification using solar energy in a developing country in Sub-Saharan Africa, the author leveraged her internal supervisor's connections to find a suitable collaboration partner. This effort resulted in the author contacting Tumaini's school director, Ezekiel, who agreed to a collaboration. As the author wanted to combine her graduate studies with humanitarian work, she contacted Engineers Without Borders Norway (EWB-N) and applied for their Meaningful Master's program. She was invited to join the program, which enabled her to travel to Tabora to conduct fieldwork and independent research at Tumaini.

While basic education can be provided without electricity, access to reliable power can significantly enhance educational quality. It allows teenage mothers to excel in their studies and future careers by facilitating the use of digital tools and enabling nighttime studying, among other benefits. Consequently, the author was motivated to provide Tumaini with a customized solar PV system while also empowering local stakeholders and fostering ownership of the project through training. The reliable supply of solar electricity is expected to enhance the educational environment and create job and income opportunities for young females.

1.3 Aim

This section presents the overall purpose and objectives for the master's thesis to establish the foundation for the entire study and guide the methodology, data collection, and analysis.

Research Goals

The research goals, i.e. the key purpose of this research, are outlined below:

- RG1: Develop a holistic assessment framework that can be utilized for future PV system projects in diverse rural contexts across Sub-Saharan Africa.
- RG2: Address the specific benefits and opportunities a DPVS offers a school already connected to Tanzania's national grid.
- RG3: Provide actionable insights and recommendations for external stakeholders to enhance rural electrification and development through sustainable and reliable PV systems, addressing challenges and opportunities specific to Tanzania's context.

The result of RG1 is presented in section 3.4, the result of RG2 is presented in section 4.1, while the result of RG3 is presented in section 5.2.

Hypotheses

Given Tanzanian's outdated electricity infrastructure, financial constraints, and inefficiencies within government utilities, which lead to limited and unreliable electricity access, particularly in rural areas, the hypotheses of the master's thesis are articulated as follows:

- If achieving universal access to clean, reliable, and affordable electricity in countries facing rapid demand growth, dispersed populations, and persistent infrastructure challenges is more effectively realized through DPVS rather than CPVS, then development aid for sustainable energy should prioritize the deployment of DPVS.

Research Questions

The overall research question, derived from the aim and hypothesis and to guide the focus of the research, is presented below:

- Is it more beneficial to allocate development aid for sustainable energy to DPVS rather than CPVS when aiming to achieve a reliable electricity supply and promote sustainable development in rural Tanzania?

To allow the author to answer The overall research question step-by-step, it is divided into several sub-research questions, as presented below:

- RQ1: How does a reliable solar electricity supply from a residential-scale hybrid PV system impact empowerment, the learning environment, and job opportunities at Tumaini Open School in rural Tanzania?
- RQ2: What are the advantages and challenges of DPVS compared to CPVS in underdeveloped rural communities when considering techno-economic, socio-economic, environmental, and institutional perspectives?
- RQ3: What policy interventions and institutional frameworks are needed from policymakers, investors, development organizations, and researchers to maximize rural development through solar electricity in Tanzania?

The result of RQ1 is presented in section 4.1, the result of RQ2 is presented in section 4.2, while the result of RG3 is presented in section 5.2.

Research Objectives

The specific, measurable steps the author intends to take to address the research questions and achieve the overall research goals of her research are presented below:

- RO1: Conduct a thorough literature review to identify all relevant evaluation criteria for a comprehensive assessment framework that can be used to systematically evaluate the feasibility and potential of CPVS and DPVS in rural areas.
- RO2: Conduct a case study in which a DPVS is designed and installed, then evaluated for its economic potential and socio-economic impacts.

- RO3: Conduct a comparative analysis of CPVS and DPVS using the assessment framework.

RQ1 is achieved in section 2.3, 2.5, 2.6 and 2.7, RQ2 is achieved in section 3.5 and 3.6, respectively, while RQ3 is achieved in section 3.7.

Expected Outcomes

To communicate what the author anticipates achieving and producing by the end of the research, the expected outcomes are presented below:

- The study is expected to create a framework that can be used to assess the viability, sustainability, and impact of both CPVS and DPVS in rural areas.
- The case study at Tumaini Open School is expected to provide concrete evidence of the benefits and challenges associated with DPVS and offer a model for similar projects.
- The thesis is expected to contribute to the academic discourse on renewable energy, rural development, and sustainable infrastructure in developing countries, particularly in the context of Sub-Saharan Africa.

1.4 Scope

This section outlines what will and will not be covered in the study. It outlines the boundaries of the research and specifies the particular aspects of the topic that will not be examined, ensuring the study remains focused and manageable.

Geographic and Contextual Scope

The study focuses on addressing the unique challenges of rural electrification in dispersed and underdeveloped rural areas in Tanzania. Insights gained may be relevant to other Sub-Saharan African countries. Urban areas or regions with well-established electricity infrastructure are excluded.

The study uses the Tumaini Open School on the rural outskirts of Tabora as a case study to explore the impacts of DPVS in a real-world context. This case study emphasizes the

significance of reliable energy access in rural communities for empowering women, improving the educational environment, and facilitating the development of small businesses.

Scope of Solar PV Systems

The study focuses primarily on DPVS, using CPVS as a comparative benchmark. While islanded or grid-connected mini-grids share some characteristics with DPVS, they are excluded from this study because they usually serve larger clusters of households or businesses, which is outside the scope of the research. Additionally, very small-scale devices designed only for task lighting are also excluded, as their markets and regulatory frameworks differ significantly from those associated with DPVS and CPVS.

Technology and Energy Sources

The study does not delve into specific technological components or configurations of photovoltaic systems. It emphasizes the comprehensive system-level analysis of CPVS and DPVS instead of focusing on individual technological variations.

The study does not include other energy technologies and sources, such as wind, geothermal, and fossil-fueled generation, as it focuses solely on PV generation approaches.

Development Aid and Policy Analysis

While development aid is discussed in the context of supporting rural electrification, the study does not extend to a detailed analysis of global or national development aid policies. The discussion remains limited to their relevance to sources of funding and the effectiveness of aid for PV system initiatives. The study evaluates the cost and affordability of CPVS and DPVS but does not analyze financing mechanisms, donor funding models, or policies in depth.

Literature and Data Limitations

Comparing studies on PV systems can be difficult due to the wide variety of configurations. Additionally, many studies do not provide detailed information about the specifics of the system(s), such as size, specific location, whether the system is coupled with battery storage, or other contextual factors. This variability often prevents "apples-to-apples" or "pears-to-pears" comparisons, complicating analysis and limiting the transferability of findings.

Therefore, this study uses CPVS and DPVS as interchangeable classifications for utility-scale/large systems and residential-scale/small systems, respectively. While these terms are helpful for consistency and allow for comparison, it does not fully account for variations in system design and configuration across different contexts. It is important to consider these variations when interpreting the results.

Temporal Scope

The study primarily assesses the short- to medium-term effects of DPVS and CPVS. It does not explore projections for long-term sustainability, such as what may happen after advancements in electricity infrastructure or energy storage technologies. This focus ensures practical and actionable insights into current rural electrification challenges in Tanzania.

1.5 The Scientific Method and Thesis Structure

The scientific method is a systematic approach to collecting and evaluating evidence to test ideas and answer empirical questions (Price, Jhangiani, Chiang, Leighton & Cuttler, 2017). This thesis primarily relies on existing literature but also finds new real-world case study data regarding the implementation and impacts of a DPVS.

The research process follows a structured six-step methodology, which is reflected in the six chapters of this master's thesis, outlined as follows:

- Chapter 1 introduces the thesis, setting the stage for the study by presenting the research topics and their significance.
- Chapter 2 provides a comprehensive theoretical foundation and literature review, synthesizing relevant studies and data for the case study and assessment framework.
- Chapter 3 describes the research design and methodology, outlining the study's procedures, the methods employed, and the grounds for their selection.
- Chapter 4 details the research results, showcasing the main findings from the data collection and analysis.

- Chapter 5 offers a critical discussion of the research results, addresses the study's limitations, and proposes actionable recommendations based on the findings.
- Chapter 6 concludes the thesis by summarizing the study's contributions and highlighting areas for future research.

2 Theoretical background

This chapter lays a solid theoretical foundation for the study and situates the research within the broader academic dialogue. This is to ensure accuracy and make the content accessible to readers from diverse backgrounds. The methodology for the systematic literature review conducted in this chapter is outlined in section 3.3.

The chapter contextualizes key terms within the field of PV systems and development aid, and presents the specific characteristics of the case study area. Its primary purpose is to provide a comprehensive review of studies that focus on the techno-economic, socio-economic, environmental, and institutional perspectives of CPVS and DPVS. The comparative analysis, outlined in section 4.2, retrieved key secondary data from the last four sections.

2.1 PV Systems

This section defines key terms related to PV systems to enhance clarity and ensure consistent usage throughout this master's thesis.

2.1.1 Main Components

A PV system consists of one or more PV modules to collect sunlight and convert it into direct current (DC), an inverter to convert direct current (DC) into alternating current (AC), and other electrical and mechanical hardware needed for electricity generation (Energy Education, n.d.). Everything apart from the PV modules is collectively known as the balance of system (BOS) components. These components, constituting more than half of the system's cost and a significant portion of maintenance, encompass inverters, racking, wiring, combiners, disconnects, circuit breakers, and electric meters.

This sub-section will briefly explain each of the main components of a PV system.

PV Module

A PV module is an assembly of numerous solar cells connected in series (Energy Education, n.d.). The solar cells have semiconductor properties that enable them to capture the photons from the sun and convert their energy into electricity. The amount of electricity generated by

each cell depends on the sun's light intensity (Bhatia, n.d.). The PV modules are usually encased between a transparent cover, such as glass, and a weatherproof backing (often made of a thin polymer or glass).

An arrangement of PV modules is called a PV array (Bhatia, n.d.). PV modules are typically first connected in series to achieve the desired voltage and then connected in parallel to increase the system's current. PV arrays are typically measured by their electrical output in watts (W), kilowatts (kW), or even megawatts (MW).

Kilowatt peak (kW_p) represents the maximum power output (P_{max}) of a PV module or system achieved under “full sun” conditions, called Standard Test Conditions (STC) (Bhatia, n.d.). STC specifies conditions of a cell temperature at 25°C and an irradiance level of 1000 W/m^2 , under an air mass 1.5 spectrum (Weimar, n.d.). The kW_p is referred to several times throughout this thesis, since STC is a universal industry standard for measuring the electric output performance of PV modules and ensures a relatively autonomous assessment and evaluation of various PV modules.

Battery

A battery stores chemical energy and converts it to electrical energy through electron flow between electrodes via an external circuit (Australian Academy of Science, 2016). This flow generates electric current, while charged ions move through an electrolyte to balance the process. Different combinations of electrodes and electrolytes influence the battery's performance, energy capacity, and voltage. Batteries in solar power systems store electricity from PV arrays or the grid for later use, such as during cloudy days, nights, or power outages (Renoogy, 2022).

There are four types of batteries used for solar installations: lead-acid, lithium-ion, nickel cadmium, and flow batteries (Lane, 2024). Lead-acid batteries are the most mature technology, favored for their affordability and reliability, and commonly used for off-grid solar or backup storage in case of a power outage. Lithium-ion batteries, while costly, are the preferred type for residential PV systems due to their long lifetime and lack of maintenance needs. For commercial applications, nickel-cadmium batteries are favored because they function well in extreme temperatures and do not need complex battery management systems. Flow batteries

are large and costly, so this new battery technology is primarily utilized for large-scale energy storage.

As mentioned in the introduction, this study defines DPVS as residential PV systems with battery storage, while CPVS refers to utility-scale PV systems without battery storage. Therefore, this study will only provide a brief overview of the two main types of residential solar batteries, without mentioning terms that will not be mentioned later in this master's thesis.

Currently, two of the most common types of residential solar batteries are lithium-ion batteries and a newer type of lead-acid battery known as AGM (Absorbed Glass Mat) batteries (Renoogy, 2022). Although lithium-ion batteries have significantly higher initial costs than AGM batteries, this price difference reflects the clear advantages of lithium-ion technology. They provide a higher depth of discharge (DoD), a longer operating time and lifespan, and greater efficiency, and a lighter weight for the same usable capacity, among other things. A short comparison of the two battery types is outlined below:

- The DoD describes how much (in percentage) a battery can be discharged without the risk of being damaged (Renoogy, 2022). Lithium-ion batteries should typically be discharged between 90-95%, while AGM batteries handle around 50%. This allows lithium-ion batteries to run longer per charge compared to AGM batteries.
- Battery life is measured by cycles and DoD (Fire Mountain Solar, n.d.). One cycle occurs when a battery is discharged (to its DoD) and then recharged. Lithium-ion batteries can provide around 7000 cycles at a 70% DoD, equating to over 19 years if cycled daily. If AGM batteries are cycled daily at 50% DoD, about 1500 cycles or 4-5 years of life is expected. According to JYC Battery (2023) AGM batteries typically have a lifespan ranging from 4 to 8 years, influenced by usage habits and charging methods along with environmental factors. This means that AGM batteries must be replaced up to 4 times as often as lithium-ion batteries.
- A lithium-ion battery has an efficiency of 98-99% and maintains this efficiency throughout its lifespan (Fire Mountain Solar, n.d.). A newly purchased AGM battery has an efficiency of approximately 85% due to power loss during both the charging and discharging processes, and its efficiency will decline throughout its lifespan.

For the reasons described above and as mentioned in sub-section 3.5.2, the author favored a lithium-ion battery for the DPVS at Tumaini. However, since the local solar company did not provide this option, AGM lead-acid batteries were ordered and installed. The typical DoD and the approximate efficiency for AGM batteries are incorporated into calculations in sub-section 3.5.2 (for the PV system sizing). The expected lifespan of AGM batteries is incorporated into calculations in sub-section 3.5.6 (for the evaluation of economic potential)

Inverter and Charge Controller

An inverter is an electrical device that converts direct current (DC) from PV modules or batteries into alternating current (AC), which is used to power electronics locally or be transmitted to the grid for use elsewhere (Energy Education, n.d.).

Many inverters come with built-in solar charge controllers, such as the inverter installed at Tumaini (Deye, n.d.). A solar charge controller is an electronic device that adjusts the voltage and current from solar panels to safely and efficiently charge batteries, protecting the batteries from overcharging, being discharged more than their DoD, and against short circuits (Jingsun, 2024). It also offers instantaneous updates on system performance, such as battery voltage, charging current, and energy generation. The solar charge controller is positioned between the solar panels and the batteries, whereas the inverter is placed between the batteries and home devices.

Racking system

The racking system is generally made of steel or aluminum and serves as the mounting system that secures solar modules to the ground, rooftops, or other structures (Energy Education, n.d.). The racking system also enables the adjustment of solar module tilt to optimize their alignment with the sun. Racking systems should be designed to endure extreme weather conditions and ensure proper electrical bonding and grounding of the solar modules to minimize the risk of electrocution.

2.1.2 Grid-tied, Off-grid and Hybrid

PV systems can be categorized into three main types based on grid connection: Grid-Tied, Off-Grid, and Hybrid (Rooij, n.d.). Each type has distinct characteristics, advantages, and challenges, making it suitable for different applications and user needs. This sub-section will explain the three categories as they are utilized several times throughout this master's thesis.

Grid-tied PV Systems

Grid-tied PV systems are always connected to the electrical grid (Rooij, n.d.). The electricity generated by the PV modules is used on-site or fed directly into the grid. During periods without sunlight, like nighttime, the grid supplies the electricity needed, which eliminates the requirement for battery storage. One significant drawback is that users lose electricity during a grid failure. Additionally, customers must pay monthly connection fees to utility companies. The primary advantage of grid-tied systems, compared to off-grid or hybrid systems, is their cost-effectiveness. They are generally cheaper because they do not require batteries or other standalone components. Through net metering, users can sell excess electricity back to the utility company, which helps reduce their overall electricity costs.

Off-Grid PV Systems

Off-grid PV Systems, also called standalone systems, operate independently from the grid (Rooij, n.d.). The electricity produced by the PV modules is stored in batteries for use during periods without sunlight. This system is particularly suitable for remote areas without grid access. One advantage is self-sufficiency, where users do not need to rely on grid supply and are unaffected by grid failures and downtimes. A notable disadvantage is that off-grid systems tend to be more expensive than grid-tied and hybrid systems. This is because they require battery storage and, in some cases, alternative power sources like diesel generators. They also have a higher number of components, which means higher maintenance requirements, especially for the batteries, adding to the overall cost.

Hybrid PV Systems

Hybrid PV Systems combine elements of both grid-tied and off-grid systems, providing the flexibility of off-grid systems with the reliability of grid connection (Rooij, n.d.). These systems allow users to toggle between grid and battery power, usually through an automatic mechanism. Hybrid systems are less expensive than fully off-grid systems since the grid connection serves

as a backup, which allows for a smaller battery bank and eliminates the need for a generator. This reduces costs and maintenance needs.

2.1.3 Centralized and Distributed PV

Solar power can come from either centralized or distributed generation (Hongyuan, 2023; Egret Solar, 2024). This sub-section will explain both approaches, as these key terms are utilized several times throughout this master's thesis.

Centralized PV

Centralized PV generation typically involves utility-scale PV systems with generation capacities ranging from several megawatts to hundreds of megawatts (Hongyuan, 2023; Rose, 2023; Egret Solar, 2024). These systems are primarily designed to feed electricity directly into the grid rather than storing it. CPVS requires a substantial amount of land, often spanning hundreds or even thousands of acres in sun-rich rural or remote locations. CPVS needs adequate electricity infrastructure to transmit the generated power over long distances to end-users. Implementing this infrastructure can be challenging and costly, especially in areas far from the main power grid.

CPVS are generally owned by utility companies, independent power producers (IPPs), or large energy corporations (Rose, 2023). They are integrated into the grid to enhance a region's energy capacity. Additionally, their integration supports grid services such as voltage regulation and frequency control, essential for maintaining grid stability. CPVS typically sells electricity to utilities through long-term power purchase agreements (PPAs), which outline pricing, duration, and terms and offer revenue certainty (Raza, 2023).

Distributed PV

Distributed PV generation generally includes grid-tied, off-grid, and hybrid systems, along with mini-grids and microgrids (Odarno, Martin, & Angel, 2015). These solutions are usually paired with battery storage (World Bank, 2022) and can often supply surplus electricity to the grid (Hongyuan, 2023). They are often owned by individuals, businesses, or communities, helping them lower their energy costs (Rose, 2023). DPVS typically sells excess power through simpler mechanisms like net metering or feed-in tariffs (FIT), often relying on regulatory support (Raza, 2023).

DPVS typically refers to residential-scale PV installations with capacities of less than one megawatt (Lee & Moses, 2015). These installations are situated near the demand point, such as on rooftops or in parking lots (Rose, 2023). This proximity reduces the need for long-distance electricity transmission and minimizes energy losses. This capability can alleviate stress on the transmission grid and enhance grid resilience by reducing congestion.

A short explanation of mini-grids and microgrids is provided to clarify the distinction between them and DPVS. A mini-grid comprises distributed generation sources and interconnected loads within a defined electrical boundary (Cox, Gagnon, Stout, Zinaman, Watson & Hotchkiss, 2016). It operates as a single, controllable entity that can either connect to the grid or operate independently when disconnected. A microgrid, on the other hand, is a completely off-grid model. These installations can provide electricity to individual customers, or to clusters of households, businesses, and institutions (Cox et al., 2016; World Bank, 2022).

2.2 Case Study Area and Environmental Factors

Since the case study relies on specific values for design, calculations, and evaluations, this section includes site-specific parameters for Tumaini's location. The primary focus here is the environmental factors influencing the PV system's energy output (specific yield). These factors were utilized when designing the PV system, sizing it, and evaluating its economic potential. These steps were conducted in sub-sections 3.5.1, 3.5.2, and 3.5.6, respectively.

Location of Tumaini

Location is the starting point when designing a PV system since the environmental factors depend on the climate of the location and the latitude (Bhatia, n.d.).

Tumaini is located on the rural outskirts of Tabora, Tanzania. According to the Global Solar Atlas [GSA] (2024a), the school building has an elevation of 1213, a latitude of -5.125535° N (i.e. in the southern atmosphere) and a longitude of 32.778150° S. The geographical coordinates are shown in the figures below.

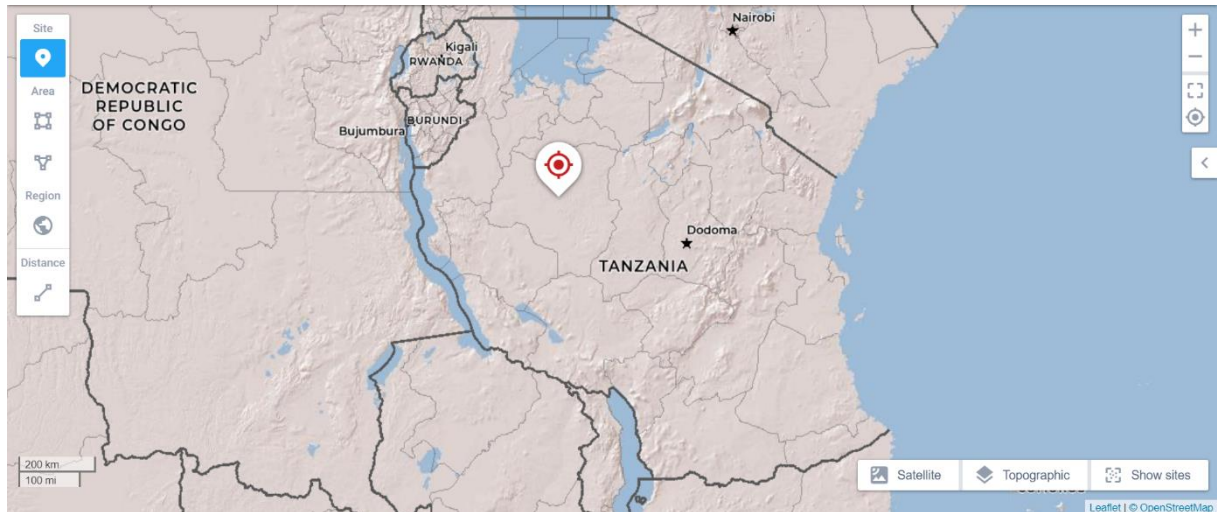


Figure 1: Location of Tumaini Open School in Tanzania

Note: Screenshot of an interactive topographic map (scale 1:200 km). Retrieved from "Kipalapala", by GSA, 2024b. <https://globalsolaratlas.info/map?c=-6.579829,34.025389,6&s=-5.125535,32.77815&m=site>. Credit: Satellite tiles © Esri, © OpenStreetMap contributors.

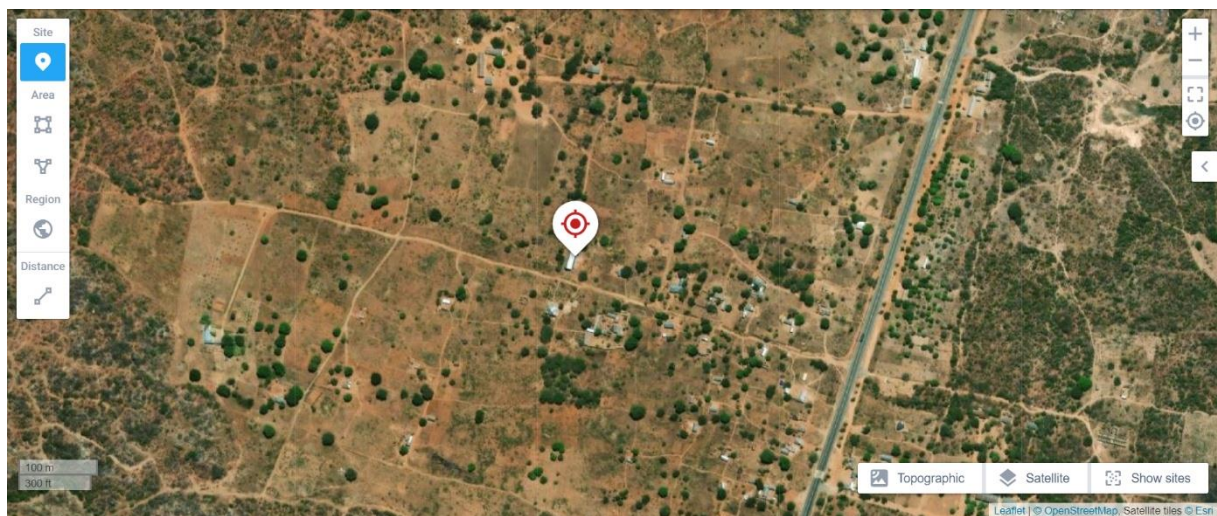


Figure 2: Tumaini Open School's rural surroundings, south of Tabora town.

Note: Screenshot of an interactive satellite map (scale 1:100 m). Retrieved from "Kipalapala", by GSA, 2024c. <https://globalsolaratlas.info/map?c=-5.125622,32.778567,17&s=-5.125535,32.77815&m=site>. Credit: Satellite tiles © Esri, © OpenStreetMap contributors.

The specific yield

The specific yield (PV_{OUT}), expressed in kilowatt-hours per kilowatt peak (kWh/kW_p), represents the amount of electricity (kWh) generated per unit of installed PV capacity (kW_p) over the long term (ESMAP, 2020). PV_{OUT} simulates how sunlight is converted into electricity,

accounting for factors like air temperature, terrain, reflection (albedo), orientation (azimuth angle), inclination (tilt angle), shading, soiling, and various other factors affecting the system's performance. Most losses are design issues, varying according to temperature, weather, and load conditions (Bruce, 2023). PV system losses substantially impact the overall efficiency and the PV_{OUT} of the PV module arrays. Total losses in a PV system, including those from PV modules, amount to around 26% of the power generated.

The annual PV_{OUT} in a specific geographical location is often the most indicative value for PV project evaluation (ESMAP, 2020). According to GSA (2024a), the site-specific estimates for PV_{OUT} at Tumaini are 4.871 kWh/kW_p/day and 1998.1 kWh/kW_p/year.

Tumaini's annual PV_{OUT} is utilized to in sub-section 3.5.2 (for the PV system sizing) and sub-section 3.5.6 (for the evaluation of economic potential).

Climate, Air temperature, and Degradation rate

During the high-sun months, Tabora's wet season is characterized by warmth, humidity, and overcast sky conditions (Weather Spark, n.d.). During the low-sun months, the dry season is characterized by heat, wind, and partly cloudy conditions. Tabora's average annual air temperature varies from an annual average minimum air temperature of 17° to an annual average maximum air temperature of 29°C (Climate.top, n.d.). According to GSA (2024a), the average annual air temperature for Tumaini's location, in the rural outskirts of Tabora is 23.4 °C.

The degradation rate is the percentage of power output or efficiency loss per year (D.T. Multi Tech, 2024). High temperatures, humidity, and dust can severely increase the degradation rate and reduce the lifespan of PV modules and related components, such as inverters and batteries (Pillota, Muselli, Poggi, & Diasa, 2017). For instance, the degradation rate of PV modules can rise from a nominal value of about 0.5% per year to as much as 3% in the harsh climates of Sub-Saharan Africa. Similarly, dust accumulation significantly decreases module efficiency and contributes to long-term degradation, necessitating regular maintenance to ensure system performance. Given that lead-acid batteries, commonly used in solar applications, already have short nominal lifespans and low tolerance for extreme temperatures, these factors severely impact the overall economic viability of PV systems. Pillota et al. (2017) state that lead-acid batteries' lifetime is halved for every 10°C increase above the recommended operating

temperature, and Léna (2013) states they can lose 15-20% of their lifetime for every 5°C rise above the standard operating temperature of 25°C.

The degradation rate of Tumaini's PV modules are outlined in sub-section 3.5.6 (for the evaluation of economic potential), together with the expected lifetime of the batteries.

According to D.T. Multi Tech (2024), the degradation rate of solar inverters ranges from approximately 0.1% to 2%. This variation depends on environmental, operational, and manufacturing factors. If inverters degrade at a rate of 1%, their power output, or efficiency, will decline by about 22% over a 25-year lifespan. This translates to an estimated 11% decrease in energy generation from PV systems and around a 13% reduction in the revenue generated by these systems.

Solar Irradiation

The performance of a PV module is directly related to the amount of sunlight it receives (Bhatia, n.d.). In Tabora, due to its proximity to the equator, sunrise and sunset times do not vary significantly throughout the year. The average daylight duration ranges from 11 hours and 49 minutes in June to 12 hours and 24 minutes in December, with an annual average of approximately 12 hours (Climate.top, n.d.). Daily sunlight hours remain relatively consistent throughout the year, varying from 10 hours in July to 6 hours and 54 minutes in January, with an annual average of about 8 hours and 30 minutes. Comparing the average annual hours of sunlight to the average annual daylight hours reveals that roughly 71% of the day experiences sunny conditions. The remaining 29% is likely marked by low sun intensity, clouds, haze, or shade, which can reduce light absorption and consequently diminish the effectiveness of the PV modules.

Solar irradiance, expressed in W/m^2 , represents the power received from the sun per unit area (GSA, n.d.). Solar irradiation, expressed in Wh/m^2 , represents the sum of energy received from the sun over a specific period, per unit area. The solar irradiation that directly reaches a surface perpendicular to the sun is known as Direct Normal Irradiation (DNI). In contrast, the portion scattered by the atmosphere and received by a surface horizontal to the ground is referred to as Diffuse Horizontal Irradiation (DIF). When combined, they form Global Horizontal Irradiation (GHI), which refers to a surface horizontal to the ground.

GHI is the most important parameter for calculating the specific yield and assessing the performance the PV modules (ESMAP, 2020). GHI is considered a simplified approximation and allows comparisons of PV technology conditions without being limited to a particular power plant design or mode of operation. The site-specific estimate for GHI at Tumaini's location is 6.123 kWh/m²/day and 2235.1 kWh/m²/year (GSA, 2024a). The daily value for GHI was utilized in sub-section 3.5.2 (for the PV system sizing).

Tumaini's GHI value is quite representative of the average GHI value in Sub-Saharan Africa. The World Bank (2019) provides data indicating that large parts of Sub-Saharan Africa receive average daily GHI values between 5-7 kWh/m²/day, as shown in the figure below.

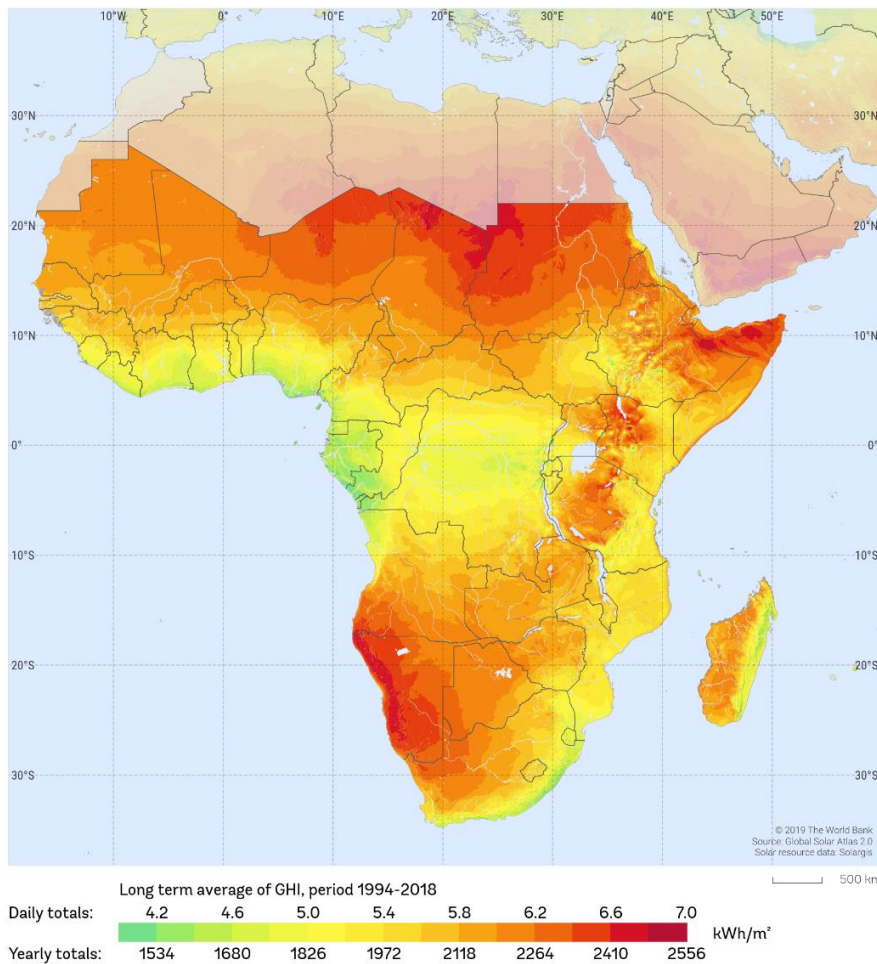


Figure 3: GHI in Sub-Saharan Africa.

Note: Cropped Image. Retrieved from “Global horizontal irradiation: Sub-Saharan Africa”, by the World Bank, 2019. https://api.globalsolaratlas.info/download/Sub-Saharan%20Africa/Sub-Saharan-Africa_GHI_mid-size-map_156x192mm-300dpi_v20191016.png

Peak Sun Hours

More intense sunlight leads to higher energy output from the PV modules (Bhatia, n.d.). Peak Sun Hours (PSH), also called daily insolation, refers to the hours of the day when the sun's intensity equals an average of 1 kW/m^2 . By combining the module's power output with the PSH, the author can calculate the energy a PV module produces on an average day.

Since the GHI value for Tumaini's location is $6.123 \text{ kWh/m}^2/\text{day}$ (GSA, 2024a), the PSH is 6.123 hours. This value for PSH was utilized in sub-section 3.5.2 (for the PV system sizing).

Azimuth and Tilt Angle

Installing the modules with optimal azimuth and tilt angles is essential to maximize energy generation from PV modules and improve the system's economic viability (N'Tsoukpoe, 2021). This ensures they receive the maximum amount of DNI. The azimuth and tilt angles discussed below were considered during the planning of the PV system, as outlined in sub-section 3.5.1.

The azimuth refers to the horizontal angle measured from the cardinal direction where the sun reaches its peak: In the Northern Hemisphere, 0° azimuth points south, while in the Southern Hemisphere, 0° azimuth points north (PV*SOL, n.d.-b). PV modules should generally be oriented at 0° azimuth, i.e., toward the Equator (N'Tsoukpoe, 2021).

The tilt angle of PV modules refers to their vertical tilt relative to the ground: When solar panels are flat, they have a 0° tilt, while standing upright, perpendicular to the ground, they are at a 90° angle (Prostar, 2020). The tilt angle should generally match the local latitude (N'Tsoukpoe, 2021). This means that as latitude increases, so does the recommended tilt angle.

GSA (n.d.) explains the optimum tilt of PV modules as “the inclination which, for a specific azimuth, makes the PV module surface harvest the maximum amount of solar radiation”. At Tumaini's location, the optimum tilt is 10° (GSA, 2024a). The annual average global irradiance value at this tilt angle is $2264 \text{ kWh/m}^2/\text{year}$. This value is approximately 1,3 % higher than the GHI of $2235.1 \text{ kWh/m}^2/\text{year}$, referring to a surface horizontal to the ground.

Research from West and Central African regions with latitudes between 0° and $\pm 15^\circ \text{ N}$ concludes that a deviation of up to 20° from the ideal azimuth and tilt angle results in less than a 5% reduction in solar radiation received (N'Tsoukpoe, 2021). Therefore, constructing specific

structures or modifying buildings to achieve the optimal fixed orientation and tilt is often unnecessary.

A minimum tilt angle of 5° to 10° is recommended to allow some dust and debris to slide off the PV modules via rainwater runoff (N'Tsoukpoe, 2021). A steeper tilt would increase the amount of dust and debris sliding off the PV modules, resulting in a lower frequency of manual cleaning required (Solarud, 2023). Unlike roof-mounted systems, this is a notable drawback for ground-mounted systems due to decreased ground space utilization and increased shading between rows.

Ideally, a solar tracking system (utilizing either single-axis or dual-axis tracking technology) would be used to follow the sun's shifting position in the sky as it changes throughout the day and the seasons (Prostar, 2020). However, despite the potential increase in specific yield (PV_{OUT}), the costs associated with such systems often outweigh the benefits, making them a less attractive option. Solar tracking systems are also impractical, especially for smaller rooftop installations (N'Tsoukpoe, 2021). As a result, fixed panels are generally used.

This information about the azimuth and tilt angle was used when the author planned Tumaini's PV system, which is described in section 3.5.1.

2.3 Development Aid for Sustainable Energy

This section explains development aid as it directly influences the feasibility and sustainability of PV systems and significantly supports the expansion of electrification in Sub-Saharan African nations (Aly, Moner-Girona, Szabó, Pedersen & Jensen, 2019). The differences in funding between CPVS and DPVS are discussed in sub-section 2.7.2.

Development aid, often called Official Development Assistance (ODA), refers to the financial resources provided by governments and public institutions in wealthy countries to improve living standards in underdeveloped nations (Petit, n.d.). ODA typically includes grants or loans offered on favorable terms aimed at funding projects that enhance access to clean water, healthcare, electricity, education, adequate housing, environmental conservation, and more. This assistance supports both long-term development initiatives and emergency humanitarian relief efforts. It can encompass everything from small community-based projects to large-scale

national programs. Regardless of the specific approach, the goal is always to benefit local populations. ODA comes within the UN's framework of the SDGs

The implementation of ODA is carried out by various local entities, including government ministries, local authorities, financial institutions, professional organizations, NGOs, and businesses (Petit, n.d.). In this master's project, the support for Tumaini's DPVS came from two sources: The non-governmental organization (NGO) EWB-N provided technical expertise through qualified engineers, while the Norwegian company Trainor contributed a small business grant.

The Effectiveness of Development Aid for Sustainable Energy

The effectiveness of aid is often evaluated based on long-term economic growth (Petit, n.d.), but several aspects must be considered. Below are four interconnected dimensions for this evaluation, as Rogner (2013) outlined:

- Increased access to clean energy services.
 - Access involves delivering energy from modern sources to households, community institutions, small-scale businesses, and agricultural activities. This implies ensuring a reliable and sufficient electricity supply (through grid-tied, off-grid, or hybrid systems). For off-grid and hybrid systems, this involves having adequate backup or storage capacity. At the national level, access relates to energy security.
- Improved affordability of energy services.
 - Affordability refers to the costs of acquiring electric devices, connection fees, and electricity and fuel charges (including supply costs). These costs can be barriers to access, even when infrastructure is in place.
- Reduced environmental impacts.
 - Environmental impacts include health issues, air and water pollution, and disruptions to agricultural productivity and climate patterns, among other things. Negative environmental consequences of energy extraction and conversion (such as pollution and waste) are putting ecosystems at risk. Over time, the financial costs associated with environmental damage are becoming more

significant, thereby diminishing the economic gains from the production and use of energy services.

- Rates of efficiency improvements.
 - Efficiency improvements refer to the deployment of renewable energy technologies and energy-efficient infrastructure and devices. Enhancing energy generation and usage efficiency not only reduces pollution and waste but also increases energy security and can lower energy service costs, thus improving affordability.

These dimensions have inspired some of the perspectives and criteria used in this study's assessment framework, outlined in section 3.4.

To ensure the success of development aid efforts and promote private sector engagement, it is vital to grasp these dimensions and to pinpoint the most effective areas to allocate funding. For instance, just installing a solar power system in a remote village without electricity is not enough to judge if development aid is working for sustainable energy. It is also essential to look at how the project improves the community's economic, social, environmental, and institutional conditions. But there are several challenges that hinder the evaluation of aid projects. According to Riddell (2014), these include data inadequacies (insufficient or non-existent baseline and monitoring data), attribution problems (difficulty determining the specific contributions of aid to outcomes), and counterfactual issues (not knowing what would have happened without the aid).

The complexity of institutions and incentive systems can be overlooked, leading to the failure of many development aid initiatives. Easterly (2007, as cited in Rogner, 2013) advocates for shifting development aid away from the unrealistic goal of achieving overall development. Instead, he proposes directing aid towards incremental, specific tasks with significant demand. This approach would aim to enhance opportunities for impoverished individuals rather than attempting to overhaul entire impoverished societies. While addressing these targeted initiatives' knowledge and incentive challenges is not simple, they appear more manageable than those associated with traditional development assistance.

NGOs, like EWB-N, are widely recognized as essential for promoting socioeconomic development in developing countries, especially in contexts with limited government resources

and revenues. Evaluating whether NGO aid projects are effective or not is complicated by methodological challenges, data limitations, attribution issues, and the diversity of projects in terms of activity, scale, and reach (Riddell, 2014). Tens of thousands of different NGOs implement hundreds of thousands of projects, ranging from very small initiatives under 30 USD to large-scale projects valued at over 10 million USD. Most NGOs focus on tangible outputs of their aid, such as health services, education, rural development, and micro-credit programs, while also aiming to empower beneficiaries to shape their lives. Evaluations that concentrate solely on immediate goals provide only partial insight into the more complex questions about the long-term impact of aid.

The knowledge gained from this chapter not only provided inspiration for the assessment framework but also informed the development of more specific and targeted recommendations for the external stakeholders involved in sustainable energy initiatives, as outlined in section 5.2. This included pinpointing the most effective area to allocate funding.

2.4 Techno-Economic Evaluation Criteria

This section offers evaluation criteria and comparative data on CPVS and DPVS from a techno-economic perspective. Each sub-section corresponds to an individual criterion within the assessment framework. Key data from this section is presented in section 4.2.

Many aspects of technical and economic considerations are interconnected. Combining these into a techno-economic perspective allows a clearer understanding of how technological choices directly influence financial outcomes.

2.4.1 Levelized Cost of Energy

Levelized cost of energy (LCOE) represents the relationship between the overall expenses throughout the operational life of the PV system, and the total energy output anticipated from the PV system over its lifespan (ESMAP, 2020). The equation considers discount rates over the typical lifespan of a PV system. It overlooks market potential, which varies based on site-specific factors like land costs, grid infrastructure, logistics, legalities, and political framework.

LCOE can be calculated for a reference year by dividing the total system costs by the total amount of energy produced within that year. Should the LCOE be lower than the electricity

price achievable by the energy generation system, the project could yield profits (Rodríguez, 2022). Conversely, if the LCOE surpasses the electricity price, the project is expected to incur losses. Therefore, the LCOE is the lowest price at which energy must be sold for the project to cover its costs and break even.

According to IRENA (2024b), the global average LCOE for utility-scale PV projects commissioned in 2023 was 0.044 USD/MWh, down from 0.060 USD/MWh in 2020. For residential-scale PV projects (presumably without battery storage), the latest data available is for projects commissioned in 2020, which shows that country-based average LCOE ranged between 0.055 USD/kWh and 0.236 USD/kWh (IRENA, 2021). This creates a global average of 0.124 USD/kWh. In South Africa, the average LCOE for residential-scale PV projects (presumably without battery storage) commissioned in 2020 was 0.091 USD/kWh.

To compare these values to a solution that includes battery storage: The global average LCOE of a best-in-class solar hybrid mini-grid was 0.38 USD/kWh in 2021, decreasing from 0.55 USD/kWh in 2018 (ESMAP, 2022).

Due to the insufficient data for LCOE from African countries, data from the United States (U.S.) is provided. The graphs below, shown in Figure 4 (NREL, 2024a) and Figure 5 (NREL, 2024b), illustrate estimated values for LCOE, CAPEX, fixed O&M costs, and CF for a utility-scale and a residential-scale PV system, respectively. Both systems are without battery storage. Graphs are adjusted to represent areas with an average annual GHI above 5.75 kWh/m²/day (the highest available option), as large parts of Sub-Saharan Africa receive average daily GHI values between 5-7 kWh/m²/day (World Bank, 2019), as shown in Figure 3. However, the graphs do not accurately reflect the locations and markets of Sub-Saharan Africa.

Based on Figure 4 (NREL, 2024a), the U.S. average LCOE for utility-scale PV systems was 40.9 USD/MWh in 2023 and is estimated to be 16.5 USD/MWh in 2050. Based on Figure 5 (NREL, 2024b), the U.S. average LCOE for residential-scale PV systems was 90.1 USD/MWh in 2023 and is estimated to be 50.8 USD/MWh in 2050. Although different capacity ratings are used (AC for the utility-scale and DC for the residential-scale), the LCOE values remain comparable because the PV systems utilize consistent capacity ratings.

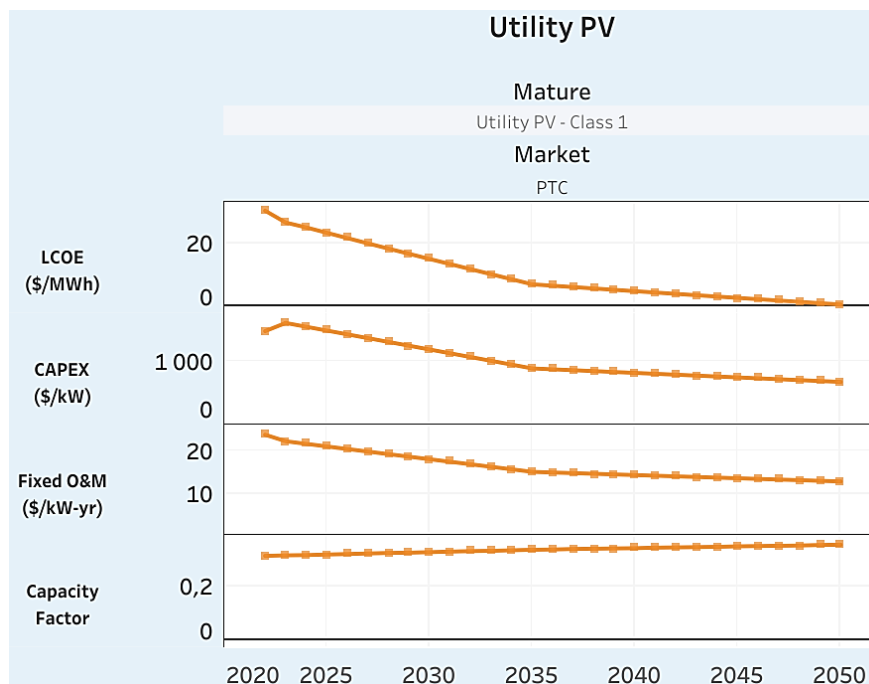


Figure 4: Average LCOE, CAPEX, fixed O&M costs, and CF for utility-scale PV systems in the U.S. Note: Screenshot of an interactive graph of a 74.6 MW_{AC} (100 MW_{DC}), one-axis tracking PV system. Modified to show a Moderate Scenario, the Market Case, GHI>5.75 kWh/m²/day, and a payback period of 30 years. The latest historical data is from 2023, with projections for 2035 and 2050. Retrieved from "Utility PV", by NREL, 2024a. https://atb.nrel.gov/electricity/2024/utility-scale_pv

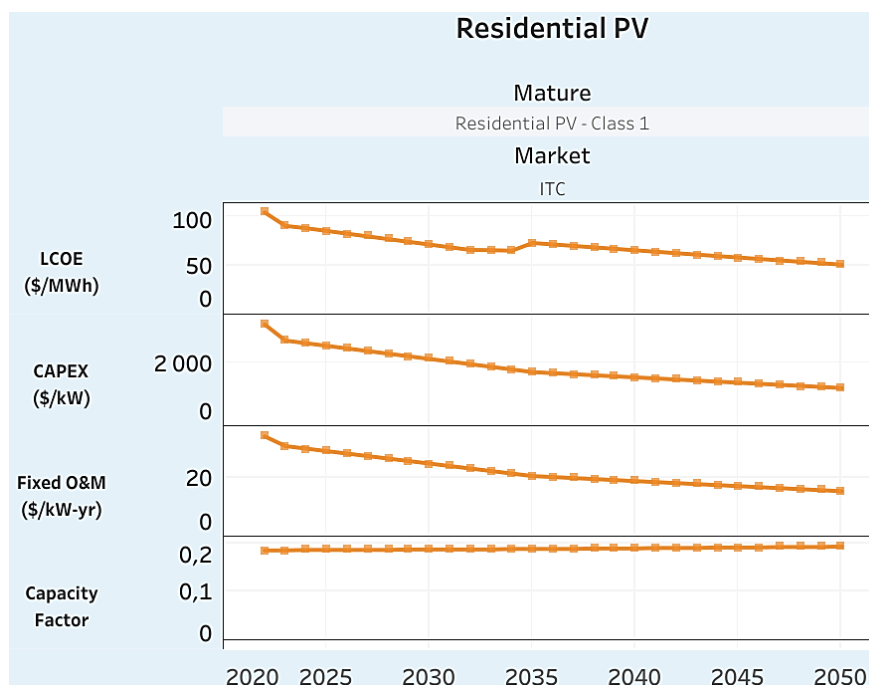


Figure 5: Average LCOE, CAPEX, fixed O&M costs, and CF for residential-scale PV systems in the U.S. Note: Screenshot of an interactive graph of a 7.9 kW_{DC}, fixed tilt, roof-mounted PV system. Modified to show a Moderate Scenario, the Market Case, GHI>5.75 kWh/m²/day, and a payback period of 30 years. The latest historical data is from 2023, with projections for 2035 and 2050. Retrieved from "Residential PV", by NREL, 2024b. https://atb.nrel.gov/electricity/2024/residential_pv

2.4.2 Capital Expenditures

Capital expenditure (CAPEX) covers the total expenses involved in making the system operational (NREL, n.d.). It includes costs of all the components that make up a PV system, electrical infrastructure, grid connection and interconnections, installation, land area (acquiring, leasing, or preparing), and the owners' expenses (permitting, legal fees, insurance, financing fees, and contingency funds). For CPVS, land costs may account for up to 20% of the total system cost, while for rooftop mounted DPVS, these costs are often negligible (Azevêdo, Junior, Rocha, Chicco, Aquila & Peruchi, 2020).

CPVS requires a significant capital investment for construction, operation, maintenance, and infrastructure, which can extend the payback period and affect financial profitability (Egret Solar, 2024). The payback period is the time needed to recover the initial investment cost (Azevêdo et al., 2020). In contrast, DPVS generally requires lower initial investment, offers owners energy savings and enhanced energy security, further improves their overall economic benefits, and results in a shorter payback period.

CPVS have lower total costs per watt produced (and per kilowatt-hour) compared to DPVS, due to economies of scale (NREL, 2010; Cox et al., 2016; Rose, 2023; Raza, 2023; Hongyuan, 2023; IEA et al., 2024). Due to their large size, CPVS projects have reduced per-unit energy costs through bulk purchasing, standardized designs, and optimized operational efficiencies. This makes them highly competitive in terms of energy production costs. Even with transmission and distribution costs factored in, CPVS often represents the most cost-efficient method for deploying PV energy.

Based on Figure 4 (NREL, 2024a), the U.S. average CAPEX for utility-scale PV systems was 1610.9 USD/kW_{AC} in 2023 and is estimated to be 682.9 USD/kW_{AC} in 2050. Based on Figure 5 (NREL, 2024b), the U.S. average CAPEX for residential-scale PV systems was 2682.2 USD/kW_{DC} in 2023 and is estimated to be 1208.1 USD/kW_{DC} in 2050.

2.4.3 Total Installed Costs

Total installed cost is a subset of CAPEX, encompassing all installation and indirect costs needed to build and set up the PV system (NREL, n.d.). This includes direct installation labor and materials, engineering and procurement, and startup and commissioning.

Due to the smaller scale of its systems, the residential rooftop PV market generally has higher total installed system costs per unit of capacity than the utility-scale market (IRENA, 2021).

According to IRENA (2024b), the global average total installed cost for utility-scale PV projects commissioned in 2023 was 758 USD/kW_{DC}, down from 1019 USD/kW_{DC} in 2020. In South Africa, the average total installed cost for utility-scale PV projects commissioned in 2023 was 1255 USD/kW_{DC}. For residential-scale PV projects (presumably without battery storage), the latest data available is for projects commissioned in 2020, which shows that the country-based average total installed cost ranged between 658 USD/kW_{DC} and 4236 USD/kW_{DC} (IRENA, 2021). This created a global average of 1747 USD/kW_{DC}. In South Africa, the total installed cost for residential-scale PV projects commissioned in 2020 was 1575 USD/kW_{DC}.

Due to the insufficient data from African countries, average data from the U.S. is provided. The has total installed costs for residential-scale and utility-scale PV systems in U.S from 2010 to 2023, according to NREL (2024c) are presented in the figure below.

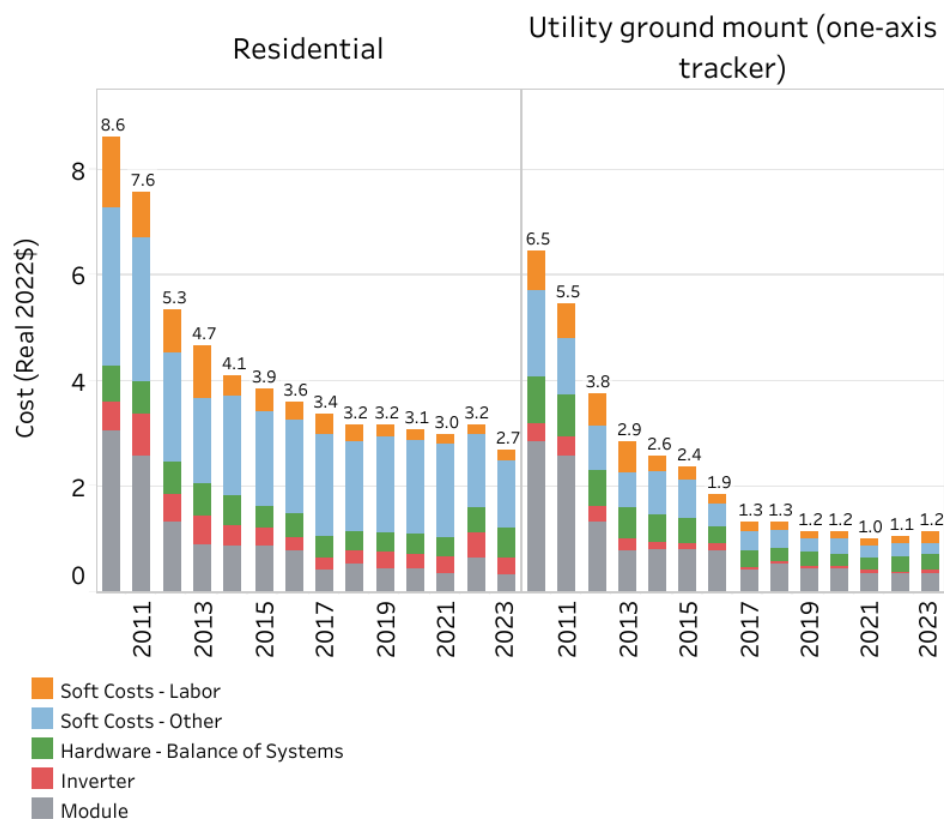


Figure 6: Total Installed Cost for residential-scale and utility-scale PV systems in the U.S.
Note: Screenshot of an interactive graph modified to show: Residential and Utility ground mount (one-axis tracker). Retrieved from “Solar Costs”, by NREL, 2024c. <https://www.nrel.gov/solar/market-research-analysis/solar-installed-system-cost.html>

Based on the histograms in Figure 6 (NREL, 2024c), the average total installed cost in 2023 was 1.2 USD/MW for utility-scale PV systems and 2.7 USD/MW for residential-scale PV systems (without battery storage).

2.4.4 Operation and Maintenance Costs

Operation and Maintenance (O&M) Cost encompass all fixed, maintenance, and replacement costs, including fixed and variable cost components (NREL, n.d.). It is the cost of maintaining the system per unit of installed capacity.

O&M costs are necessary to ensure ongoing PV system performance and power quality (Azevêdo et al., 2020). These costs, which vary with the system's capacity and energy generation, are generally low due to the simplicity of solar power plants, which require minimal mechanical components. PV systems with sun-tracking configurations can be more profitable due to their ability to optimize the tilt and azimuth angles, enhancing solar radiation capture. However, fixed PV systems are generally more affordable, as sun-tracking configurations require higher maintenance due to the mechanical components.

Batteries increase maintenance needs and decrease the lifetime of the PV system (Bhatia, n.d.). The life-cycle costs of DPVS are primarily driven by battery replacement costs, which are often overlooked when only initial CAPEX or total installed costs are considered (Nässen, Evertsson & Andersson, 2002).

CPVS benefits from economies of scale and requires fewer technicians per watt compared to DPVS (LA Solar Group, n.d.; Waaree RTL, 2024). This leads to lower long-term O&M expenses, making CPVS more cost-effective in the long run.

According to IRENA (2024b), the average capacity-weighted O&M cost for utility-scale PV projects commissioned in 2023 was 10.3 USD/kWh per year. IRENA does not mention O&M costs for residential-scale PV projects.

Based on Figure 4 (NREL, 2024a), the U.S. average annual fixed O&M cost for utility-scale PV systems was 22.2 USD/kW_{AC} in 2023 and is estimated to be 12.8 USD/kW_{AC} in 2050. Based on Figure 5 (NREL, 2024b), the U.S. average annual fixed O&M cost for residential-scale PV systems was 30.4 USD/kW_{DC} in 2023 and is estimated to be 15.4 USD/kW_{DC} in 2050.

2.4.5 Capacity factor

The capacity factor (CF) is the ratio of the annual average energy production to the theoretical maximum annual production if the system operates at its rated capacity continuously throughout the year (NREL, 2024b). This means that the higher the CF, the better. The CF is intended to reflect the system's long-term average performance, which is influenced by factors such as the solar profile throughout the day, the type of technology used, expected downtime, and losses during the conversion from DC to AC power.

DPVS are more frequently placed in areas where shadows from trees or surrounding obstacles are prevalent, thereby reducing the efficiency of the PV modules, unlike CPVS, which are typically positioned in broad, unobstructed areas (Waaree RTL, 2024). CPVS's PV modules can be precisely aligned with optimal azimuth and tilt angles, enhancing solar radiation capture (Azevêdo et al., 2020). Consequently, CPVS often generates a greater energy output per unit of installed capacity, leading to an increased CF. Other environmental factors affecting the specific yield, and therefore the CF, are mentioned in Section 2.2.

According to IRENA (2024b), the global weighted average CF for utility-scale PV projects commissioned in 2023 was 0.162 (16.2%). IRENA does not mention CF for residential-scale PV projects.

Based on Figure 4 (NREL, 2024a), the U.S. average CF for utility-scale PV systems was 0.317 in 2023 and is estimated to be 0.357 in 2050. Based on Figure 5 (NREL, 2024b), the U.S. average CF for residential-scale PV systems was 0.185 in 2023 and is estimated to be 0.193 in 2050. Over this lifespan, system output typically decreases due to PV module degradation, which is accounted for in the CF estimates. Since the two PV systems use different capacity ratings (AC for the utility scale and DC for the residential scale), the values for CF are not directly comparable.

2.4.6 Scalability

Scaling CPVS is challenging due to their complex processes, including site selection, permitting, financing, and construction (ESCAP, n.d; RES4Africa, 2023; Raza, 2023). Therefore, CPVS generally requires 2-3 years to integrate into the electrical grid. DPVS have shorter development timelines and fewer permitting hurdles.

DPVS, are highly scalable and can be deployed quickly (ESCAP, n.d.; Cox et al., 2016; Rose, 2023). Additional units can be installed incrementally based on demand and available funding (provided there is sufficient space), and there is no need for extensive transmission infrastructure that can be difficult to finance. DPVS can, therefore, be especially significant in countries with high demand growth, geographically dispersed loads with minimal electricity needs, and ongoing or planned energy infrastructure development. The shorter transmission distance for DPVS also reduces inefficiencies, resulting in lower energy losses than CPVS (ESCAP, n.d.; Picard & Toulemont, 2022; Waaree RTL, 2024).

2.5 Socio-Economic Evaluation Criteria

This section offers evaluation criteria and comparative data on CPVS and DPVS from a socio-economic perspective. Each sub-section corresponds to an individual criterion within the assessment framework. Key data from this section is presented in section 4.2.

The social and economic dimensions of energy access are closely linked, so combining these allows for a clearer understanding of how electricity access directly affects both the quality of life and economic opportunities available to rural communities.

2.5.1 Affordability of Energy Services

Electricity affordability is crucial for maximizing the social, economic, and health benefits of extending electricity services (IEA, 2022). Due to low social tariffs, grid-based electricity is generally the cheapest option. In 2021, more than three-quarters of the population in Sub-Saharan Africa (almost 390 million people) struggled to pay for more than essential electricity services, such as lighting, phone charging, radio, fans, and television. Thirty percent of the population (over 150 million people) had no financial resources to afford essential electricity services at national residential electricity prices.

In Tanzania, electricity prices are relatively low compared to global and regional averages (GlobalPetrolPrices, n.d.). Residential electricity prices in the country are 59.2% of the global average and 73.9% of the average for African countries. For businesses, Tanzanian electricity prices are 61.6% of the world average and 85.6% of the African average.

As of March 2024, the fixed residential electricity price in Tanzania is set at 0.084 USD per kilowatt-hour (USD/kWh), while the fixed price for businesses is 0.087 USD/kWh (GlobalPetrolPrices, n.d.). These are subsidized retail rates for electricity and encompass the costs of electricity generation, distribution, transmission, and taxes. Additionally, TANESCO has introduced a tiered pricing system to address the needs of different customer groups regarding electricity and fuel prices. For instance, residential customers with low electricity consumption pay only 86.5% of the price charged to those with high consumption levels. This pricing structure aims to make electricity more affordable for small, low-income families and organizations. Conversely, small businesses face a significant challenge, as they pay 131.61% more for electricity than larger companies, which may strain their finances, particularly in rural areas with limited energy access.

The upfront cost of connecting to the grid is a significant barrier, with many customers facing charges from service providers and the cost of purchasing appliances (IEA, 2022). For those in extreme poverty, these costs can amount to as much as six months of income. Some African countries have subsidized these connection costs through government support or regulatory measures. Extending such support to DPVS (and mini-grids) could make off-grid electricity more affordable for poor households.

In Tanzania, the cost of connecting to the national grid varies based on several factors, including the type of connection (single-phase or three-phase), the customer's location (rural or urban), and the distance to the nearest existing infrastructure (30, 60, or 90 meters) (TIC, n.d.). Single-phase connections are less expensive than three-phase connections, customers in rural areas pay lower costs than those in urban areas, and shorter distances to existing infrastructure result in lower connection fees. Even though rural families face lower connection costs, these fees can create substantial financial barriers, making it challenging for many to afford electricity access without external financial assistance.

In summary, electricity generated from centralized sources, such as CPVS, is affordable for customers. However, the cost of connecting to the grid can pose a financial barrier. For DPVS, the potential savings from the electricity that would otherwise be purchased from the grid may not be enough to justify a significant investment for rural customers. Instead, the reduced expenses for fuel to backup generators and for cooking and the income opportunities DPVS provides serve as a stronger reason to invest in these systems.

2.5.2 Empowerment and Gender Equality

Women and girls are disproportionately affected by energy poverty because of gender norms and traditions, which hinder access to modern energy services (IEA et al., 2024). In many rural communities, decision-making processes are often male-dominated, which can marginalize women from discussions that directly impact them (Odarno et al., 2015). Women may have lower purchasing power and limited access to credit, which could hinder their ability to pay for energy services. Addressing these challenges through gender-sensitive engagement can lead to more effective and equitable outcomes.

There is a noticeable gap in women's awareness and access to information about new technologies that can foster skill development and economic opportunities (IEA et al., 2024). In addition to reducing dependence on external energy sources, installing DPVS gives consumers more knowledge and control over their electricity supply (Waaree RTL, 2024). Research in the stand-alone off-grid solar sector has found that the inclusion of women as consumers, employees, and entrepreneurs improves service delivery, enhances financial performance, supports employee retention, and promotes innovation (ESMAP, 2022). Acquiring knowledge gives them power, which enables them to empower themselves.

DPVS can offer significant developmental benefits, particularly in advancing gender equality, as highlighted by Cox et al. (2016) and RES4Africa (2023). One key benefit is enhanced educational opportunities for women and girls. With reliable electricity for electric appliances, less time is spent collecting fuel, and household responsibilities (such as cooking) become more effective, freeing up time for education or business activities. This increased availability of time supports both learning and women's productive activities, ultimately improving their quality of life. This promotes social justice and equity within local communities.

Other benefits of reliable electricity for electric appliances include fewer respiratory illnesses due to reduced indoor air pollution, better food quality through refrigeration, improved water sanitation through water treatment and distribution systems, reduced maternal mortality rates through the electrification of rural clinics, and enhanced personal safety through outdoor lighting (Cox et al., 2016). Improved lighting services also create better study environments, while access to computers, advanced technologies, and communication tools facilitates higher-level education. These advancements contribute to overall health and well-being, illustrating the wide-reaching impact of access to reliable electricity on communities.

2.5.3 Job Creation and Entrepreneurship Opportunities

The global energy transition creates significant demand for resources and jobs, positioning the renewable energy sector to generate substantial employment opportunities across the value chain (RES4Africa, 2023). This presents a promising future for Africa's upcoming generations. Several projects also include training programs for young people to foster entrepreneurship and job creation.

Achieving universal energy access in Sub-Saharan Africa is projected to create an additional four million energy-related jobs by 2030 (IEA, 2022). Many of these jobs provide entry into the formal economy and enhance entrepreneurial opportunities for women. African energy companies are increasingly significant, with joint ventures and technology transfers fostering local expertise.

In Tanzania, job opportunities related to CPVS and DPVS are expected to grow significantly between 2020 and 2030 as the country plans to install approximately 3.8 GW by 2030 (IRENA, 2017). By then, it is estimated that there will be 19190 jobs connected to CPVS and 994 jobs connected to DPVS. Most of these jobs will be in construction and installation, operation and maintenance, decommissioning, and manufacturing. The construction and installation sector, particularly for PV projects, will create roles for construction workers, technicians, and engineers. Additionally, new employment opportunities will emerge for professionals in marketing, distribution, and supply chain management, particularly within the small-scale solar PV value chain.

Key public institutions in Tanzania, such as the national utility TANESCO, lack sufficient technical expertise in assessing and executing large-scale solar power projects (Aly et al., 2019). Local Tanzanian companies often face challenges in meeting the technical requirements of international funders, which limits their participation in renewable energy projects. Foreign companies, on the other hand, often dominate the proposals submitted for funding, leading to most of the energy-related funds being allocated to non-African entities. This undermines the development of local skills, industries, and jobs in Tanzania. DPVS, on the other hand, requires local businesses to build, operate, and maintain the facilities, thus generating more opportunities for local enterprises and employment in Tanzania (ESCAP, n.d.).

DPVS can enhance enterprise and business development in rural communities (Cox et al., 2016). Examples are enabling battery charging, mobile phone rentals, and the operation of

various businesses utilizing equipment like welders, mills, pumps, and power tools. DPVS facilitates integration with sectors like agriculture and water management, boosting efficiency and resilience (RES4Africa, 2023). This integration offers enhanced agricultural activity and productivity at reduced costs.

2.6 Environmental Evaluation Criteria

This section offers evaluation criteria and comparative data on CPVS and DPVS from an environmental perspective. Each sub-section corresponds to an individual criterion within the assessment framework. Key data from this section is presented in section 4.2.

2.6.1 Carbon Footprint

Due to similar technology, CPVS and DPVS should presumably have a comparable carbon footprint per unit of electricity generated. The differences may arise from factors such as energy losses during transmission and the frequency of needing to replace components.

Unlike DPVS, the electricity generated by CPVS typically has long transmission distances, which can lead to increased transmission losses (ESCAP, n.d.; Picard & Toulemont, 2022; Waaree RTL, 2024). This results in an increased need for generation, which leads to increased emissions and a larger carbon footprint.

DPVS carbon footprint is affected by battery replacement. The absence of both physical and legislative infrastructures to effectively handle waste generated from electronic products is a well-recognized problem that presents serious health and environmental hazards throughout Sub-Saharan Africa (Kinally & Schmid, 2024). Due to the lack of established waste management systems, informal technicians recycle lead-acid batteries by smashing them and melting them using cooking stoves before manually constructing improvised battery cells. These informal practices can release more than 3.5 kg of lead pollution from one solar home system battery.

Limited access to grid-based electricity has led businesses and agricultural sectors to depend more heavily on decentralized, fossil fuel-based energy solutions over the past decades (RES4Africa, 2023). This trend is evident in both remote and urban regions, as well as in industrial areas. This is even though modern DPVS can effectively power schools, health

centers, and small businesses and serve other productive purposes, thereby reducing the carbon footprint, fostering economic opportunities, and enhancing the quality of life in rural areas.

In 2023, 38.7% of firms in Tanzania own or share a generator due to significant sales losses caused by power outages (Enterprise Surveys, 2023). When a generator is used, it accounts for an average of 24.3% of the user's electricity consumption. This reliance on generators increases costs, reduces profit margins, and contributes to a larger carbon footprint. Installing DPVS with adequate battery storage could help cover electricity demand during power outages, potentially reducing the user's carbon footprint by 24.3 %. Creating CPVS without addressing the issues causing power outages in the grid will not effectively reduce the user's carbon footprint.

In institutional settings, such as schools and health centers, hybrid systems below 5 kWp are often deployed (Léna, 2013). These systems must balance peak daytime demand with evening needs, often using batteries to store solar energy and generators/the grid to supplement power during periods of high demand or low solar output. The ability to adjust to fluctuating loads and optimize the use of solar energy can reduce system costs and fuel consumption.

Selling excess energy back to the grid can offer a substantial financial incentive for owners of DPVS to prioritize efficient energy production and consumption (ESCAP, n.d.). This added income motivates individuals and businesses to focus on reducing their energy usage, which ultimately lowers the carbon footprint associated with DPVS.

2.6.2 Land Use

Due to their larger scale, CPVS require extensive land areas for development, often spanning hundreds or even thousands of acres. This can lead to the occupation of land resources and impact the surrounding ecological environment (Rose, 2023; Raza, 2023; Egret Solar, 2024; Waaree RTL, 2024). Additionally, CPVS may consume significant water resources and alter natural landscapes during both construction and operation. The environmental impacts associated with CPVS include effects on biodiversity (affecting birds, bats, and insects) as well as impacts on soil, water consumption, and human health (Hernandez et al., 2014, as cited in Aly et al., 2019).

Acquiring large parcels of land for CPVS can be challenging, especially in densely populated regions (Waaree RTL, 2024). However, Tanzania has an abundance of land available for large-scale photovoltaic installations, facing little competition from other land uses (Aly et al., 2019).

The considerable land area required can lead to complex and lengthy permitting processes that involve multiple government agencies (LA Solar Group, n.d.). These processes can result in project delays and increased costs due to the need to secure land access rights. Additionally, CPVS requires additional land for the infrastructure necessary to transmit generated electricity to end-users (Hongyuan, 2023).

DPVS, on the other hand, generally have a much smaller environmental footprint because their installation typically takes place on rooftops, parking lots, or other available areas close to where electricity is consumed (Rose, 2023; Raza, 2023; Egret Solar, 2024; Waaree RTL, 2024). This approach minimizes land alteration and reduces disruption to natural habitats and local ecosystems.

2.7 Institutional Evaluation Criteria

This section offers evaluation criteria and comparative data on CPVS and DPVS from an institutional perspective. Each sub-section corresponds to an individual criterion within the assessment framework. Key data from this section is presented in section 4.2.

2.7.1 Policy and Regulatory Support

In addition to working to improve the electricity infrastructure and expedite rural electrification, the Tanzanian government is focused on adopting renewable energy sources (ITA, 2022). Policymakers can significantly contribute to the energy transition by implementing policies that support the growth and use of renewable energy sources (IRENA, IEA & REN21, 2018). The primary goal of supportive policies for renewable energy is to encourage growth in both capacity and production. Clear and effective policies help to increase the use of renewable energy and lower costs. They support the growth of the renewable industry, create new markets, and encourage innovation. These policies also provide the stability needed for investing in renewable energy, which in turn reduces costs and improves competitiveness. For instance, Tanzania has removed value-added and import taxes on main solar components (panels, batteries, inverters, and regulators) to make PV systems more affordable and accessible (Maswi, 2013).

Due to their alignment with national energy security strategies, CPVS often faces strict regulatory requirements, particularly regarding land use, environmental assessments, and power transmission regulation, as well as market participation rules (Raza, 2023; Egret Solar, 2024). These policies can slow down their development. Political interference in the operations of the utility company TANESCO and the regulatory body EWURA is a considerable concern (Aly et al., 2019). Political leaders have substantial influence over critical decisions in the energy sector, which undermines the independence and effectiveness of regulatory institutions. This interference hinders investment in large-scale solar projects, contributing to a broader environment of uncertainty and risk.

In contrast, regulatory frameworks are evolving to promote DPVS, which often receive benefits from incentives like net metering policies, tax credits, loan support, subsidies, and repayments (Raza, 2023; Egret Solar, 2024). While DPVS can be economically viable, they may not offer substantial economic benefits, making some private investors reluctant to engage in private generators (Azevêdo et al., 2020). In Tanzania, the government is incentivizing a national and regional net-metering program to encourage self-generation of electricity (Multiconsult, 2022; IRENA, 2024a). As it has not yet been adopted, the country is missing out on valuable small-scale and distributed investments in renewable energy projects. Thus, a net-metering program is recommended.

According to Aly et al. (2019), insights from diverse stakeholder groups in Tanzania (public institutions, research organizations, private investors, civil society groups, development partners, and financial institutions) suggest that institutional barriers hinder the deployment of CPVS. These include the uncertainty regarding the government's long-term commitment to large-scale solar initiatives and the perception that solar power is unsuitable for large-scale generation.

Tanzanian financial institutions are generally hesitant to finance CPVS, viewing them as risky due to the perceived unpredictability of revenue from solar energy (Aly et al., 2019). The high upfront costs and long project timelines associated with solar power make these projects less attractive to Tanzanian banks, which typically prefer shorter loan terms for conventional energy projects like gas-fired power plants. As a result, private investors in solar energy often face very high interest rates, sometimes reaching 20%, which further increases the already high initial costs. These unfavorable financing conditions make large-scale solar power projects less

competitive compared to conventional energy sources, which can secure more favorable financing backed by government guarantees.

A challenge hindering private sector investment is the restrictive financial environment, where high borrowing costs make securing investment loans difficult (IRENA, 2017). The government perceives many private investors as problematic and unreliable (Aly et al., 2019). As a result, the government has been focusing on leading the power sector through predominantly state-owned projects, seeking to maintain control to prevent corruption and ensure fair revenue from national resources, including energy and minerals.

Although changes in leadership have sometimes shifted these priorities, Tanzania still tends to support large-scale, state-owned gas and hydro projects because they are seen as less politically risky (Pedersen & Poncian, 2024). For years, this focus limited the growth of private renewable energy projects. Recently, under President Samia Suluhu Hassan, the energy sector is moving towards market-friendly reforms (Pedersen & Poncian, 2024). Efforts to separate TANESCO's operations and change tariffs have restarted, showing a willingness to invite foreign investment and private sector participation. Thanks to changes in leadership and support from flexible donors, Tanzania has begun its first large-scale, state-owned solar project. In 2021, the public financial institution French Development Agency (AFD), financed Tanzania's first grid-tied PV power plant, as well as several investments aimed at upgrading TANESCO's transmission network and transforming it into a "smart grid" capable of managing being fed with intermittent production, like solar power (AFD, 2021).

2.7.2 Sources of Funding

Funding for PV generation initiatives typically comes from four primary sources: government subsidies and incentives, donor grants, debt and equity financing, and consumer tariffs (Odarno et al., 2015). The specific financing method often varies depending on the type of actor involved in the project. Large-scale generation typically requires funding from development banks, government bonds, and public-private partnerships, while distributed solutions that leverage a broader range of stakeholders, including consumers, private investors, microfinance institutions, and NGOs (IRENA et al., 2018; IEA et al., 2024). Subsidies, often provided by national and sub-national governments, donors, or other electricity consumers, typically cover capital expenses, reducing the initial costs of implementing PV technologies (Odarno et al.,

2015). However, one-time capital subsidies, such as donor grants, may not contribute to long-term financial sustainability.

The long-term financial viability of PV projects, whether implemented by governments, private developers, or communities, depends on consistent financial resources to cover initial capital costs and ongoing operation and maintenance expenses (Odarno et al., 2015). Private developers of DPVS typically use loans and private equity, though concerns about financial sustainability can limit these options. Governments and donors can mitigate these risks with loan guarantees and low-interest loans, alongside clear policies to reduce investment risks. The financial viability for DPVS projects hinges on consistent funding to cover capital and O&M costs.

Consumer financing options are necessary to address the upfront costs of DPVS (Odarno et al., 2015). However, banks often view low-income consumers as high-risk and are reluctant to provide credit. Government and donor support can help by offering loan guarantees, enabling poor consumers to access financing. Some African DPVS providers offer payment alternatives, such as PayGo, based on rent-to-own or leasing arrangements, to address upfront cost challenges (IEA, 2022). For DPVS between 20 and 80 Watts, customers typically pay a small upfront deposit of 20-70 USD for the system and appliances and then pay back the cost of the system through monthly fees of 20-30 USD for the next 3 years.

Private sector investments in renewables are one of the key enablers of the clean energy transition in Tanzania (Multiconsult, 2022). But, despite the availability of feed-in tariffs and power purchase agreements (PPAs) for CPVS, private investors are reluctant to invest in Tanzania (IRENA, 2017). This reluctance stems from the weak financial status of TANESCO and the government's inability to ensure payments if TANESCO defaults. The risk of non-payment by TANESCO, which has large debts owed to various investors and suppliers, is one of CPVS's most significant financial barriers (Aly et al., 2019). This non-payment risk is among the highest in Sub-Saharan Africa, making it a major deterrent to investment in large-scale solar power projects. The high risk of non-payment also affects financing conditions, leading to increased interest rates from lenders, which in turn raises the overall cost of PV projects.

Development aid from developed countries significantly supports the expansion of electrification in Sub-Saharan African nations (Aly et al., 2019). An investigation by the International Institute for Environment and Development (IIED) assessed funding

commitments for CPVS versus DPVS by the Tanzanian government and its development partners, concluding that a significant majority of funding for energy projects from international and domestic sources is directed toward large grid-connected initiatives, such as grid expansion (Kaijage et al., 2017, as cited in Aly et al., 2019).

2.7.3 Energy Security

CPVS increases a region's electricity generation capacity, thereby enhancing the national energy security (Rose, 2023). They can support grid reliability by providing low-cost, clean energy during periods of high demand and offering ancillary services like voltage support and frequency regulation (Raza, 2023). However, they are challenged by issues like intermittency and grid constraints. If a significant CPVS fails, it impacts the entire grid. Severe natural disasters might also harm a country's electrical grid (Picard & Toulemont, 2022).

DPVS can offer resilience to the grid, as failures are localized, affecting only a small area rather than large regions (Rose, 2023). DPVS are, therefore, particularly valuable in areas prone to grid instability or outages, such as rural regions. During times of high demand, DPVS can be effectively utilized to reduce electricity consumption from the grid, thereby alleviating stress on infrastructure (Picard & Toulemont, 2022). Energy storage integration, such as with solar batteries, can also improve grid stability and resilience (Raza, 2023).

DPVS contributes to local energy security by generating electricity close to where it is used, which reduces the reliance on the grid (Rose, 2023). Off-grid DPVS without sufficient battery backup can experience power reliability issues during periods of low solar generation (Egret Solar, 2024).

2.7.4 Financial Profitability

One significant factor affecting the profitability of a PV project is the electricity prices associated with both the reduction in purchased electricity and the reimbursement for generated electricity (Verhelst, Desmet, Debruyne, Van Landeghem & Vandeveld, 2010). For the former, most relevant for DPVS projects, profitability hinges on the savings from the electricity that would have been purchased from the grid. For the latter, most relevant for CPVS, profitability hinges on the tariffs being high enough to cover operation, maintenance, and

capital expenses (Odarno, et al., 2015). High electricity tariffs can make PV generation a lucrative investment even in countries with low specific yield potential (ESMAP, 2020).

Verhelst et al. (2010) presents an equation that defines profitability across four terms to account for varying weekday and weekend pricing. Since Tanzania's energy prices remain consistent throughout the week, the author has simplified this equation to contain two terms, as shown in the equation below.

Eq. 1

$$profit = \left(TP * \%P * \%OC * \frac{USD}{kWh_{pu}} \right) + \left(TP * \%P * \%S * \frac{USD}{kWh_{so}} \right)$$

Where: TP = Total annual electricity production,
 %P = Percentage of production,
 %OC = Percentage of on-site consumption,
 USD/kWh_{pu} = Purchase cost of electricity,
 %S = Percentage of electricity sold, and
 USD/kWh_{so} = Sales revenue cost of electricity.

In the equation above, the purchase cost of electricity the key factor for DPVS, whereas the sales revenue cost is more critical for CPVS. This is because DPVS are often designed for self-consumption, so their profitability relies on the cost savings from reduced grid electricity purchases, In contrast, CPVS typically exports most of its generated electricity to the grid, meaning its profit depends on the reimbursement price per kWh.

A challenge for CPVS comes from the Tanzanian government's proposed limit on electricity tariffs (Aly et al., 2019). The Tanzanian government's maximum tariff for all electricity generation projects has led to difficulties in signing PPAs with solar power developers, as they usually need higher fees. Enforcing strict tariff limits to keep the subsidized retail rate for electricity affordable for users contributes to investor uncertainty.

As mentioned in sub-section 2.5.1, Tanzania, the subsidized retail rate for electricity is affordable for users (GlobalPetrolPrices, n.d.). The residential electricity prices in the country are 73.9% of the average for African countries, at a fixed rate of 0.084 USD per kilowatt-hour (USD/kWh) in March 2024. Due to these low social tariffs, where grid-based electricity is generally the cheapest option for customers, the profitability of DPVS is also low, as the savings from the electricity that would have been purchased from the grid is low. Due to insufficient

grid electricity, DPVS provides financial savings by reducing expenses for fuel to backup generators and for cooking, as well as time spent gathering fuel resources or traveling for battery charging services (Cox et al., 2016).

Although many installers suggest that PV systems are highly profitable in the short term, this claim should be cautiously approached (Verhelst et al., 2010). While installers might suggest payback periods of 6-7 years, the actual payback period may be nearly double when all relevant technological, environmental, and economic factors are accounted for. Sensitivity analyses indicate that the discount rate and panel efficiency are the most influential factors.

2.7.5 System Sustainability

For the successful implementation, operation and expansion of PV projects, it is essential to develop the necessary technical expertise, institutional capacity, and business skills (Odarno et al., 2015). This calls for targeted training programs for stakeholders such as project developers, regulators, utilities, financiers, and sometimes consumers. Agencies, including rural electrification bodies, may require additional training to effectively oversee and regulate PV systems and proactively identify the specific knowledge and skills required for long-term planning. This includes understanding the necessary regulatory oversight, technical knowledge, financing options, stakeholder participation, and monitoring protocols.

The sustainability of DPVS in remote areas hinges not only on technical design but also on proper management, community engagement, and financial planning (Léna, 2013; Odarno et al., 2015). With the right combination of local involvement, well-designed systems, and supportive policies, these systems can provide reliable and sustainable energy to underserved areas. Traditional methods for electrifying public institutions (such as healthcare facilities and schools) have often struggled to maintain sustainability due to limited capacity and insufficient funding for continuous maintenance (IEA et al., 2024). Innovative approaches can achieve long-term sustainability by integrating private sector expertise and investment with carefully designed financing mechanisms and incentives.

Local technicians and operators who manage the O&M of DPVS play a key role in ensuring their sustainability (Odarno et al., 2015). Unlike CPVS owners, DPVS owners in rural areas are frequently left without adequate technical support after the installation, leading to issues with system operation and sustainability (Pillota et al., 2017). If DPVS owners are unaware and do

not expect deteriorating system performance, especially considering battery performance, it can lead to dissatisfaction and abandonment of the technology. The high O&M costs associated with DPVS in Sub-Saharan Africa, further complicate the situation as they are often underestimated, leading to unexpected expenses for the owners.

Unlike CPVS initiatives, engaging users in DPVS initiatives, both as communities and individuals, is vital for building support and ensuring the financial sustainability (Odarno et al., 2015). By engaging users during the planning phase, local energy needs, socio-economic characteristics, and capacity requirements are more likely to be accurately understood. This engagement allows for more informed decisions regarding technology selection, business models, and operational and maintenance structures for DPVS solutions. Consumer input is crucial in determining whether to use DPVS or mini-grids in electrification efforts. Moreover, it informs decisions on tariff levels and payment methods that align with the target consumers' income flows and livelihood patterns.

3 Methodology

This chapter provides an overview of the research methodology employed in this study. This included the systematic approach taken to address the research questions and achieve the objectives described in section 1.3.

Statement: The software program Grammarly, developed by Grammarly, Inc., was used for proofreading, paraphrasing, and improving sentences written by the author. The author has reviewed the output and takes full responsibility for the content.

3.1 Mixed-methods Research Approach

This study utilized a mixed-methods research approach, integrating qualitative and quantitative approaches (George, 2021). The author benefited from the detailed information from qualitative data, as well as the broadly applicable information from quantitative data. Using qualitative data to support quantitative results helped add more substance to the information.

Qualitative research is expressed in words (Streefkerk, 2019). Typical qualitative approaches include interviews with open-ended questions, written observations, and literature analyses investigating concepts and theories. Qualitative research aims to examine the daily experiences of various groups and communities in their natural environments and to understand a social situation from participants' perspectives (UIR, n.d.).

Quantitative research is represented through numerical data and graphs (Streefkerk, 2019). Typical quantitative approaches consist of experiments, numerical observations, and surveys with multiple-choice questions. Quantitative research aims to describe, compare, and attribute causality, establish relationships between measured variables, and achieve a deeper comprehension of the social environment (UIR, n.d.).

3.2 Primary Research Approach

The primary research method involves using first-hand information (primary data) collected by yourself (George, 2023a). This approach is commonly utilized in qualitative research, especially in techniques like surveys, questionnaires, focus groups, and different forms of interviews. In this study, the primary data was used to supplement/strengthen existing secondary data.

3.2.1 Observations

Participatory observations were conducted during fieldwork from March 5th to March 16th. This data collection method provided primary qualitative data. The goal was to capture live interactions, techniques, community acceptance, and knowledge transfer processes that emerged during the installation and operation of a PV system and an InfoSpot.

To capture the nuances of PV system installation, the author closely followed the installation team, documenting the process through mobile photography and detailed notetaking. This is outlined in sub-section 3.5.3. The goal was to observe not only the technical procedures but also the social interactions and exchanges of expertise between the installers and local stakeholders, including the school director, volunteers, teachers and students.

Throughout the PV system installation, observations captured situations such as stakeholder engagement and installers using battery power to operate hand tools during an unexpected power outage (as outlined in sub-section 3.5.3). This illustrated the resilience of a PV system paired with batteries. These observations provided a comprehensive understanding of how the PV system was installed, the technical challenges encountered, and the practical solutions applied in a real-world setting.

The researcher took part in the installation and training sessions for the InfoSpot system, working alongside local volunteers, as outlined in sub-section 3.5.4. During this phase, observations focused on the technical setup process and the researcher's role in explaining the system's configuration and functionality to local participants. The study highlighted how community members engaged with the system and learned to operate it. This demonstrated the importance of providing accessible and relevant training for the sustainable adoption of technology. The findings also contributed to an understanding of how community involvement can enhance the integration of technology in under-resourced areas.

3.2.2 Interviews

Unstructured verbal and textual interviews were conducted before, during, and after fieldwork to collect qualitative and quantitative primary data. The interviews consisted of informal discussions with local stakeholders through in-person conversations, online meetings, emails, and direct messages. Efforts were made to clarify questions and ensure that responses were accurately interpreted.

Given that all interviews were conducted in English, the author was attentive to potential language barriers that might influence understanding. As of March 2024, based on the author's personal observations during fieldwork, both the school director and the volunteers possessed a reasonably extensive English vocabulary; the teachers had a limited vocabulary, while the students had almost none.

By using this research method, the author gained detailed information and a comprehensive understanding of key aspects of her study, such as challenges, preconditions, wishes and effects. These insights were utilized for the PV system sizing (outlined in sub-section 3.5.2), the evaluation of economic potential (outlined in sub-section 3.5.6), among other things. This data is referred to as “personal communication” in this master's thesis.

3.2.3 Survey

A small-scale survey was conducted using questionnaires with open-ended questions to collect primary qualitative data. The purpose of the survey was to collect, assess, and interpret insights from Tumaini's local stakeholders about the changes that occurred following the installation of the PV system. Since the InfoSpot is now powered by the PV system, along with other electrical equipment that had been used less frequently before the installation, such as computers, the survey also included questions about the effects of the InfoSpot.

To bring structure to this research method, the author created three sets of questionnaires with open-ended questions: one directed towards students, one for teachers, and one aimed at leaders/volunteers. The open-ended questions provided flexibility in the responses, allowing participants to express their thoughts, experiences, and emotions in their own words without being limited by the author's predefined response options. Additionally, this allowed the author to assess whether respondents fully understood the questions or were responding to different interpretations.

Each questionnaire contained specific interview questions designed to achieve distinct research objectives related to the transformative effects of the DPVS and InfoSpot. The goal was to understand how these technologies have influenced various aspects, including student empowerment, improvements in the learning environment, access to educational resources, digital and internet literacy, the effectiveness of class sessions and self-study routines, understanding of renewable energy, motivation and satisfaction with the educational experience, learning outcomes, and skill development, as well as expectations for future studies, employment, and economic opportunities. These insights provide a comprehensive view of the impact of implementing modern technology.

Six weeks after the PV system was completed, the author forwarded the three sets of questionnaires to John, a volunteer at Tumaini. John (personal communication, May 14, 2024) translated the questionnaires into Swahili and assisted both students and teachers in formulating their responses in English. It should be emphasized that this may have influenced the respondents' responses, potentially reducing their nuance. This influence was particularly evident when nine out of twelve responses in one of the completed documents from a student were worded identically to the responses in a document from another student. The author pointed out this issue, to which John explained the reason as the students collaborating and receiving help translating and typing their responses (John, personal communication, June 12, 2024). The questions and the directly quoted answers from the respondents are presented in Appendix 1.

Before analyzing the raw data, the author took steps to create backup files. This was done to ensure that any future inquiries regarding procedures, data integrity, or participant consent could be addressed effectively. Then, the author did a thorough review of the raw data to make sure that it was complete and accurate, without missing responses, clear misunderstandings or any identifiable information about individual participants. No outliers were identified, indicating that no responses significantly influenced the mean and standard deviation of the sample.

The questionnaires were specifically designed for three stakeholder groups, Appendix 1 was divided into three sections: 1A, 1B, and 1C. Each section systematically organized direct quotes from respondents based on their respective questions. This clear separation allowed for easy differentiation of insights from each group. This structured approach provided a comprehensive view of the raw data, enabling in-depth analysis while preserving the integrity of the

participants' original responses. Although the number of participants was very limited, their responses provided valuable insights on various topics that may have been overlooked by observations or close-ended questions. The analysis of this data is outlined in section 3.6, in the content analysis.

3.3 Secondary Research Approach – Systematic

Literature Review

The secondary research method involves using secondhand information (secondary data) collected by someone else (George, 2023b). This approach can be used in either qualitative or quantitative research. It frequently utilizes information obtained from published peer-reviewed articles, meta-analyses, or databases and datasets provided by the government or private sectors.

A systematic literature review was conducted to collect secondary qualitative and quantitative secondary data. During structured research, comprehensive data for the assessment framework and the case study were gathered. This encompasses key terms and data related to PV systems, development aid, environmental factors affecting the PV system, the advantages and challenges of CPVS and DPVS in rural electrification projects, and secondary data used for the case study calculations. This search process systematically searched relevant journals, reports, and case studies.

Levy & Ellis (2006) describe the literature review as a systematic process divided into three stages: The input stage is where the research problem/question, objectives, search terms, and tools are defined; The processing stage is where searches are conducted and analyzed, filters are applied, and applicable sources are found; and The output stage is where the data collected during the search is examined, assessed, and then displayed. Adapting their model, this systematic literature review process is divided into three phases, as outlined below

The input stage

In the input stage, the author explored theoretical frameworks, key concepts, and previous studies on the effects of rural electrification with PV systems. This was to define the research questions and identify the necessary objectives to address them.

Engaging in this early literature review was a key source of inspiration and proved instrumental in several aspects of the research. First, it helped determine whether the research question had already been answered in the existing studies. Second, it provided a way to evaluate the research question's relevance and significance. Third, it offered useful insights into possible methods for conducting the study and helped the author understand how the research would fit within the context of previous studies.

Key terms from the research goals, research questions, and objectives, such as “Centralized”, “Distributed”, “Photovoltaic”, “Rural”, “Development”, “Aid”, “Technical”, “Economic”, “Social”, “Environmental”, “Institutional”, “Tabora”, “Tanzania” and “Sub-Saharan Africa”, were identified as relevant search terms for the literature search. Google Scholar was selected as the leading search engine for scholarly literature due to the author's previous experience of it providing quick and easy access to a vast repository of academic content across multiple disciplines.

The processing Phase

The processing phase involved searching using different variations of the predefined search terms and applying filters to refine the search according to the study's scope. Articles, theses, books, abstracts, and other scholarly sources were skimmed to identify the sources applicable to the study. The selection process was conducted in multiple stages on different dates throughout 2024 due to the size of the sample publications. Articles were initially collected based on the specified search terms, followed by applying filters such as the publication time frame and language limitations to Norwegian and English articles. The selected articles were analyzed according to several themes relevant to the study.

The author prioritized finding recent research, meaning publications from 2020 to 2024, as PV systems and rural electrification projects in Sub-Saharan Africa are emerging topics actively being researched. However, less recent research is also included to build a strong case for the study's relevance.

The literature review also highlights gaps in data and trends across different regions. When reviewing the literature, it became evident that technical and economic perspectives for DPVS and CPVS dominate. There has been an increase in studies addressing environmental impacts, reflecting the urgency of climate change concerns. However, social and institutional

perspectives remain underexplored for Tanzania and many other countries in sub-Saharan Africa.

The literature review was treated as a dynamic part of the study, evolving as new findings emerged. As new concepts, updated methodologies, and conflicting research became apparent, the review required ongoing investigation. This continuous process only concluded when the study was finalized. This iterative approach enhanced the reliability and depth of the assessment framework, ensuring that it reflects the latest industry standards and addresses real-world challenges in rural electrification.

The output phase

In the output phase, data from the sources was analyzed and evaluated to differentiate between opinions, theories, and established facts. Additionally, much of the qualitative data in existing studies is outdated, given the rapid advancements in PV technology and changing socio-political landscapes. By citing academic sources, this master's thesis strengthens the validity and trustworthiness of the information presented.

It was essential to stay informed about relevant research during the study. The review was dynamic and adapting as the study progressed. Methodological changes, the introduction of new concepts, and emerging conflicting literature necessitated additional research. Therefore, the literature review remained ongoing until the entire master's thesis was concluded.

3.4 Assessment Framework

Creating an assessment framework for CPVS and DPVS is crucial for evaluating their effectiveness in promoting rural development through solar electricity. While traditional energy assessments often focus on economic and technical criteria, this study takes a more comprehensive approach by incorporating multiple perspectives: techno-economic, socio-economic, environmental, and institutional.

The author's assessment framework for CPVS and DPVS in underdeveloped rural areas is presented in the figure below.

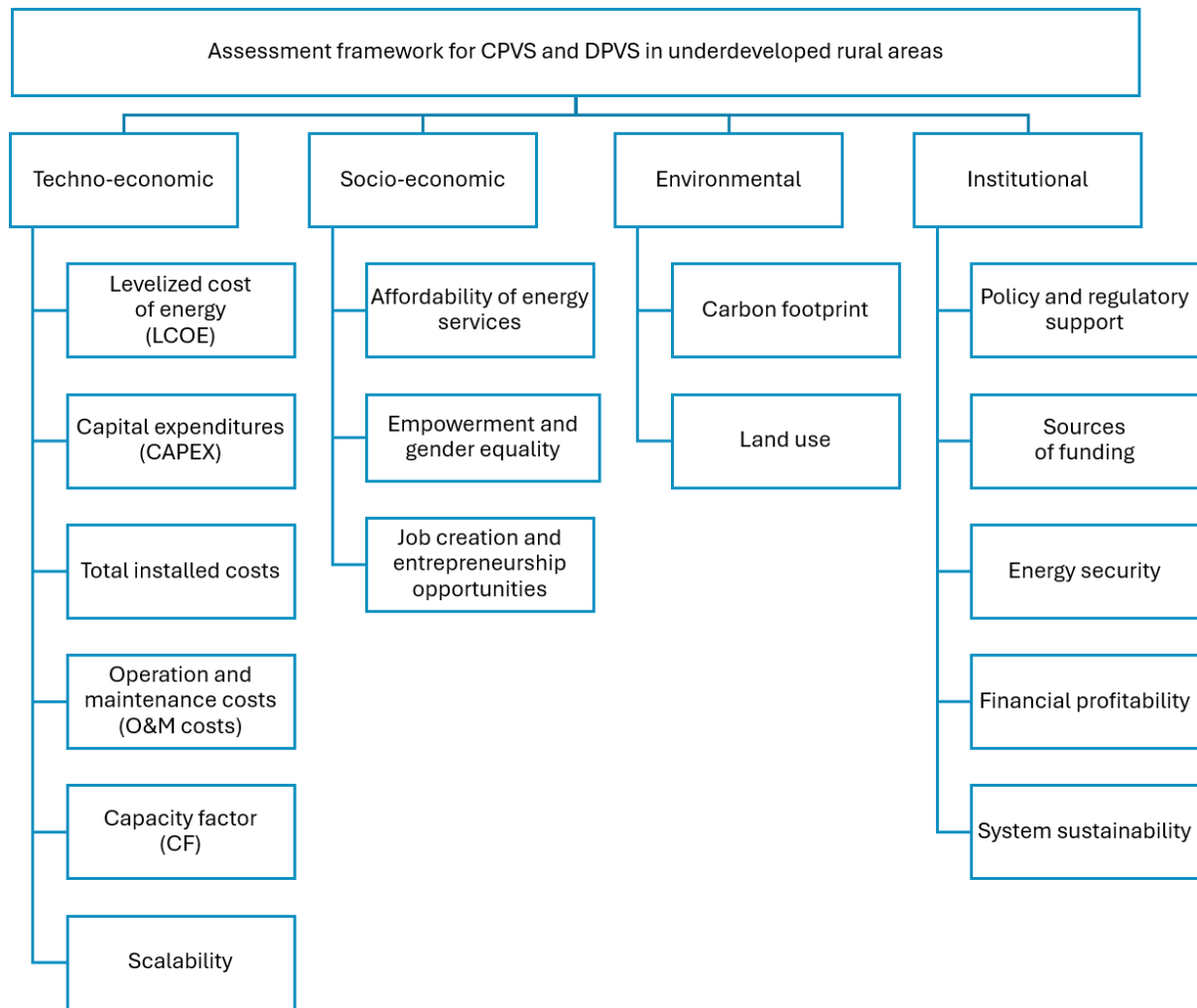


Figure 7: Assessment framework for CPVS and DPVS in underdeveloped rural areas.
Note: Own work. Bergen, October 31, 2024.

Numerous studies have highlighted key decision-making criteria for the deployment of renewable energy projects. This framework draws inspiration from key works such as the framework for sustainable utility-scale renewable energy in South Africa by Naicker and Thopil (2019), the multidimensional high-resolution assessment method by Moner-Girona, Bender, Becker, Bódis, Szabó, Kararach, and Anadon (2021) aimed at enhancing decentralized energy investments in Sub-Saharan Africa, and Rogner's (2013) four interconnected dimensions for the evaluation on effectiveness of aid, as mentioned in section 2.3.

Several factors were considered when the author selected the criteria to be included in this study's assessment framework since she wanted to ensure a thorough, balanced, and relevant evaluation of CPVS and DPVS. Secondary data were gathered through a comprehensive literature review of relevant academic papers, government reports, and industry publications.

Criteria commonly used in similar projects and recognized as industry standards were included, allowing for benchmarking against other projects and ensuring adherence to best practices in project evaluation. Additionally, study-specific criteria were chosen based on their direct relevance to the goals, research questions, and objectives of this study.

Justification of the Framework

The assessment framework was selected and developed for several key reasons, as outlined below:

- The framework’s multi-dimensional structure is essential for providing a comprehensive analysis of PV systems. It evaluates not only techno-economic performance but also socio-economic benefits, environmental impacts, and institutional feasibility. By incorporating these diverse perspectives, the framework provides a holistic view of how well each system aligns with the challenges and needs of rural communities.
- It facilitates a comparative analysis of CPVS and DPVS, highlighting each system’s relative strengths and weaknesses in rural settings. The framework’s design allows it to be refined and adapted based on primary data from case studies, making it versatile and suitable for application in various regions. This flexibility is essential in a constantly evolving field like renewable energy, where technological advancements, policy shifts, and community needs necessitate adaptable assessment tools.
- Each criterion within the framework addresses the priorities of different stakeholders, such as cost-effectiveness for investors, community benefits for NGOs, and policy alignment for government entities. By considering these varied needs, the framework ensures that the assessment is focused on stakeholders, making it practical and actionable for real-world applications in underdeveloped regions.
- Inspired by frameworks like Naicker and Thopil’s (2019) sustainable renewable energy assessment and Moner-Girona et al.’s (2021) decentralized energy assessment approach, this framework leverages established best practices while adapting them to the specific conditions of underdeveloped rural areas. This alignment with proven methods enhances the framework’s reliability and rigor.

Application of the Framework

This framework and its criteria were applied to evaluations and analysis, as outlined below:

- The Evaluation of Economic Potential, presented in section 3.5.6, considered the criteria “Capital Expenditures”, “O&M cost” and “LCOE”.
- The Content Analysis, presented in section 3.6, considered the criteria “Empowerment and Gender Equality,” “Job Creation and Entrepreneurship Opportunities,” and “System Sustainability”.
- The Comparative Analysis, presented in section 3.7, considered all the criteria. This means that the entire framework was applied.

3.5 Case Study

The case study research design became the chosen qualitative research method for describing, comparing, assessing, and understanding various aspects of the research questions. A case study makes analytical generalizations and extends a specific set of findings to broaden theoretical concepts with limited time and resources (UIR, n.d.).

This section presents the case study of Tumaini Open School in rural Tabora, Tanzania. It outlines the primary and secondary used during the case study, the considerations and calculations undertaken according to the timeline and budget of the project, the fieldwork carried out at Tumaini during the author’s stay from the 5th to the 16th of March, the monitoring conducted after the PV system was installed, and the economic potential of the PV system. The case study focuses on qualitative data using surveys, private and unstructured interviews, in-field observations, and analysis of primary and secondary sources. Key primary data from the case study is presented in the research results (in the last column of Table 9).

3.5.1 Preparatory Work Before Fieldwork

Before traveling to Tabora and conducting fieldwork, the author held meetings with the school’s school director, Ezekiel, to include him in the decision-making process and clarify project goals, expectations, and roles. The author initially contacted Ezekiel through her supervisor, J. Noll.

A few months after Ezekiel had agreed to collaborate with the author and participate in EWB-N's Meaningful Master's program, there was a start-up meeting. During this meeting, Ezekiel (Personal communication, January 8, 2024) informed the author that although the school is connected to the electricity grid, frequent and prolonged blackouts necessitated a reliable alternative energy system. He wished for a PV system that could cater to the electricity needs of the existing classroom building and the classroom building under construction. He emphasized the importance of installing the system on the roof to mitigate the theft risk.

Additionally, Ezekiel (Personal communication, January 8, 2024) informed the author that the school suffers from inadequate mobile network coverage, with no wired or wireless network available, which limits access to online resources. Teachers must use their private mobile phones to access the Internet, while students are prohibited from using mobile phones at the school's premises. After the author presented the idea, Ezekiel wished for a local network and web server to enable students and teachers to access locally stored information and the Internet.

On-line system diagram

Considering the variable nature of solar energy availability, along with the frequent disruptions in the grid's electricity supply, the author understood the necessity of incorporating battery storage into Tumaini's PV system. This addition would provide a reliable power supply when sunlight is insufficient (such as on cloudy days or at night) or during unexpected power outages. As Tumaini already is connected to the main grid, this PV system must not only harness solar energy and utilize battery storage, but also seamlessly integrate with grid. In Tanzania, regulations currently prevent privately owned photovoltaic systems from feeding excess electricity back into the grid (Gadgetronix, 2022; Multiconsult, 2022; IRENA, 2024a). However, the flexibility inherent in the hybrid system means that such integration could be considered in the future.

The hybrid system aims to ensure a consistent and dependable energy supply. To visualize her concept, the author created a one-line system diagram of the proposed hybrid PV system, presented in the figure below.

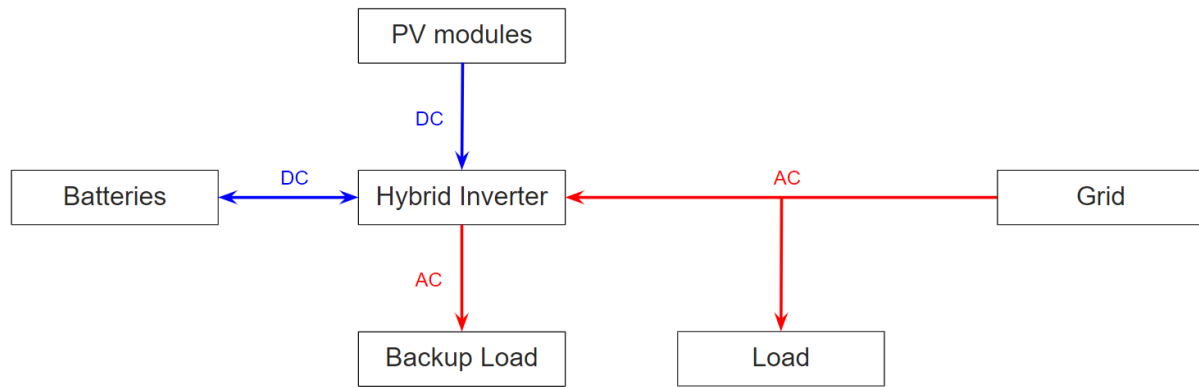


Figure 8: One-line System Diagram for PV System.
 Note: Own work. Bergen, February 26, 2024.

The following is an explanation of the one-line system diagram:

- When the sun shines, DC power from PV modules is converted into AC power for all the connected loads. Any excess DC power from the PV modules charges the batteries. In compliance with Tanzanian regulations, excess power from the PV system cannot be exported back to the grid.
- When the sun does not shine or under less-than-ideal conditions, DC power from the batteries is converted into AC power for connected loads. During extended periods of low solar production (such as multiple cloudy days) or high energy consumption, where the batteries reach a low threshold (their DoD), the grid supplies both the consumption and the charging of the batteries (unless there is a power outage).

Planning the PV for Fundraising Purposes

Based on input from Ezekiel, the author created a rough estimate of Tumaini’s daily energy consumption. The funding and final budget for the PV system was unknown at this stage, but the author wanted to get an idea of how big the PV system should be. She needed to create an initial budget proposal to present to companies for fundraising purposes, based on the number and type of standard PV modules and BOS components. In sub-section 3.5.2, detailed calculations of energy consumption and system size are provided, but these are adjusted based on the final budget and the local solar company’s available components. The author prioritized designing a system with locally sourced components and a local solar company for the installation, aiming to create jobs and facilitate easier and faster technical maintenance in the future.

The initial phase of planning Tumaini's PV system involved assessing the school building and its surrounding areas. This was done through online maps and pictures provided by Ezekiel, one of which is presented in Figure 9. This assessment included gathering data on the building's location, azimuth, and environmental conditions.



Figure 9: The Front of the Classroom Building

Note: Received from Ezekiel, Personal communication, January 17, 2024.

According to the author's observations, the roof slopes had an angle of approximately 35° . The author assumed the PV modules were to be mounted on a racking system that followed the same steep angle as the roof's slopes, to reduce costs of materials, wind loads. The PV modules would then have had a tilt angle of 35° , 15° more than the optimum tilt of 10° (GSA, 2024a). At this tilt, some dust and debris would likely be sliding off the PV modules, reducing the frequency of manual cleaning. Additionally, constructing specific structures to achieve the optimal fixed orientation and tilt is often unnecessary considering the low reduction in solar radiation received (N'Tsoukpoe, 2021).

Specifically, attention was given to the azimuth of the roof slopes, evaluating PV module placement and sunlight exposure throughout the day. The roof's front slope (the roof plane that faces the front of the building) faces east, while the roof's back slope faces west. Since the ideal azimuth in the Southern Hemisphere is 0° azimuth points north (PV*SOL, n.d.-b), none of the roof's orientations was ideal.

The author considered three options for PV module placement, as listed below:

- Position the PV modules on the roof's front slope to capture morning sunlight, allowing for early recharging of the batteries after a night without sun exposure.
- Position the PV modules on the roof's back slope to maintain the aesthetics of the front side of the school, and since the back side of the school is slightly more north facing. Considering the variable availability of solar energy and the frequent disruptions in the grid's electricity supply during the day, this positioning would help capture the evening sun, to recharge the batteries before the increasing energy consumption in the afternoon.
- Position the PV modules on both of the roof's slopes to maximize electricity generation throughout the day. This configuration is advantageous for optimizing energy production, but due to increased costs for installation and maintenance, not the first choice.

PV*SOL was used to conduct simulations to explore various system configurations and evaluate the performance of each proposed installation configuration effectively. PV*SOL is a simulation tool that calculates the PV system's specific yield, PV module size, and system performance, among other things, based on various parameters, including geographical location, panel azimuth, and tilt angle (PV*SOL, n.d.-a). The author did some simulations in PV*SOL with different azimuth and tilt angles to calculate how a certain number of standard PV modules would affect the specific yield. Input parameters such as geographic coordinates, roof dimensions, panel specifications, and local weather data were entered into the PV*SOL software to create an accurate simulation model of the proposed solar PV installations.

To help identify the most critical factors influencing energy production and inform decision-making regarding system design and optimization, the impact of variations in input parameters, such as panel tilt angle and azimuth, on system performance was assessed. However, the author wanted Ezekiel and the installers from the local solar company to determine both the placement and tilt angle of the PV modules, as this decision should be based on what they want to prioritize in terms of aesthetics and their experience with local conditions. Each option presents distinct advantages and challenges that must be carefully evaluated. The local solar company had more technical expertise than the author and was contractually obligated to find the best solution for the specific components they planned to use.

Secure Funding

Based on the estimated energy consumption and size of the PV system, the author created an initial budget using unit prices from similar PV projects available online. Following this, efforts were made to secure funding and support. The author reached out to various companies via email, resulting in a partnership with Trainor. Although Trainor made a significant financial contribution towards the PV system, the available funds covered only two-thirds of the system that Tumaini's stakeholders had envisioned. To bridge this financial gap, Tumaini successfully secured the remaining funds necessary to meet its desired system capacity.

In parallel with the PV system planning, the author's supervisor, J. Noll, organized the funding for an InfoSpot. He arranged for the Basic Internet Foundation to fund an antenna, a router, a local server, and cables. This decision to implement an InfoSpot in this project was due to the poor mobile network reception and lack of network at the school (Ezekiel, personal communication, January 8, 2024), which limits access to information. The InfoSpot will be operational thanks to the electricity from the PV system.

The components for the InfoSpot were delivered to the author before the fieldwork, allowing her to assemble, test, and familiarize herself with the system. Educational content, including animated videos on health, electricity, renewable energy, PV systems, and environmental issues, was preloaded onto the server. This ensured that students and staff would have full access to valuable information even without an internet connection. This preparation enabled the author to understand the system before transferring the knowledge to the local stakeholders during the fieldwork.

3.5.2 PV System Sizing

A critical aspect of the preparation phase of this master's thesis involved finding the correct amount and size of the main components of Tumaini's hybrid PV system. This was based on a conservative estimate of electricity needed to cover the energy demand, as the funding was now known to be limited. This sub-section outlines the design process, focusing on the calculations for energy requirements and determining the essential number of PV modules and batteries needed to meet the daily energy consumption for critical equipment.

The inventory of the local solar company, Ensol, determined the components chosen for the PV system. They only had one type and size of PV module and battery available, along with a limited variety of sizes for the same type of hybrid inverter (Ezekiel, personal communication, February 23rd; Ensol, personal communication, March 5, 2024).

These specific components are listed below:

- The PV module “Tiger Pro 72HC 550-570 Watt” from Jinko Solar (2022).
- The lead-acid AGM battery “RA12-150 (12V150Ah)” from Ritar Power (n.d.)
- The hybrid inverter “SUN-3.6/5/6/7/7.6/8K-SG05LP1-EU-SM2” from Deye (n.d.).

The decision to design the PV system with components available at a solar company located in Tabora was based on the limited time, the importance of having easily interchangeable parts or using identical ones to accommodate future system growth, the support for local economic development by creating jobs for local installers, and to provide a system that can be duplicated for other buildings on the school's premises if desired.

For the calculations in this sub-section, the author used equations retrieved from an article by Mugo (2023) and a course manual by Bhatia (n.d.), together with the constants listed in the table below.

Table 1: Constants used for PV System Sizing Calculations.

Parameter	Description	Value	Source
PSH	Peak Sun Hours	6.123 h/day	GSA, 2024a
η_B	Efficiency of battery	85%	Mugo, 2023; Fire Mountain Solar, n.d.
η_i	Efficiency of inverter	97.6%	Deye, n.d.
η_{oth}	Efficiency of other components	85%	Mugo, 2023
P_{max}	Maximum (rated) power output of a PV module	0.55 kW _p	Jinko Solar, 2022
U_B	Nominal voltage of battery	12 V	Ritar Power, n.d.
U_S	Nominal voltage of battery system	48 V	(Hutchison & Galiardi, 2020)
DoD	Depth of Discharge of battery	50%	Fire Mountain Solar, n.d.
C_B	Rated capacity of battery	150 Ah	Ritar Power, n.d.
t_{backup}	The number of days the battery system should be able to supply the consumption	0.34 day (ca. 8 h/day)	Ezekiel, personal communication, August 16, 2023
SF	Safety factor for inverter	25%	Mugo, 2023

Electrical Load Calculation

The first step in designing Tumaini's hybrid PV system was to estimate the school's daily energy consumption. This involved an online meeting and follow-up discussions with the school director, Ezekiel. According to Ezekiel (personal communication, January 17, 2024), the average energy consumption for the base load of the existing classroom building was approximately 3.6 kWh per day. This base load mainly consisted of electricity for lighting and charging small electric devices. Adjacent to the existing classroom building, another identical one was under construction, for which the author assumed a similar base load. Although there was potential for increased energy demand once the PV system was installed, as the consistent electricity supply would create opportunities for new equipment or extended operating hours, this was not included in the calculations due to budget limitations.

The only additional equipment identified as essential beyond the base load were fifteen laptops, two projectors, and one tabletop incubator for chicken eggs. Since the equipment lacked nameplates indicating their nominal power usage, and given the lack of detailed data from Tanzania and other developing regions, power consumption estimates are based on the higher range of typical devices used in Western countries. Typical power consumption demand is 100 W for a laptop and 270 W for a projector (Daft Logic, n.d.), while a similarly sized tabletop incubator for chicken eggs typically requires 50 W (FarmHatch, n.d.) The laptops were expected to require electricity to charge for about two hours per day; the projectors were expected to be used three hours per day, while the incubator required a constant electricity supply (Kassanga, personal communication, January 17, 2024).

To estimate the daily energy consumption, the author added the energy usage of each load, which is outlined in the table below.

Table 2: Estimated energy consumption at Tumaini.

Description	No. of units	Power per unit (W)	Per day usage (h/d)	Energy consumption (kWh/day)
Existing classrooms building (base load)			24	3.6
New classroom building (base load)			24	3.6
Laptops	15	0.1	2	3
Projectors	2	0.27	3	1.62
Chicken egg incubator	1	0.5	24	1.2
Grand Total				13.02

To summarize, the calculations show that the PV system for the six-classroom building will need to handle a total energy consumption of 13.02 kWh/day.

PV Array Calculation

To calculate the required power output of the PV array to meet the total energy consumption, the following equation was utilized:

Eq. 2

$$Req. Power from PV Array (kW) = \frac{Tot. Energy Consumption \left(\frac{kWh}{day} \right)}{PSH \left(\frac{h}{day} \right) \times \eta_B \times \eta_i \times \eta_{oth}}$$

By using the equation above, the required power output of the PV array was determined to be:

$$Req. Power from PV Array = \frac{13.02 \frac{kWh}{day}}{6.123 \frac{h}{day} \times 85\% \times 97.6\% \times 85\%} = 3.02 kW$$

To calculate the number of PV modules required to meet the total energy consumption, the following equation was utilized:

Eq. 3

$$No. of PV Modules = \frac{Req. Power from PV Array (kW)}{P_{max} (kW_p)}$$

By using the equation above, the number of PV modules required was determined to be:

$$No. of PV Modules = \frac{3.02 kW}{0.55 kW_p} = 5.49 \cong 6$$

To calculate the total power output of the PV array, the following equation was utilized:

Eq. 4

$$Tot. Power of PV Array (kW) = No. of PV Modules \times P_{max} (kW_p)$$

By using the equation above, the total power output of the PV array was determined to be:

$$Tot. Power of PV Array = 6 \times 0.55 kW_p = 3.3 kW_p$$

To summarize, the calculations show that the PV array must consist of six PV modules (rated at 550 W_p), resulting in a total power output of 3.3 kW_p.

Battery Calculation

Although lithium-ion batteries are considered a better type of battery for several reasons (as mentioned in sub-section 2.1.1), and were the author's preferred choice, AMG lead-acid batteries were selected because they were the only type available at the local solar company. The inverter type offered by the local solar company is compatible with both lithium-ion and lead-acid batteries (Deye, n.d.). Therefore, if lithium-ion batteries become available in the future, the lead-acid batteries can be replaced.

The size or number of batteries often depends on the number of days the system must rely on battery storage, without getting input from the PV array (Bhatia, n.d.). The number of days often depends on essential or safety-critical applications. Since Tumaini is connected to the power grid, the size and number of batteries do not need to rely on the input from the PV array since they can also be charged by the grid. Because deeper discharges lead to shorter lifespans (Léna, 2013), the author wants enough batteries to have them maintain a shallow DoD.

When connecting two batteries in series, the current remains constant while the voltage doubles (Hutchison & Galiardi, 2020). Conversely, when connecting two batteries in parallel, the voltage remains constant while the current doubles. Increased current flow leads to more significant heat generation within the wires because of heightened resistance, necessitating larger wires to maintain system safety. Hutchison and Galiardi (2020) argue that opting for a 48 V battery system balances expanding capacity and mitigating potential hazards. Since Tumaini's batteries are 12V, connecting four batteries in series will create a 48V battery system.

To calculate the required battery capacity to cover the daily energy consumption, the following equation was utilized:

Eq. 5

$$Req. \text{ Battery Capacity } \left(\frac{Ah}{day} \right) = \frac{Tot. \text{ Energy Consumption } \left(\frac{Wh}{day} \right)}{U_S (V) \times DoD \times \eta_B}$$

By using the equation above, the required battery capacity was determined to be:

$$Req. Battery Capacity = \frac{13020 \frac{Wh}{day}}{48 V \times 50\% \times 85\%} = 638.24 \frac{Ah}{day}$$

To calculate the number of series (of four 12 V batteries) required to create a 48 V battery system, the following equation was utilized:

Eq. 6

$$No. of Series = \frac{Req. Battery Capacity \left(\frac{Ah}{day} \right) \times t_{backup} (day)}{C_B (Ah)}$$

By using the equation above, the number of series required was determined to be:

$$No. of Series = \frac{638.24 \frac{Ah}{day} \times 0.34 day}{150 Ah} = 1.45 \cong 2$$

These two series will be connected in parallel to maintain the voltage of the battery system.

To calculate the number of batteries required, the following equation was utilized:

Eq. 7

$$No. of Batteries = No. of Series \times \frac{U_S (V)}{U_B (V)}$$

By using the equation above, the required batteries required were determined to be:

$$No. of Batteries = 2 \times \frac{48 V}{12 V} = 8$$

To summarize, the calculations show that to meet the total energy consumption, for eight hours a day, the 48V battery system must consist of eight 12V batteries arranged in a 4S2P configuration. This setup consists of four batteries connected in series, with two of these series connected in parallel. The author has illustrated the 4S2P configuration in the figure below.

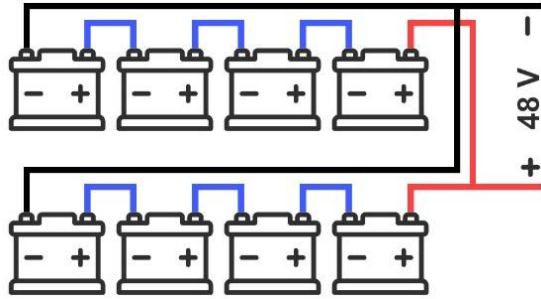


Figure 10: 4S2P configuration.
Note: Own work. Bergen, May 31, 2024.

Inverter Calculation

Finding the ideal inverter capacity involves considering the total power of the PV array, energy needs, future system expansions, the location's solar irradiance patterns, and regulatory constraints (Sykes, 2024). The inverter must have a higher input rating than the combined power of all loads and share the same nominal voltage as the battery system (Bhatia, n.d.).

Under-sizing the inverter (within regulatory limits) can enhance the operation efficiency during low irradiance conditions (Sykes, 2024). However, this can lead to energy clipping (the panels producing more power than the inverter can manage) during high irradiance conditions, and reduce the safety, efficiency, and lifespan, if the inverter is constantly operated close to its maximum capacity. One commonly accepted ratio suggests that the rated power of the PV array can surpass the inverter's capacity by up to 33%.

Over-sizing the inverter can be wise if there is a plan to increase the PV system in the near future, as it provides greater flexibility without the need for immediate inverter replacement (Sykes, 2024). As the size of the inverter increases, so does the minimum amount of input power required from the PV array to start up and continue operating. A too oversized inverter may therefore not operate during low irradiance conditions, due to a too low electricity generation from the PV array.

To account for irradiance conditions higher than the STC, which will increase the electrical current, the inverter's rated capacity should be 25% higher than the PV array's total power (Bhatia, n.d.; Mugo, 2023). Therefore, a safety factor (SF) of 25% is added to account for surge requirements.

To calculate the required capacity of the inverter, the following equation was utilized:

Eq. 8

$$\text{Req. Inverter Capacity} = \frac{\text{Tot. Power of PV Array (kW)} \times (100\% + SF)}{\eta_i}$$

By using the equation above, the required capacity of the inverter was determined to be:

$$\text{Req. Inverter Capacity} = \frac{3.3 \text{ kW} \times (100\% + 25\%)}{97.6\%} = 4.22 \text{ kW} \cong 5 \text{ kW}$$

To summarize, the calculations show that the rated inverter capacity should be 5 kW.

Since the PV system is planned to be increased in a couple of years, Ezekiel wanted one of the bigger sizes available and got an invoice from the local company for a hybrid inverter with a capacity of 8 kW (Ensol, personal communication, February 23, 2024).

Before Marius placed the order for the solar system on behalf of Tumaini, the author informed him (via personal communication on March 5, 2024) that until the number of PV modules is increased, an over-sized inverter might not generate power effectively during periods of low irradiance, such as on cloudy days or during early mornings and late afternoons. This is because, as the size of the inverter increases, the minimum input power needed from the PV array to start up and continue operating also increases (Sykes, 2024).

3.5.3 Fieldwork – PV System Installation

The fieldwork began with an inspection of the school and its surrounding areas. During this phase, the author and her mentor from EWB-N, T. Øines, assessed potential locations for installing the inverter and battery system. Various potential sites were evaluated, considering accessibility, safety, and environmental conditions. After careful deliberation, the area between the existing classroom building and the unfinished structure of the new classroom building was chosen. This location was selected for its central position, facilitating easy access and connection to the existing infrastructure.

A dedicated technical room was constructed in the chosen location area to safeguard the longevity and operational integrity of the energy system. This room was specifically designed to house the inverter and battery units, ensuring they were adequately protected from direct exposure to environmental elements such as harsh sunlight and rainfall. The technical room

lacked proper ventilation, with only barred windows at each end to facilitate airflow. Inadequate thermal management could shorten the lifespan of batteries during warmer seasons or periods of heavy use due to elevated operating temperatures, as noted by Pillota et al. (2017) and Léna (2013).

Though attempts were made to pre-order the necessary components, equipment and services from a solar company with offices in Tabora, the process was time-consuming. As a result, the order was placed after the author had arrived in Tabora, on the second day of fieldwork. To obtain the most accurate cost of the PV system in the invoice, all communication with the local solar company was handled through the school director, Ezekiel, and a volunteer from Tumaini, Marius.

The initial expectation was that the components would arrive within a week. However, significant logistical challenges arose. The delivery process was delayed because the shipment was split across multiple trucks, causing the equipment to arrive at different times instead of all at once. As a result, the installation of the PV system was postponed by an additional week, pushing it to the very end of the originally scheduled fieldwork period. These delays highlight the persistent logistical difficulties often faced during installations in remote areas. Such challenges are particularly pronounced in developing regions, where transport infrastructure is frequently inadequate. Factors such as poor road conditions, limited transport options, and issues with local supply chains are common, and they can vastly affect project timelines and overall efficiency.

The local solar company responsible for supplying the components also handled its installation. During this process, an unforeseen power outage occurred, which forced the technicians to adapt quickly to the situation. In a resourceful move, they connected four of the batteries in series, facilitating the creation of a 48V system. This setup enabled them to utilize a power outlet on the inverter, which provided the necessary electricity to operate their hand tools, allowing the installation work to continue despite the interruption in power. This incident serves as a testament to the resilience and reliability of PV systems equipped with battery backup, demonstrating their ability to operate autonomously even when the power grid is compromised.



*Figure 11: The students look at the main components of the PV system during installation.
 Note: Provided by the author (2024). All individuals depicted in the image have given their consent to be photographed.*



*Figure 12: Hand tools were powered by batteries during a power outage.
 Note: Provided by the author (2024).*



*Figure 13: Inside the technical room.
 Note: Received from John, Personal communication, April 4, 2024.*

According to the observations made by the author, the PV modules were strategically installed on the west oriented back slope of the roof, i.e. the section that faces the rear of the building. The chosen tilt angle for the installation was set at approximately 10 degrees. This is the optimal tilt angle for this specific geographic location (GSA, 2024a). The installers selected this location and tilt based on their own simulations and after consulting with Ezekiel. However, they did not provide a detailed explanation regarding their choice.

Certain basic health, safety, and environmental measures appeared to be lacking during the installation of the PV system. The author observed that the installers did not utilize specialized safety equipment, such as harnesses, ropes, or a stable ladder, which could have helped reduce the risk of falls from heights. This observation highlights a significant safety concern, particularly in projects involving technical installations in rural and resource-limited areas, where access to equipment and training in safety protocols may be restricted.

During the PV system installation, the students expressed curiosity about the new technology and gathered around the equipment. A language barrier made it difficult for the author to explain how the system worked to the Swahili-speaking students, but she assumed the role of demonstrator, as captured by a camera in Figure 11. Marius and John, the volunteers, had gained valuable knowledge about the system and informed the author that they would share this information with the students. Furthermore, the author had preloaded illustrative videos about solar energy and PV systems onto InfoSpot's server to provide additional resources.

The installation was completed on March 25, 2024, nine days after the official fieldwork period had ended (Marius, Personal Communication, March 25, 2024). Despite the delays, the successful installation of the system reflects the importance of flexibility and local partnerships in project execution, especially in rural or under-resourced areas. The inverter and batteries were installed in the technical room after the author had left Tabora. She received a picture of the completed installation in the technical room, presented in

Figure 13.

3.5.4 Fieldwork – InfoSpot Installation and Training

The second part of the fieldwork involved installing the wireless network system from the Basic Internet Foundation called InfoSpot. The InfoSpot consists of an antenna with a SIM card to enhance mobile signals, a router to create a wireless network, and a local server (a Raspberry

Pi) for storing files (Basic Internet Foundation, 2023). The InfoSpot sets up a wireless network that enables computers, mobile phones, tablets, and other wireless-enabled devices within a certain range to connect and access information available on a local cloud or the Internet. Users can log in to the local cloud with a username and password, and access the Internet through a voucher-based login.

After inserting a SIM card with an internet subscription into the antenna, local workers assisted the author in mounting it on the classroom building's roof to avoid surrounding trees blocking the signal it was capturing. The antenna was directed toward the nearest mobile tower to maximize signal strength. The author connected the antenna to the router with a cable. The local server was also linked to the router and a monitor, to function as a computer.



*Figure 14: During the installation of the antenna.
Note: Provided by the author (2024).*



*Figure 15: Knowledge transfer about the InfoSpot.
Note: Provided by the author (2024).*

After the author confirmed that the setup was functioning correctly, she conducted training sessions for English-speaking teachers and volunteers. The training covered downloading, uploading, and sharing files on the local server, editing websites, and accessing the Internet. The goal was to demonstrate the purpose and value of having an InfoSpot and ensure that the system would be effectively utilized in the future.

The interactions during training provided valuable insights into the community's interest and capacity for managing the technology. The local stakeholders showed a keen interest in learning how to operate the system, and the author observed their ability to manage essential functions independently after initial guidance. This engagement highlighted the importance of community involvement and knowledge transfer in ensuring the long-term sustainability of the InfoSpot.

3.5.5 Monitoring of PV System and Evaluation of Performance Curves

This sub-section describes the methodology for collecting and analyzing PV system performance data. It evaluates the performance curves from two different days, which provide insights into key patterns and offer recommendations for optimizing system performance.

The performance of the PV system, including power generation, system status, battery levels, and consumption patterns, was monitored using sensors integrated into the inverter. This data was made accessible to local stakeholders through the inverter's built-in display. Monitoring is essential for effectively managing and optimizing PV systems, as it enables stakeholders to observe power generation trends, evaluate consumption behavior, and forecast future energy needs. This information supports informed decision-making at the local level and contributes to the long-term sustainability of the system by identifying maintenance requirements and potential areas for upgrades.

To enable remote monitoring, a data logger ordered by T. Øines, the author's mentor from EWB-N, was set up to transmit performance data to a cloud service called Solarman Smart. Once connected to a wireless network, this device allows for real-time tracking of system performance, providing valuable insights into the system's operation under different conditions. Unfortunately, the data logger could not connect to InfoSpot's wireless network, which uses password-protected vouchers. Instead, Tumaini provided an external mobile broadband router, allowing occasional connectivity and enabling some data uploads to Solarman Smart. This irregular data transmission resulted in gaps in the data set, posing challenges for long-term remote system monitoring and affecting the author's precision of performance evaluations. Most days have no data uploads, some days have a few hours of data, and a few days have connectivity for most of the day.

The author analyzed the data available on the Solarman Smart web overview, which can only be accessed through account login. The analysis focused on identifying trends, detecting anomalies, and assessing system performance metrics over time. Special attention was given to comparing energy demand, power generation, and battery status at different times of the day. Additionally, the author evaluated system performance under varying conditions, such as changes in cloud cover. The performance curves in the figures below were chosen as representative examples, as they closely reflect the behavior observed on several other days. Both curves emphasize the crucial role of the battery in stabilizing the system by storing surplus energy during peak solar hours and discharging it to meet evening demand.

On April 23 (shown in Figure 16), the performance profile was influenced by intermittent cloud cover, as shown by the fluctuations in the production power (blue curve). Solar generation varied throughout the day, peaking during clear weather periods. This inconsistency in production lead to variations in battery power (green curve). The observed patterns indicate that variability in weather and consumption causes fluctuations in battery charging rates (negative values) and discharging rates (positive values). As solar production decreases in the evening, the batteries gradually discharge to fulfill demand.

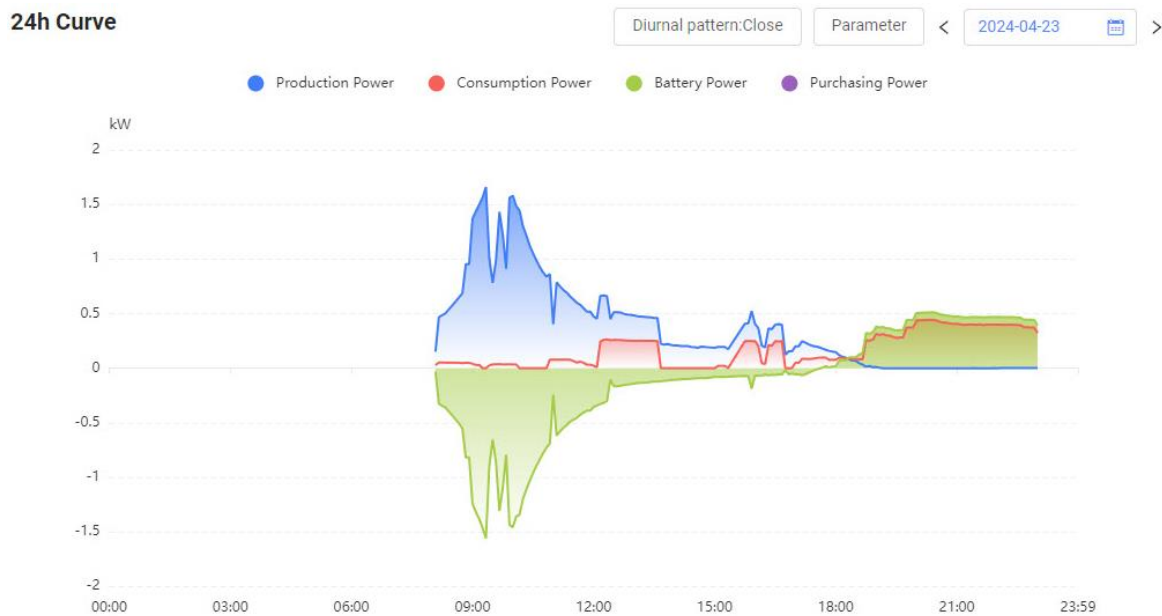


Figure 16: Performance curve for the PV System on April 23, 2024.

Note: Interactive graph to show the parameters Production power, Consumption power, Battery power and Purchasing power for April 24, 2024. Screenshot from “24h Curve”, by Solarman Smart, n.d.
<https://globalhome.solarmanpv.com/login> (only accessed through account login)

The sudden increase in consumption power (red curve) during daytime (on April 23) may be attributed to specific equipment being turned on, or to the system's load prioritization logic or load-following behavior (where the PV system attempts to meet the load directly when solar production is sufficient). The purchasing power (purple curve) remains consistent throughout the day and night. This demonstrates that the system effectively meets all energy requirements without needing support from the grid, indicating its self-sufficiency even in suboptimal solar conditions.

On May 7 (shown in Figure 17), the power output of the PV system (blue curve) indicated a typical sunny day, with a significant peak occurring between approximately 9:00 AM and 10:00 PM. From approximately 8:00 AM and 5:30 PM, energy production surpasses consumption, enabling surplus energy to be stored in the battery (green curve), as indicated by negative values in battery power. After 5:30 PM, consumption power (red curve) exceeded production as solar output declined. To meet the evening demand, the battery discharged, causing the battery power curve to shift to positive values. The purchasing power (purple curve) remained constant throughout the day and night, indicating that the system operated independently of the grid.

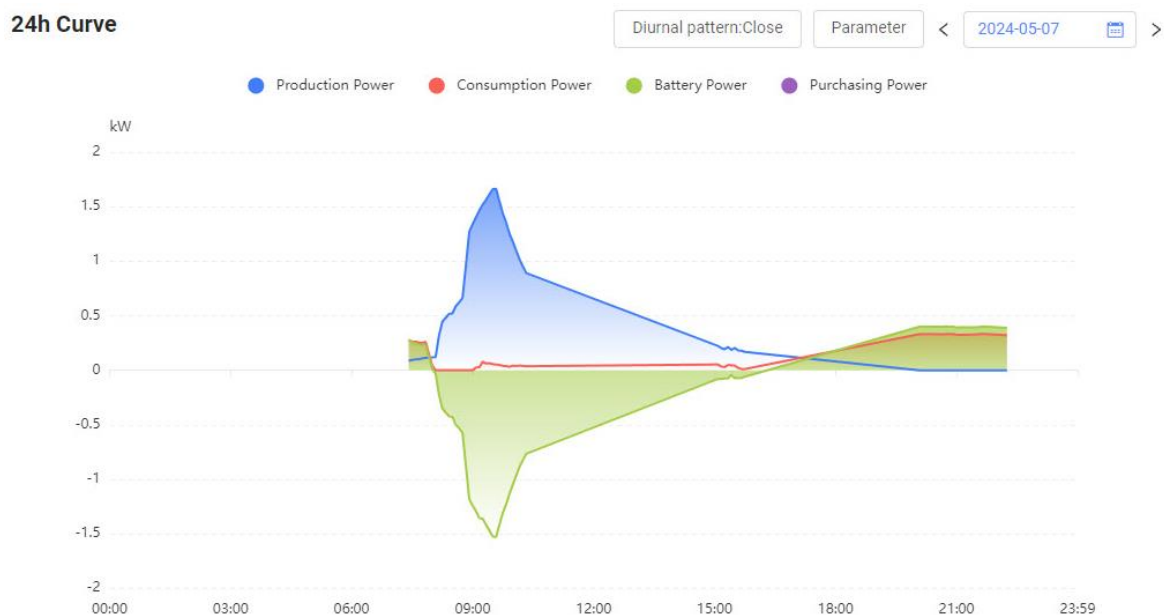


Figure 17: Performance curve for the PV System on May 7, 2024.

Note: Interactive graph to show the parameters Production power, Consumption power, Battery power and Purchasing power for May 7, 2024. Screenshot from "24h Curve", by Solarman Smart, n.d.
<https://globalhome.solarmanpv.com/login> (only accessed through account login)

Based on the analysis of available data on the Solarman Smart web overview, the author's primary recommendation for future system upgrades, in anticipation of higher energy demand, is to increase the battery storage capacity. This enhancement would improve the system's ability to meet increased evening energy demands and reduce the likelihood of wasted solar energy during peak production hours. Expanding battery capacity is expected to deliver greater benefits than simply increasing the size of the solar array, as current production levels already exceed daytime consumption significantly under optimal conditions.

Due to the lack of sufficient data and the fact that the system has not been in operation for a full year, the author has not been able to calculate the actual annual average energy production.

3.5.6 Evaluation of Economic Potential

There are various methods for evaluating the economic potential of a PV system, such as the payback period, return on investment for the owner or operator, and the LCOE (ESMAP, 2020). In this sub-section, the author illustrated Tumaini's hybrid PV system's economic potential by calculating its LCOE. As it represents the cost of generating a single unit of energy, the LCOE facilitates comparisons among a wide range of other energy generation technologies. However, it is essential to note that the method does not fully reflect specific local market conditions, as it is based on average input values.

Due to its simplicity and ease of reproduction, the author chose to utilize IRENA's comprehensive method for calculating the LCOE, as provided by ESMAP (2020), which is presented in the equation below.

Eq. 9

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1 + d)^t}}{\sum_{t=1}^n \frac{E_t}{(1 + d)^t}} = \frac{Total\ Lifetime\ Costs}{Total\ Lifetime\ Output}$$

Where: I_t = Investment costs in year t ,
 M_t = O&M costs in year t ,
 F_t = Fuel costs in year t ,
 E_t = Electricity generation in year t ,
 d = Discount rate (weighted average cost of capital), and
 n = Lifetime of the PV system in years.

The following text outlines the assumptions for each parameter and the calculations made to find Tumaini's PV system's LCOE.

Fuel costs, discount rate, and lifetime

The author used some of ESMAP's (2020) assumptions in her calculations:

- Fuel costs (F_t) are negligible.
- The discount rate (d) is 10%.
- PV system's lifetime (n) is 25 years.

Investment costs

To calculate the total investment cost, the author utilized the invoice from a local solar company dated February 23, 2024. This is shown in the figure below, with costs presented in Tanzanian Shillings (TZS).

Ref: [REDACTED]		PROFORMA INVOICE		Date 23/02/2024				
TO: TUMAINI				ENSOL				
Att:				TIN No. [REDACTED] VAT No. [REDACTED] Reg. No. [REDACTED]				
Quotation for the Supply and Installation of Hybrid Solar Power Backup System for 2 projectors, 15 desktop, 15 laptops, 2 printers, 1 photocopier machine, 30bulbs, 14 tubelighs, 1 egg incubator, 1 TV set and 1 set Sound system (classroom/hall)								
					Currency TZS			
	ITEM	DESCRIPTION	QTY	UNIT	UNIT PRICE	SUB-TOTAL	VAT	TOTAL AMOUNT
1	Solar Panel/Module	550Wp Crystalline Solar panel, Jinko	6	pcs	471,428.57	2,828,571.43	N/A	2,828,571.43
2	Solar Battery Pack.	150Ah Free Maintenance, AGM Deep Cycle Solar Battery Storage, 1000cycles@50%.	8	pcs	680,000.00	5,440,000.00	N/A	5,440,000.00
3	Solar Hybrid Inverter/Charger, Sine wave	8kVA/48V, Pure sine wave, transformer based	1	pcs	5,555,000.00	5,555,000.00	N/A	5,555,000.00
4	Battery enclosure	Metallic structure	1	pcs	720,000.00	720,000.00	129,600.00	849,600.00
5	Solar panel mounting frame	Rooftope mount	1	set	480,000.00	480,000.00	86,400.00	566,400.00
6	Installation accessories & materials	Earthing system, Lightning protection, AVS, Change-over switch, Cables (DC & AC) & other accessories.	1	set	1,685,000.00	1,685,000.00	303,300.00	1,988,300.00
7	Labour charge (Installation fee, training and commissioning)		1	syste	800,000.00	800,000.00	144,000.00	944,000.00
TOTAL					17,508,571.43	663,300.00	18,171,871.43	

Figure 18: The unit costs and total cost of Tumaini's DPVS, measured in TZS.

Note: A screenshot of an invoice from the local solar company, where specific details are covered. Received from Ensol, personal communication, February 23, 2024.

The author created the table below to simplify the invoice in the figure above and provide the cost data in USD. The author used the conversion rate 1 TZS = 0.0003922 USD, which was the exchange rate on the day of the invoice (Exchange Rates 2024).

Table 3: The total cost of Tumaini's DPVS, measured in USD.

Item	Qty	Total cost (USD)
PV module	6	1109
AGM battery	8	2134
Hybrid inverter	1	2179
Battery enclosure	1	333
Racking system	1	222
Installation accessories and materials	1	780
Labor charge	1	370
Grand total (Investment costs)		7127

In summary, the investment cost (I_t) is 7127 USD.

The author also determined the investment cost per unit of capacity by dividing the investment costs by the total power of the PV array (3.3 kWp). This calculation shows that Tumaini's DPVS had an initial capital investment of 2160 USD/kW.

As Tumaini's DPVS did not include expenses for land acquisition or leasing, grid interconnection fees, financing costs, or owner-specific expenses, the investment cost is considered both the CAPEX and the total installed cost.

O&M costs

Replacement costs of the main components are a large part of the O&M cost. The assumptions for the PV modules, inverter, and batteries installed at Tumaini are outlined below:

- The datasheet for the PV modules indicates a linear power warranty of 25 years (Jinko Solar, 2022). For the calculations, this warranty period is treated as the modules' lifespan, which means they will not be replaced during the PV system's lifetime of 25 years.
- The datasheet for the batteries states that they have a design life of 12 years (Ritar Power, n.d.). The author assumes that their operating temperature will exceed the standard value of 25°C in some periods, particularly during warmer seasons or under heavy battery use, so the lifespan of the batteries is expected to be lower than their

design life (Lèna, 2013; Pillota et al., 2017). According to JYC Battery (2023), AGM batteries typically have a lifespan ranging from 4 to 8 years, influenced by usage habits and charging methods along with environmental factors. According to Fire Mountain Solar (n.d.), AGM batteries cycled daily at 50% DoD, is expected to have 4-5 years of life. For the calculations, the author assumes a lifespan of 5 years, meaning they will have to be replaced four times during the PV system's lifetime.

- The datasheet for the inverter mentions an optional warranty of up to 10 years (Deye, n.d.). This aligns with the most average hybrid inverter lifespan of 10 years (Tycorun, 2023). For the calculations, the author uses a lifespan of 10 years, meaning they will have to be replaced two times during the PV system's lifetime.

The author aimed to identify specific cost trends and projections for lead-acid batteries and inverters. Despite extensive research, detailed sources providing specific long-term cost trajectories for these technologies were not found. While organizations such as IRENA (2024) have reported significant reductions in the overall costs of solar PV systems, including BOS-components, they do not specifically isolate cost trends for these components. For simplicity, and based on assumptions informed by broader trends, the author made the following assumptions:

- Lead-acid batteries might have a 3% reduction in costs annually. This reflects the slow pace of innovation and cost reduction typical for mature technologies.
- Hybrid inverters might have a 7% reduction in costs annually. This reflects the high pace of innovation and cost reduction typical for a less mature technology.

As presented in Table 3, the eight AGM batteries have a total cost of 2134 USD. The total cost of replacing them at the beginning of years 6, 11, 16, and 21, with a 3% reduction in costs annually from the initial cost, is represented by the following formula:

Eq. 10

$$M_{t(bat)} = 2134 * (1 - 0.03)^t \quad \text{for } t = 6, 11, 16, 21$$

For every other value of t , $M_{t(bat)}=0$. The equation above is used in calculations for the total lifetime cost, presented in Table 4.

As presented in Table 3, the hybrid inverter has a total cost of 2179 USD. The total cost of replacing it in the beginning of year 11 and 21, with a 7% reduction in costs annually from the initial cost, is represented by the following formula:

Eq. 11

$$M_{t(inv)} = 2179 * (1 - 0.07)^t \quad \text{for } t = 11, 21$$

For every other value of t , $M_{t(inv)}=0$. The equation above is used in calculations for the total lifetime cost, presented in Table 4.

The author also contacted Tumaini's school director and ask questions regarding their O&M costs. Ezekiel (personal communication, October 11, 2024) stated that:

- “Ensol is responsible for doing technical maintenance as per the contract. For regular cleaning, we have one teacher assigned for that. We have a metal ladder made from square pipes. Also we have a 50 meter hose pipe. Cleanliness is done weekly. We have purchased a blower for dust removing. Solar panels are cleaned in every two months by using water. The cost for the materials/equipment is about Tsh 200k, plus others like water bills.”

Based on the statement above, the author found the cost of cleaning ($M_{t(cle)}$) in USD by using an exchange rate of 1 TZS = 0.0003922 USD (Exchange Rates, 2024), as outlined below:

- The 200000 TZS one-time cost for cleaning supplies equals 78.4 USD. This means that $M_{t(cle)}=78.4$ for $t=1$.
- The cost of the water bills for cleaning the PV modules is a recurring expense. Cleaning the six PV modules requires 36 liters of water, based on an assumed average consumption of approximately six liters per module (Kumar, 2018). With the current water tariff set at 2760 TZS per 1000 liters for institutions (SHUWASA, n.d.), the cost for 36 liters of water per cleaning session is 99.36 TZS. Given that cleaning occurs six times per year, the total annual cost of water is 596.16 TZS. The annual cost amounts to 0.23 USD, if water tariffs and exchange rates remain stable over the lifespan of the PV system. Given its minimal impact on overall expenses, the author considers this cost to be negligible. This means that $M_{t(cle)}=0$ for $t \geq 1$.

In summary, the O&M cost is determined by the replacement cost of the batteries ($M_{t(bat)}$) every 5th year, the replacement cost of the inverter ($M_{t(inv)}$) every 10th year, and the one-time cost for the cleaning supplies ($M_{t(cle)}$). All these are included in the calculations in Table 4.

Total Lifetime Costs

To calculate the total lifetime costs $\left(\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+d)^t}\right)$, the author utilized the spreadsheet software Excel. The formulas used for the calculations are presented in Table 4, while the results from the calculations are presented in Table 5.

Table 4: Total lifetime costs – Excel formulas

	A	B	C	D	E	F	G	H
1	t	I _t	M _{t(bat)}	M _{t(inv)}	M _{t(cle)}	M _t	(1+d) ^t	(I _t +M _t)/(1+d) ^t
2	1	7127			78.4	=C2+D2+E2	=(1+0.1)^A2	=B2+F2/G2
3	2					=C3+D3+E3	=(1+0.1)^A3	=B3+F3/G3
4	3					=C4+D4+E4	=(1+0.1)^A4	=B4+F4/G4
5	4					=C5+D5+E5	=(1+0.1)^A5	=B5+F5/G5
6	5					=C6+D6+E6	=(1+0.1)^A6	=B6+F6/G6
7	6		=2134*(1-0.03)^A7			=C7+D7+E7	=(1+0.1)^A7	=B7+F7/G7
8	7					=C8+D8+E8	=(1+0.1)^A8	=B8+F8/G8
9	8					=C9+D9+E9	=(1+0.1)^A9	=B9+F9/G9
10	9					=C10+D10+E10	=(1+0.1)^A10	=B10+F10/G10
11	10					=C11+D11+E11	=(1+0.1)^A11	=B11+F11/G11
12	11		=2134*(1-0.03)^A12	=2179*(1-0.07)^A12		=C12+D12+E12	=(1+0.1)^A12	=B12+F12/G12
13	12					=C13+D13+E13	=(1+0.1)^A13	=B13+F13/G13
14	13					=C14+D14+E14	=(1+0.1)^A14	=B14+F14/G14
15	14					=C15+D15+E15	=(1+0.1)^A15	=B15+F15/G15
16	15					=C16+D16+E16	=(1+0.1)^A16	=B16+F16/G16
17	16		=2134*(1-0.03)^A17			=C17+D17+E17	=(1+0.1)^A17	=B17+F17/G17
18	17					=C18+D18+E18	=(1+0.1)^A18	=B18+F18/G18
19	18					=C19+D19+E19	=(1+0.1)^A19	=B19+F19/G19
20	19					=C20+D20+E20	=(1+0.1)^A20	=B20+F20/G20
21	20					=C21+D21+E21	=(1+0.1)^A21	=B21+F21/G21
22	21		=2134*(1-0.03)^A22	=2179*(1-0.07)^A22		=C22+D22+E22	=(1+0.1)^A22	=B22+F22/G22
23	22					=C23+D23+E23	=(1+0.1)^A23	=B23+F23/G23
24	23					=C24+D24+E24	=(1+0.1)^A24	=B24+F24/G24
25	24					=C25+D25+E25	=(1+0.1)^A25	=B25+F25/G25
26	25					=C26+D26+E26	=(1+0.1)^A26	=B26+F26/G26
27	Grand total							=SUM(H2:H26)

Table 5: Total lifetime costs – Values

	A	B	C	D	E	F	G	H
1	t	I _t	M _{t(bat)}	M _{t(inv)}	M _{t(cle)}	M _t	(1+d) ^t	(I _t +M _t)/(1+d) ^t
2	1	7127.0			78.4	78.4	1.1	7198.3
3	2					0.0	1.2	0.0
4	3					0.0	1.3	0.0
5	4					0.0	1.5	0.0
6	5					0.0	1.6	0.0
7	6		1777.6			1777.6	1.8	1003.4
8	7					0.0	1.9	0.0
9	8					0.0	2.1	0.0
10	9					0.0	2.4	0.0
11	10					0.0	2.6	0.0
12	11		1526.5	980.8		2507.2	2.9	878.8
13	12					0.0	3.1	0.0
14	13					0.0	3.5	0.0
15	14					0.0	3.8	0.0
16	15					0.0	4.2	0.0
17	16		1310.8			1310.8	4.6	285.3
18	17					0.0	5.1	0.0
19	18					0.0	5.6	0.0
20	19					0.0	6.1	0.0
21	20					0.0	6.7	0.0
22	21		1125.6	474.7		1600.3	7.4	216.3
23	22					0.0	8.1	0.0
24	23					0.0	9.0	0.0
25	24					0.0	9.8	0.0
26	25					0.0	10.8	0.0
27	Grand total							9582.0

In summary, based on the calculations performed in Excel, the total lifetime costs (which constitutes the numerator in Eq. 9) amount to 9582.0 USD.

The batteries accounted for 30.0% of the initial investment cost, while the inverter accounted for 30.6%. The high replacement costs for these components, which incur multiple times over the lifetime of the PV system, contribute significantly to the overall lifetime costs. When excluding the cost of the batteries from the calculation, the total lifetime cost nearly halved, amounting to 5472.2 USD.

Electricity generation

The specific yield (PV_{OUT}) at Tumaini's location is 1998.1 kWh/kW_p/year (GSA, 2024a). This represents the electricity generation (E_t) for year zero ($t=0$) of the plant's operation, during which the components perform at their manufactured peak.

To calculate the electricity generation of Tumaini's PV system over its lifetime, the degradation rate of the PV modules must be taken into account. The datasheet for the PV modules inform that they will experience an annual degradation of 0.55% over a 25 year period (Jinko Solar, 2022). As high temperatures, humidity, and dust can increase the degradation rate to as much

as 3% annually in the harsh climates of Sub-Saharan Africa (Pillota et al., 2017), the author assumed a higher degradation rate. She chose an annual degradation rate of 0.1%. This is represented in the equation below as $(1-0.01)^t$.

Eq. 12

$$E_t = 1998.1 * (1 - 0.01)^t \quad \text{for } 1 \leq t \leq 25$$

The equation above is used in calculations for the total lifetime output, shown in Table 6. Electricity generation is not defined as the actual energy delivered to the load. Consequently, the inverter degradation rate, ranging from 0.1% to 2% per year (D.T. Multi Tech, 2024), is not accounted for. Neither are the batteries' degradation rates of 4-6% annually (GridX, 2024).

Total Lifetime Output

To calculate the total lifetime output $\left(\sum_{t=1}^n \frac{E_t}{(1+d)^t}\right)$, the author utilized the spreadsheet software Excel. The formulas used in Excel for the calculations are presented in Table 6, while the results of the calculations are shown in Table 7. E_t was defined in Eq. 12.

Table 6: Total lifetime output – Excel formulas

	A	B	C	D
1	t	E _t	(1+d) ^t	E _t /((1+d) ^t)
2	1	=1998.1*(1-0.01)^A2	=(1+0.1)^A2	=B2/C2
3	2	=1998.1*(1-0.01)^A3	=(1+0.1)^A3	=B3/C3
4	3	=1998.1*(1-0.01)^A4	=(1+0.1)^A4	=B4/C4
5	4	=1998.1*(1-0.01)^A5	=(1+0.1)^A5	=B5/C5
6	5	=1998.1*(1-0.01)^A6	=(1+0.1)^A6	=B6/C6
7	6	=1998.1*(1-0.01)^A7	=(1+0.1)^A7	=B7/C7
8	7	=1998.1*(1-0.01)^A8	=(1+0.1)^A8	=B8/C8
9	8	=1998.1*(1-0.01)^A9	=(1+0.1)^A9	=B9/C9
10	9	=1998.1*(1-0.01)^A10	=(1+0.1)^A10	=B10/C10
11	10	=1998.1*(1-0.01)^A11	=(1+0.1)^A11	=B11/C11
12	11	=1998.1*(1-0.01)^A12	=(1+0.1)^A12	=B12/C12
13	12	=1998.1*(1-0.01)^A13	=(1+0.1)^A13	=B13/C13
14	13	=1998.1*(1-0.01)^A14	=(1+0.1)^A14	=B14/C14
15	14	=1998.1*(1-0.01)^A15	=(1+0.1)^A15	=B15/C15
16	15	=1998.1*(1-0.01)^A16	=(1+0.1)^A16	=B16/C16
17	16	=1998.1*(1-0.01)^A17	=(1+0.1)^A17	=B17/C17
18	17	=1998.1*(1-0.01)^A18	=(1+0.1)^A18	=B18/C18
19	18	=1998.1*(1-0.01)^A19	=(1+0.1)^A19	=B19/C19
20	19	=1998.1*(1-0.01)^A20	=(1+0.1)^A20	=B20/C20
21	20	=1998.1*(1-0.01)^A21	=(1+0.1)^A21	=B21/C21
22	21	=1998.1*(1-0.01)^A22	=(1+0.1)^A22	=B22/C22
23	22	=1998.1*(1-0.01)^A23	=(1+0.1)^A23	=B23/C23
24	23	=1998.1*(1-0.01)^A24	=(1+0.1)^A24	=B24/C24
25	24	=1998.1*(1-0.01)^A25	=(1+0.1)^A25	=B25/C25
26	25	=1998.1*(1-0.01)^A26	=(1+0.1)^A26	=B26/C26
27	Grand total			=SUM(D2:D26)

Table 7: Total lifetime output – Values

	A	B	C	D
1	t	E _t	(1+d) ^t	E _t /((1+d) ^t)
2	1	1978.1	1.1	1798.3
3	2	1958.3	1.2	1618.5
4	3	1938.8	1.3	1456.6
5	4	1919.4	1.5	1311.0
6	5	1900.2	1.6	1179.9
7	6	1881.2	1.8	1061.9
8	7	1862.4	1.9	955.7
9	8	1843.7	2.1	860.1
10	9	1825.3	2.4	774.1
11	10	1807.0	2.6	696.7
12	11	1789.0	2.9	627.0
13	12	1771.1	3.1	564.3
14	13	1753.4	3.5	507.9
15	14	1735.8	3.8	457.1
16	15	1718.5	4.2	411.4
17	16	1701.3	4.6	370.3
18	17	1684.3	5.1	333.2
19	18	1667.4	5.6	299.9
20	19	1650.8	6.1	269.9
21	20	1634.3	6.7	242.9
22	21	1617.9	7.4	218.6
23	22	1601.7	8.1	196.8
24	23	1585.7	9.0	177.1
25	24	1569.9	9.8	159.4
26	25	1554.2	10.8	143.4
27	Grand total			16691.9

In summary, based on the calculations performed in Excel, the total lifetime output (which constitutes the denominator in Eq. 9) amount to 16691.9 kWh.

LCOE – Calculation based on assumptions

Based on the formula presented in Eq. 9 and the assumptions outlined in this sub-section, the value for the LCOE is determined to be:

$$LCOE = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Output}} = \frac{9582.0 \text{ USD}}{16691.9 \text{ kWh}} = 0.574 \frac{\text{USD}}{\text{kWh}}$$

In summary, Tumaini's DPVS had an LCOE of 0.574 USD/kWh.

Although the system benefits from a favorable solar resource, achieving an annual specific yield of 1998.1 kWh/kWp in t=0, it has a very high LCOE. This was expected due to its small scale and frequent battery replacement costs.

When excluding the batteries from the calculation, the LCOE amounts to 0.328 USD/kWh.

If the batteries were replaced with lithium-ion batteries, it would be a significantly higher initial investment (Renoogy, 2022), but the lifetime would have been estimated to be almost four times as long (19 years) (Fire Mountain Solar, n.d).

3.6 Content Analysis

This study utilizes content analysis as a research method for data analysis. This section outlines how this analysis was conducted.

Content analysis is a research technique utilized to detect patterns within recorded communication (Luo, 2023). To do content analysis, you collect data from various texts, which can be written, spoken, or visual. You can approach this method in two ways: quantitative, which focuses on counting and measuring, and qualitative, which focuses on interpreting and understanding. In both methods, you categorize, or "code" words, themes, and ideas found in the texts, and then analyze the results.

The analysis followed the following steps, defined by Luo (2023): Selecting content, Defining categories of analysis, Developing coding rules, Coding the text according to the rules, and Analyzing the results. The goal of the analysis is to identify patterns in the perceptions of local stakeholders and document how their newly installed PV system has influenced their daily activities, education, and socioeconomic opportunities.

Selecting Content

The qualitative responses from three students, three teachers, and one volunteer regarding their experiences after the PV system installation at Tumaini, serve as the primary content for this analysis. Their responses were collected through questionnaires and are presented as “raw data” in Appendix 1.

Defining Categories of Analysis and Developing Coding Rules

The author has defined five categories for this analysis based on three criteria from the assessment framework. The categories are listed below each criterion, along with the coding rules established for each category:

- Empowerment and gender equality:
 - Empowerment: This category includes words and phrases directly mentioning empowerment, autonomy, or self-determination.
 - Digital Literacy: This category includes words and phrases regarding the use or learning of digital tools, computers, the Internet, or technology-related skills.
 - Learning Environment: This category includes words and phrases regarding changes in classroom conditions, access to learning resources, and improvements in teacher-student interactions.
- Entrepreneurship Opportunities:
 - Job and Entrepreneurship Opportunities: This category includes words and phrases regarding entrepreneurial activities, training, income, and profit.

- System Sustainability:
 - Community Engagement: This category includes words and phrases regarding renewable energy and community engagement.

Coding the Text According to the Rules

The “raw data” presented in Appendix 1 was manually coded using the coding rules. Phrases and statements from each respondent were reviewed and then categorized according to the defined categories. Some of the responses, coded according to the rules of each category, are outlined below:

- Empowerment:
 - Yamina (student) feels deeply empowered since she can choose when to study without experiencing power outages.
 - Walidah (teacher) feels empowered now that she can access instructional materials and other teaching resources. She has a better understanding of how to organize, prepare, and accomplish her tasks.
- Digital Literacy:
 - Yamina’s (student) digital literacy has increased because she can now use electronic devices, such as computers and tablets, with free internet services.
 - Walidah’s (teacher) digital skills had stagnated due to the lack of internet access and insufficient electricity. Addressing these issues has contributed to improving her literacy skills.
 - John (volunteer) states that the school is now actively teaching students about computers (as captured by camera in Figure 19). This initiative creates opportunities for girls to develop digital skills, which they can use to pursue various digital job opportunities such as digital marketing, providing secretarial services, and other digital services.

- Learning Environment:
 - Zalika (student) explained that the learning environment has completely changed and improved due to continuous electricity and access to the Internet. She highlights that accessing educational information has become much easier.
 - Tanishia (teacher) stated that she now consistently incorporates technological techniques into her lessons, such as using videos for demonstrations, to engage her students.
- Entrepreneurship Opportunities:
 - John (volunteer) stated that Tumaini plans to introduce new equipment, including incubators and water pumps, to make productive use of the available energy. The profits generated from this initiative will help support school activities.
 - John (volunteer) stated that Tumaini launched a poultry project immediately following the installation of the PV system and is thinking about establishing simple fish-keeping programs and bakeries.
- Community Engagement:
 - Walidah's (teacher) understanding of the use of renewable energy has increased since she is one of the primary beneficiaries of the solar energy installed.
 - John (volunteer) notes that the community's engagement in Tumaini has significantly increased. The community now comes to learn about technology. Their perception of the school as a source of community development has increased.



*Figure 19: Computer courses began as soon as the PV system was installed.
Note: Received from John, Personal communication, April 4, 2024.*

Analysis of the Results

When all responses were coded according to the rules, the author analyzed the coded responses. This analysis revealed patterns and insights within each category, enhancing the qualitative interpretation of the meanings related to each category. The key findings from the content analysis are presented in section 4.1.

3.7 Comparative Analysis

This study utilizes comparative analysis as a research method for data analysis. This section presents how this analysis was conducted.

Comparative analysis is a structured method for evaluating and contrasting two or multiple entities, variables, or options (Appinio, 2023). This approach aims to identify similarities, differences, and patterns among the items being compared. By examining the strengths, weaknesses, opportunities, and threats related to each entity or option, comparative analysis helps in making well-informed decisions.

The comparative assessment methodology for this study follows the systematic approach outlined by Appino (2023). This method organizes the assessment process into the following steps: Identify Key Variables and Metrics, Visualize Data for Clarity, Evaluate and Score Criteria, and Assign Importance to Criteria. By following these steps, the methodology ensures a thorough, transparent, and data-driven comparative assessment of CPVS and DPVS. A structured comparison across the criteria will guide decision-makers in selecting the most suitable generation method for rural areas.

Identify Key Variables and Metrics

This comparative analysis employed the author’s assessment framework. This allowed for a structured and uniform basis for evaluating and comparing CPVS and DPVS. The framework’s variables and metrics, referred to as criteria, were utilized in this comparative analysis.

The data for this analysis were gathered from multiple data sources to provide a comprehensive assessment. The secondary data detailed in sections 2.3, 2.5, 2.6 and 2.7, was collected through a systematic literature review. The primary data was collected through observations, interviews, and a survey. The illustration below provides the process flow for the comparative analysis.

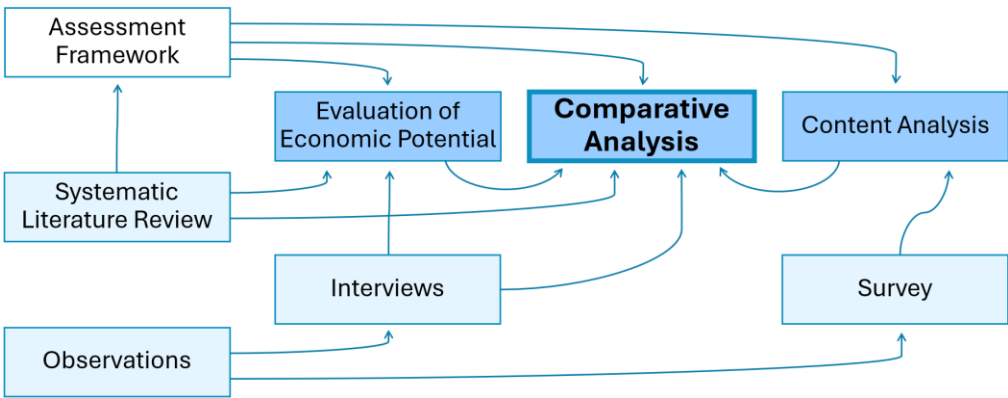


Figure 20: The process flow for the comparative analysis.
Note: Own work. Bergen, November 13, 2024.

Visualize Data for Clarity

To make the comparison more accessible, the main findings for each criterion were organized into a table, as shown in Table 9. This table displays CPVS and DPVS side by side across all criteria, providing a clear visual representation of their advantages and challenges and helping stakeholders interpret the results effectively.

Evaluate and Score Criteria, and Assign Importance to Criteria

Each criterion was scored based on its performance for CPVS and DPVS. Quantitative data, such as LCOE or CF, is normalized for comparability, while qualitative data, like empowerment or institutional challenges, is assessed descriptively. These scores are compiled to reflect the overall performance of each PV system.

Not all criteria are equally important in determining the suitability and effects of CPVS and DPVS in underdeveloped rural areas. Higher weights are assigned to those criteria that are crucial for achieving rural development goals. For example, the criterion “Scalability” is prioritized because it aligns with Tanzania’s urgent need for reliable electricity in regions lacking adequate electrical infrastructure. The criterion “Job creation and entrepreneurship opportunities” receive greater weight due to their direct relevance to community empowerment and economic growth in rural Tanzania. Consequently, the perspectives within the assessment framework are automatically given importance, as they encompass various scored criteria. The assigned importance of each perspective is detailed in Figure 21 and Table 10.

4 Research Results

This chapter presents the main findings from the data collection and analysis.

4.1 Content Analysis – Main Findings

Using the assessment framework criteria to create the categories for the content analysis, the significant impact Tumaini's DPVS has had on its stakeholders was categorized and revealed. Main findings from the content analysis are provided in the table below.

Table 8: Main findings from content analysis

Criteria	Category	Tumaini's DPVS
Empowerment and Gender Equality	Empowerment	All students and teachers expressed a strong sense of empowerment, particularly the ability to control their study and teaching schedules. Students highlighted improved autonomy and self-determination, while teachers felt more capable of utilizing modern teaching tools and engaging students.
	Digital Literacy	Access to digital resources (tablets, computers, and the Internet) enabled both students and teachers to develop digital skills. This improvement in digital literacy is particularly significant for students in rural areas, as it prepares them for future job opportunities in technology and entrepreneurship.
	Learning Environment	The PV system transformed the school environment by enabling reliable lighting, digital learning resources, and interactive teaching methods. Teachers could incorporate audiovisual aids, while students benefited from extended hours of their homework, more engaging study environment, and access to a broader array of learning materials.
Job Creation and Entrepreneurship Opportunities	Entrepreneurship Opportunities	The reliable energy supply enabled entrepreneurial activities at Tumaini, such as poultry farming, with plans for further initiatives like fish farming. These activities not only support the school financially but also equip students, especially teenage mothers, with practical skills that could be used for future income generation and employment.
System Sustainability	Community engagement	Stakeholders reported a growing understanding of renewable energy's environmental and practical benefits. Both teachers and students are now more aware of its significance, emphasizing that the PV system has positively influenced their attitudes toward sustainable practices. The community's engagement in Tumaini has significantly increased. The community comes to learn about technology and views the school as a source of community development.

These results show that the DPVS had a multifaceted impact beyond just providing electricity for essential equipment. Key benefits include increased empowerment, enhanced digital literacy, improved educational environment, new income and employment opportunities, heightened awareness of renewable energy, and increased community engagement.

4.2 Comparative Analysis – Main Findings

This section presents a comparative analysis of CPVS and DPVS, focusing on identifying the most effective model for sustainable rural electrification in Tanzania, a country facing significant challenges in its power grid and political environment. The purpose of this analysis is to guide the development of effective rural energy solutions that contribute to sustainable development while also serving as a foundation for further research and informing decision-making among stakeholders. The comparison is structured around the four perspectives outlined in the assessment framework: techno-economic, socio-economic, environmental, and institutional.

The table below summarizes important secondary data derived from the systematic literature review, and primary data from observations, interviews, and a survey.

Table 9: Main findings from comparative analysis

	Secondary data		Primary data
Criteria	CPVS	DPVS	Tumaini's DPVS
Techno-economic perspective			
Levelized cost of energy (LCOE)	Lower LCOE per unit capacity, benefiting from economies of scale. Had a global average LCOE of 0.060 USD/kWh in 2020 and 0.044 USD/kWh in 2023 (IRENA, 2024b).	Higher LCOE per unit capacity due to individual unit costs Had a global average LCOE of 0.124 USD/kWh in 2020 (IRENA, 2021).	Had an LCOE of 0.574 USD/kWh in March 2024. (Without batteries, the LCOE amounts to 0.328 USD/kWh.)
Capital Expenditures (CAPEX)	Higher CAPEX per project due to larger scale. Lower CAPEX per unit capacity, benefiting from economies of scale.	Lower CAPEX per project due to smaller scale. Higher CAPEX per unit capacity due to individual unit costs. Had a U.S. average CAPEX of 2682.2	Had a CAPEX of 2160 USD/kW in March 2024.

	Had a U.S. average CAPEX of 1610.9 USD/kW in 2023 (NREL, 2024a).	USD/kW in 2023 NREL (2024b).	
Total installed costs	Lower total installed cost per unit capacity. Infrastructure, installation, and large land areas increase costs but spread across output. Had a global average total install cost of 1019 USD/kW in 2020 (IRENA, 2024b).	Higher total installed cost per unit capacity. No land or infrastructure costs. Had a global average total install cost of 1747 USD/kW in 2020 (IRENA, 2021).	Had a total installed cost of 2160 USD/kW in March 2024.
Operation and Maintenance (O&M) Costs	Lower O&M costs due to centralization and fewer technicians required per unit capacity. Had a U.S. average O&M cost of 22.2 USD/kW in 2023 (NREL, 2024a). Had a global average O&M cost of 10.3 USD/kW in 2023 (IRENA, 2024b).	Higher O&M due to dispersed locations. Had a U.S. average O&M cost of 30.4 USD/kW in 2023 (NREL, 2024b).	The reoccurring O&M costs are determined by the replacement cost of the batteries and the inverter.
Capacity factor (CF)	Higher CF due to optimal siting and azimuth adjustments. A U.S. average CF of 0.317 in 2023 (NREL, 2024a).	Lower CF due greater likelihood of shading and suboptimal positioning. A U.S. average CF of 0.185 in 2023 (NREL, 2024b).	
Scalability	Low scalability since they require extensive planning, permits, and infrastructure development over 2–3 years.	High scalability, due to their ease of deployment quickly and increase incrementally in rural regions.	Sufficient inverter capacity and space on the roof to easily and incrementally add more PV modules and/or batteries.
Socio-Economic perspective			
Affordability of energy services	Grid-based electricity is generally the cheapest option for customers, but grid connection fees in rural areas are still prohibitive for some. May not directly benefit the poorest households.	Direct savings on fuel, charging services, and affordability are enhanced by financing options like PayGo.	Provides continuous energy at a predictable maintenance cost, which aids long-term planning.

Empowerment and gender equality	Limited impact on empowerment and gender equality due to centralized nature. Typically requires male-dominated roles in construction and technical jobs.	Empowering rural women through better access to education, health, and safety. Promotes economic roles for women and girls in using PV systems for entrepreneurship.	Strong impact on empowerment. Increased educational environment and programs that equip women with skills for self-sufficiency and financial independence, and job opportunities.
Job creation and entrepreneurship opportunities	19190 jobs are expected in Tanzania by 2030, primarily in construction, maintenance, and manufacturing (IRENA, 2017). Local Tanzanian companies struggle to meet the technical requirements of international funders, limiting their participation in renewable energy projects, which hinders the development of local skills, industries, and jobs.	994 jobs are expected in Tanzania by 2030 (IRENA, 2017). More opportunities for local entrepreneurship in rural areas, including battery charging and water pumping. Requires local businesses to build, operate, and maintain the facilities, thus generating more opportunities for local enterprises and employment.	Enables programs, such as poultry and potentially fish farming, to help secure future employment.
Environmental perspective			
Carbon footprint	Lower carbon footprint per unit capacity. Transmission losses, due to long transmission and distribution lines, significantly contribute to the carbon footprint.	Higher carbon footprint per unit capacity. Periodic replacement of batteries and inadequate waste management increases carbon footprint. Electricity generation near the point of consumption minimizes infrastructure requirements and transmission losses.	Replacement of batteries every 5th year increases the carbon footprint.
Land use	Requires extensive land use, increasing habitat disruption. Environmental impacts include effects on biodiversity and impacts on soil, water consumption, and human health	Do not require land areas due to using existing rooftops or infrastructure, reducing habitat disruption.	Did not require land area due to roof installation.

Institutional perspective			
Policy and regulatory support	Tanzania often supports large-scale, state-owned energy projects but is hesitant to finance CPVS due to the unpredictability of revenue. As a result, private investors in solar energy face very high interest rates, up to 20% (Aly et al., 2019). Face stringent regulatory requirements, which can delay development.	Favorable regulatory environment with incentives like tax credits, loan support and net metering policies. The latter has not yet been implemented in Tanzania.	
Sources of funding	Relies on international funding, development banks, and public-private partnerships. Investment risks are high due to TANESCO's debt, limiting private sector interest .	Supported by a mix of private loans, microfinance, and NGO funding. Development aid aims to promote this as a viable alternative for rural electrification.	NGO provided technical expertise through qualified engineers, while a private investor contributed a small business grant.
Energy security	Enhances national energy security, but grid failures or natural disasters can lead to large-scale outages. Grid reliance makes the energy supply more vulnerable.	Provides local energy security, reducing dependence and stress on the grid. Failures are localized, affecting only a small area. Batteries reliance makes the energy supply less vulnerable.	Provided local energy security, completely without power outages, due to sufficient size.
Financial profitability	Longer payback due to high initial investment. The low tariff cap for reimbursed electricity creates low profitability and challenges in signing Power Purchase Agreements (PPAs) with solar power developers.	Shorter payback period due to lower upfront costs. Minimal savings and low profitability due to affordable grid electricity, but reduced expenses on fuel for backup supply and cooking.	Resulted in self-sufficiency, increasing savings from the electricity that would have been purchased from the grid.
System sustainability	Sustainable if supported by national technical expertise and trained personnel, but risks sustainability if poorly managed.	Sustainability relies on technical design, proper management, community engagement, and financial planning.	Increased awareness of solar energy. Increased community engagement.

The comparative analysis between CPVS and DPVS revealed distinct advantages and challenges across the four perspectives. The author has created a visual summary of these main findings, illustrated in the figure below. Each plate in the figure represents a perspective, and the size of each plate reflects the level of advantage within the specified perspective. Each plate size is represented by a distinct color to highlight its size.

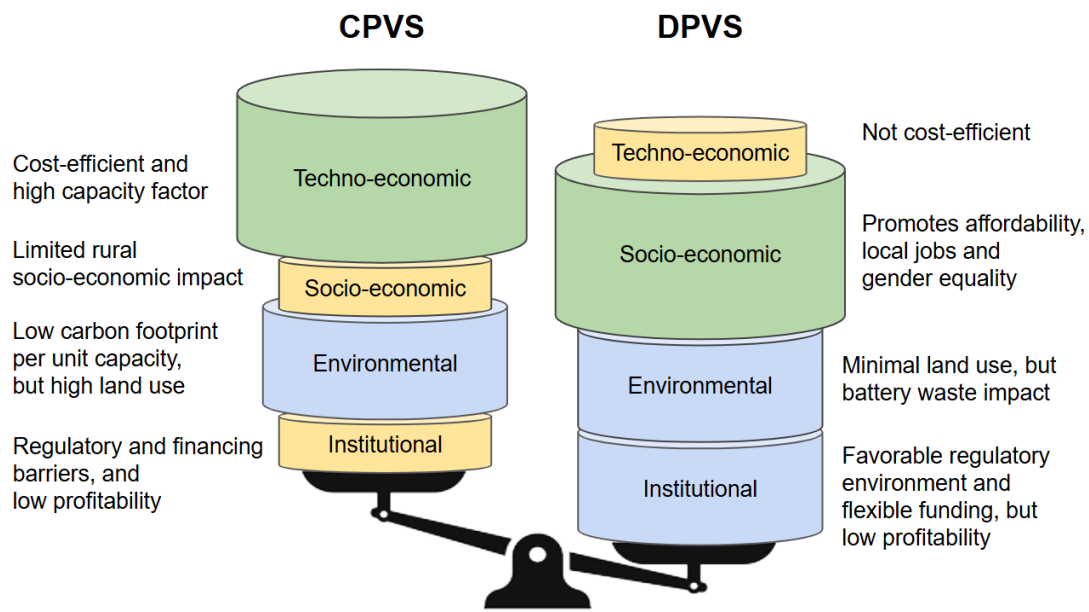


Figure 21: A dual-scale infographic of CPVS and DPVS in rural Tanzania, where the size of each plate indicates the level of advantage within the specified perspective.

Note: Own work. Bergen, November 1, 2024.

A justification for the size of each plate in the figure above is provided below:

- Techno-Economic Perspective:
 - CPVS have a large advantage in LCOE and CF, reflecting cost-efficiency at scale. However, they face scalability and higher CAPEX disadvantages due to extensive infrastructure requirements, planning, and permitting. CPVS's cost advantage per unit capacity outweighed scalability challenges, justifying their large plate.
 - DPVS are advantageous in scalability and affordability for small, rural installations, but they have significantly higher LCOE, CAPEX, and total installed cost per unit capacity. These strengths allow DPVS to be deployed incrementally without needing extensive electricity infrastructure and with less

regulatory burden, but the cost disadvantages still prevent them from achieving anything larger than a small plate.

– Socio-Economic Perspective:

- CPVS have limited socio-economic benefits from job creation, especially in technical fields. However, Key public institutions in Tanzania, lack sufficient technical expertise in assessing and executing large-scale solar power projects, hindering the development of local skills, industries, and jobs in Tanzania. Therefore, CPVS have a small plate as their socio-economic disadvantages weigh heavily.
- DPVS have a large advantage in job creation, local economic empowerment, affordability, and gender equality. These systems provide energy directly to rural communities, allowing women and marginalized groups to benefit from improved access to energy services, job opportunities, and educational outcomes. The large plate reflects DPVS's transformative socio-economic benefits despite some dependency on community involvement for maintenance.

– Environmental Perspective:

- CPVS face large environmental disadvantages from high land use but have a lower carbon footprint per unit of capacity than DPVS. This justifies a medium plate.
- DPVS offer a low environmental footprint due to installation on or near existing infrastructure, reducing land area and transmission losses significantly. However, battery replacements create moderate environmental concerns due to electronic waste, balancing their environmental benefits. Thus, DPVS are rated with a medium plate for a mixed impact.

– Institutional Perspective:

- CPVS face significant regulatory and financing hurdles. High investment costs and interest rates, and longer timelines for securing land and infrastructure, adds risk for private investment. Low profitability for solar developers due to low electricity tariffs. The small plate reflects these institutional challenges.

- DPVS benefit from evolving regulatory support and simpler financing models, but face limitations in creating a large-scale impact on national energy security. Although profitability is limited due to affordable grid electricity, DPVS offers cost savings as it does not depend on an unreliable grid supply, which requires purchasing or collecting backup fuel. This balanced impact justifies a medium plate for DPVS.

The level of advantage within the specified perspective (as illustrated by different-sized plates in Figure 21), can also be depicted through stars, as shown in the table below.

Table 10: The level of advantage for each perspective depicted through stars.

Perspectives	CPVS	DPVS
Techno-Economic	★ ★ ★	★
Socio-Economic	★	★ ★ ★
Environmental	★ ★	★ ★
Institutional	★	★ ★

5 Discussion

This chapter discusses the broader implications of the research findings, evaluates the study's limitations, and offers actionable insights for external stakeholders.

The results underscore the crucial role that governance and policy play in creating a stable policy and regulatory environment that supports and encourages the development of PV systems. In Tanzania, the lack of net metering policies and the dominance of government-led energy initiatives hinder the growth of DPVS and discourage private sector investment. For CPVS, high investment costs, interest rates, and regulatory challenges limit its feasibility as part of long-term energy strategies. Additionally, CPVS must meet the technical requirements set by international funders, which many public institutions and companies in Tanzania struggle to comply with (Aly et al., 2019). This leads to most of the energy-related funds being allocated to non-African entities.

While the research results confirm that CPVS are cost-effective at scale, they are limited by the weaknesses of Tanzania's electricity infrastructure. The fact that the Tabora region can only utilize 14 MW of the 40.5 MW supplied by the national grid (Mwanri, 2020) highlights the challenges in transmitting generated power. Tanzania needs substantial investment in grid infrastructure and institutional reforms to enhance TANESCO's ability to manage and expand centralized energy systems effectively. Therefore, in the foreseeable future, deploying CPVS will primarily increase access to affordable, reliable, sustainable, and modern energy for Tanzania's urban and industrial customers, but not for rural customers.

This emphasizes the need for decentralized solutions, such as DPVS, to effectively address the electricity needs of rural communities. This confirms the statement from IEA et al. (2024) that achieving SDG 7 by 2030 necessitates a multifaceted approach that includes grid, mini-grid, and stand-alone off-grid solutions. Achieving SDG 7 will contribute to other goals, including SDG 3 (good health and well-being), SDG 4 (quality education), and SDG 5 (gender equality).

The sustainability of DPVS in remote areas hinges on technical design, proper management, community engagement, and financial planning (Léna, 2013; Odarno et al., 2015). In planning Tumaini's DPVS, the author chose to use locally available components for the PV system and a local solar company for the installation, ensuring that replacements and technical maintenance would be easily accessible. According to the contract, Ensol is responsible for technical

maintenance, while one of the teachers is assigned to handle regular cleaning (Ezekiel, personal communication, October 11, 2024). To reduce our dependence on donations, some of the business opportunities that emerged at Tumaini will hopefully generate income to help finance future expenses, such as battery replacements. Lithium-ion batteries might be locally available by the time AGM batteries reach the end of their life, reducing the replacement frequency and lead pollution.

The research results confirm that DPVS provide clear advantages, including empowerment, enhanced educational resources, and new business opportunities. This aligns with existing literature that states DPVS contribute to significant developmental benefits, particularly in advancing gender equality (Cox et al., 2016; RES4Africa, 2023). However, achieving these gender equity benefits does not occur automatically, it requires equipping women with the necessary skills and knowledge to succeed. Initiatives like vocational training and computer courses offered by Tumaini are essential in this regard. While DPVS has facilitated empowerment at Tumaini, replicating these outcomes in different locations will require the integration of case-specific strategies and resources.

5.1 Study Limitations

This section highlights the research's weaknesses or challenges in achieving comprehensive or definitive key findings, discusses how they might impact them, and proposes strategies to mitigate these limitations.

Generalization of Data

The study relies on generalized data for key metrics such as LCOE, CAPEX, and O&M costs due to the scarcity of detailed data for African countries. Many global averages were used, which may not reflect local realities. This limitation reduces the universal applicability of the findings and highlights the need for region-specific data collection in future studies.

Although the case study at Tumaini offers valuable insights, its focus on a single location limits the scope of the findings. The survey questionnaires generated responses from three students, three teachers, and one volunteer. This small sample size restricts the generalizability of the

results. However, since the respondents are key informants who offer valuable perspectives, a limited number of responses can still provide significant depth and richness in the data.

Limited Quantitative Data

The analysis incorporates both quantitative data, such as costs, energy capacities, and scalability metrics, while also emphasizing a holistic assessment that integrates qualitative perspectives. This approach is important because the impacts of rural electrification are multi-dimensional and extend beyond purely numerical outcomes. Metrics such as gender empowerment, job creation, and policy adaptability are critical, though they can be more challenging to quantify. Therefore, the framework includes descriptive insights to capture these broader socio-economic and institutional dynamics, offering a more comprehensive and actionable evaluation for stakeholders.

Environmental Impact Constraints

The study recognizes that battery waste from DPVS presents environmental challenges. However, it does not offer specific solutions or investigate alternative battery technologies. This oversight leaves the sustainability of DPVS only partially addressed, especially in terms of waste management in rural areas where recycling infrastructure is lacking.

Potential Researcher Bias in Qualitative Analysis

As qualitative interpretations of socio-economic and institutional impacts are subjective, researcher bias may influence findings. Although the framework aims to be objective, interpretations can still reflect the researcher's perspectives, which may affect the study's conclusions.

5.2 Actionable Insights for External Stakeholders

The results offer actionable insights for addressing challenges associated with achieving sustainable energy access in underserved rural regions. This section outlines these specific actions.

For Policymakers

- Upgrade the transmission network and transform it into a "smart grid" capable of managing being fed with intermittent production, like solar power. These improvements will also reduce the utilization gap observed in regions like Tabora, where only 14 MW of 40.5 MW is usable due to infrastructure limitations (Mwanri, 2020), and mitigate the 1548 annual power outages reported between 2016 and 2019 (NAO, 2020).
- Combat corruption and inefficiencies within TANESCO by implementing transparent tendering processes and introducing mechanisms to monitor the performance of contracted projects. This approach will reduce revenue losses from unauthorized grid connections and enhance the execution of projects.
- Update regulations to reduce bureaucratic delays that often hinder CPVS deployment. Streamline land acquisition processes and reduce political interference to enhance private sector confidence and encourage CPVS investments.
- Implement net metering programs for grid-connected systems, allowing rural households and institutions to sell excess energy back to the grid. This enhances affordability, energy security, and the use of DPVS. For DPVS in micro and mini-grids, enable peer-to-peer energy trading and promote community-based energy management.
- Increase subsidies for DPVS to make them affordable for rural households, schools, and small businesses. Target these subsidies at reducing upfront CAPEX, particularly for off-grid systems that alleviate pressure on the unreliable national grid.
- Regulate the hazardous informal lead-acid battery recycling industry. Gain a better understanding of the impacts of lead poisoning and collaborate with neighboring countries and international partners to implement regulated lead recycling practices.

For Investors

- The most effective area to allocate funding is DPVS in rural areas with no or limited access to the electricity grid, where decreased reliance on unreliable electricity supply from the national grid can provide significant socio-economic benefits.
- Target CPVS investments in urban or industrial areas where grid capacity and demand support the implementation of a large-scale investment.
- Collaborate with development banks and governments to create guarantee schemes. These schemes will lower the risks of investing in CPVS in Tanzania, especially in areas where political issues affect how institutions operate.

For Development Organizations (Including NGOs)

- Provide technical training to local electricians and technicians to address the shortage of licensed professionals. This training will ensure proper system installation and maintenance, reducing delays in connecting rural communities to energy sources.
- Support the establishment of community-owned DPVS systems, allowing revenue from energy sales to be reinvested in local development projects, such as schools and healthcare facilities. Empower rural communities through vocational programs and guide them in creating transparent governance structures to manage these systems effectively and sustainably.
- Establish community-based battery recycling programs to address environmental issues linked to DPVS, especially in areas without formal recycling systems. Launch awareness campaigns to inform communities about proper waste disposal and the environmental advantages of renewable energy solutions.

For Researchers

- Use the study's framework to conduct field research in diverse rural contexts across Sub-Saharan Africa, addressing the lack of quantitative data in this region. This is especially true for critical techno-economic metrics like LCOE, CAPEX, O&M costs, and payback periods. Socio-economic metrics such as job creation and empowerment should also be quantified for rural areas.

- Conduct case studies on the socio-economic impacts of CPVS in rural areas, exploring whether these systems can create local jobs and empower communities, particularly in regions where DPVS is less viable.
- Conduct long-term studies to evaluate how the socio-economic and environmental impacts of DPVS evolve over time, particularly in areas where infrastructure or policy conditions may shift.
- Research innovative battery technologies, such as second-life batteries or modular storage solutions, to address the waste challenges associated with DPVS. Study successful recycling initiatives in other developing regions and adapt these models to rural Tanzania.
- Use comparative studies to identify how CPVS and DPVS perform in different Sub-Saharan countries, and the impacts of it by utilizing standardized methods for measuring qualitative data, creating a robust data set to refine the framework further.

6 Conclusion

This study presents a comprehensive assessment framework that facilitates a structured comparison of CPVS and DPVS in underdeveloped rural areas, considering four perspectives: techno-economic, socio-economic, environmental, and institutional. Using this multidimensional assessment framework to compare CPVS and DPVS, the study concluded that DPVS provides a more effective and practical solution for rural electrification in Tanzania, given the current state of the electricity grid.

As of 2021, only 23.3% of Tanzania's rural population had access to electricity, despite rural areas comprising 64% of the national population (World Bank, 2023). Tanzania's national power grid supplies 97.5% of the country's electricity (EWURA, 2021), but its outdated electricity infrastructure fails to meet the needs of the rural population. For instance, while the national power grid supplies the Tabora region with 40.5 MW of electricity, only 14 MW can be effectively utilized (Mwanri, 2020). TANESCO encounters systemic challenges, such as 1548 power outages annually due to outdated electricity infrastructure, financial constraints, and inefficiencies within government utilities (NAO, 2020).

While CPVS are cost-effective at scale, their dependence on Tanzania's outdated electricity infrastructure means they will not provide reliable electricity in rural areas in the near future. This situation highlights the urgent need for DPVS, which can function independently from the national grid, and be deployed rapidly and incrementally by local solar companies. However, the reliance on DPVS will require addressing some limitations, such as high per-unit costs and the environmental impact of battery waste. If Tanzania's grid infrastructure significantly improves, CPVS may become a viable alternative in the future.

For customers, electricity generated from centralized sources, such as CPVS, is affordable. However, the cost of connecting to the grid can pose a financial barrier. The potential savings from the electricity that would otherwise be purchased from the grid may not be enough to justify a significant investment in DPVS. Instead, the reduced expenses for fuel to backup generators and for cooking, and the socio-economic opportunities DPVS provides, serve as a stronger reason to invest in these systems.

The case study of Tumaini Open School demonstrated that DPVS not only provided reliable electricity for energy-dependent activities but also increased empowerment, enhanced digital

literacy, improved educational environment, new income and employment opportunities, heightened awareness of renewable energy, and increased community engagement. This motivated individuals to create entrepreneurship programs and start small businesses that rely on electricity. Right after a DPVS was installed on the roof of Tumaini's classroom building, the school launched computer courses and poultry farming programs. Additionally, plans for fish-keeping programs and bakeries were developed. These initiatives were not possible earlier because the school building relied solely on the unstable national electricity grid.

This initial application of the assessment framework provided results that laid a foundation for broader evaluations and offered valuable insights for various external stakeholders. Among these, the study highlighted several critical areas that need further research. It is essential to collect quantitative data for metrics such as LCOE, CAPEX, and O&M costs in Sub-Saharan Africa. This information is vital for enhancing future techno-economic analyses for the region. Case studies on CPVS are necessary to determine whether they can offer significant socio-economic advantages in rural areas. Conduct long-term studies to evaluate how the socio-economic and environmental impacts of DPVS evolve over time, particularly in areas where infrastructure or policy conditions may shift. For instance, research the carbon footprint of Tumaini's hybrid PV system. Conduct comparative studies to examine the performance and effects of CPVS and DPVS across various Sub-Saharan countries, while utilizing standardized methods for measuring qualitative data. This will create a robust dataset to refine the framework further.

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Appendixes 1 – Questionnaires

This appendix includes unedited, direct quotes from Tumaini's local stakeholders retrieved from questionnaires containing responses to open-ended questions. This “raw data” is presented in quotation marks below each question.

Since the author created three separate questionnaires for students, teachers, and leaders/volunteers, this appendix is organized into sections 1A, 1B, and 1C, respectively. All documents were obtained through personal communication between the author and John in May and June 2024.

In accordance with the General Data Protection Regulation, students' and teachers' names have been replaced with other common African names.

Appendix 1A – The questionnaire for the students, and their responses

A short description of the female student respondents, along with the date they completed the questionnaire:

- Yamina is 17 years old and currently in stage 1 of her secondary education. She completed the questionnaire on May 2, 2024.
- Akili is 22 years old and currently in stage 2 of her secondary education. She completed the questionnaire on May 2, 2024.
- Zalika is 19 years old and currently in stage 1 of her secondary education. She completed the questionnaire on May 2, 2024.

The introduction to the questions, the questions, and the directly quoted answers are presented below:

Before, there was neither a solar PV system nor an InfoSpot.

Now, there is access to continuous electricity, Wi-Fi, and a local server with information.

How have these new circumstances influenced:

1. your feeling of empowerment (autonomy and self-determination) as a student?
 - Yamina: “Yes I feel empowered because both the electric system and community web server brought self dependability to my studies hence I can

access and get all important resources that actually facilitate my studies as student without a close supervision of teachers”

- Akili: “I real feel empowered and the level of self -determination is high due to the changing of my learning environment, I feel helped and empowered to high self-determination due to the presence of nonstop electric power also due to the presence of free internet service, personally I can access basic information to the web community anytime.”
- Zalika: “Before we had no solar system and internet service in our school compound the level of empowerment was too low, but we are witnessing the changes and raise of empowerment environment due to the present of nonstop power and internet service, I real observe self-determination has increased to me.”

2. your feeling of empowerment in your personal life?

- Yamina: “I deeply feel empowered and helped hence I can study anytime as mi schedule guide me without getting other disturbances of no power and no access of information, unlike the past days currently I can do the best, so I feel empowered.”
- Akili and Zalika: “I feel empowered personally hence the life in institute is really good because there is assurance of electric supply always for lights, running different devices such as computers, tablets.”

3. your learning environment at Tumaini Open School?

- Yamina: “My learning environment at Tumaini open school are better and are well improved compared to the days back where we had no nonstop electricity so through the improvements of this environment our future in our studies looks so brighter.
- Akili: ”My learning environment at Tumaini open school I well improved especially in electric energy supply also digital interactions now we can access the materials and information I need for my studies.”
- Zalika: “The great changes observed compared to the time with no solar energy system in our school compound, the learning environment at Tumaini school has total changed and well improved. hence the life with nonstop power makes a conducive learning environment.”

4. your access to educational information and resources?

- Yamina: “Yes, I can access the educational information and other learning resources because of the availability of free basic internet services and frequently use of community web server.”

- Akili: “After the installations of both PV solar and basic internet service now we can access the information, such as learning tutorial, movies, books and notes.”
 - Zalika: “Previously without internet and continuous electricity the access of educational materials was so difficult but after installation of internet system and continuous electricity the access of educational information is so easy and almost all material is being accessed.”
5. the quality or variety of educational materials available to you?
- Yamina: “Yes, I real get quality material through community web server that installed in our school compound.”
 - Akili and Zalika: “Unlike before installations of both PV solar system and web community server currently we can get quality materials which are helpful in my studies.”
6. your digital literacy (skills) and internet literacy?
- Yamina: “Unlike the past days without the free internet in our school compound currently my digital literacy skills now are increased due to the use of electronic devices such as tablets, computer with the free internet services that is installed in our school.”
 - Akili and Zalika: “My digital literacy skills now are step up due to the frequently use of internet and web server community this help to sharpen my digital skills.”
7. the effectiveness of the teacher-led class sessions?
- Yamina: “is better because he always used to teach us on use of the system of basic internet services in order, we can adapt the system of internet and proper use of electric devices.”
 - Akili and Zalika: “The effectiveness of teacher – led class is so good hence he always emphasized us on use of the system and trying to all efforts on impacting people in the community of Tumaini open school to adapt the system of internet and proper use of electric system.”
8. the effectiveness of your self-study sessions and routines?
- Yamina: “the effectiveness of my studies sessions and routine are well organized hence I can observe anything I plan to do because of presence of studying facilities such as internet and electricity.”

- Akili and Zalika: “The effectiveness of my personal studies and management of my daily routine I well improved due to the availability of alternative power system.”

9. your understanding of renewable energy and sustainability?

- Yamina: “Since we started use of PV solar system, I gain a knowledge and awareness on importance of renewable energy because the system has positive impact to the environment and assurance of its availability.”
- Akili and Zalika: “Currently I added some awareness about renewable energy, and it advantages such as use of solar energy. Through the PV solar in our compound my knowledge concerning use of solar energy is increasing daily.”

10. your motivation, engagement, and overall satisfaction with your educational experience?

- Yamina: “Since we got the PV solar system and the basic internet, I feel motivated, engaged and satisfied with the learning environment of our school and it all comes to simplify our road Map to our education experience.”
- Akili and Zalika: “My motivation and engagement in my education experience is nice now unlike the past moment when there were no assurance of electricity and with no internet, I surely being satisfied with the current environment of our school.”

11. your learning outcomes and skill development?

- Yamina: “Yes, my skills are developed because we all have supportive learning facilities which help to enrich our skills.”
- Akili and Zalika: “I witness on advancement and improvements in my studies results also my skills are developed well this is highly influenced by presences of supportive facilities like nonstop electricity and presence of electricity frequently.”

12. Your expectations for future studies, employment and/or economic opportunities?

- Yamina: “The expectations I have for my future studies Is to achieve better in the journey of my studies and this are influenced by the currently environment to which am studying this gives me dream to capture mostly of economic opportunities in use of renewable energy and applications of digital skills.”
- Akili and Zalika: “My future expectations in my studies are score best results and perform good also for my future employment and career I expected big outcomes because through competencies and capacity I impacted from Tumaini will enable me to make good in technological industry.”

Appendix 1B – The questionnaire for the teachers, and their responses

A short description of the female teachers respondents, along with the date they completed the questionnaire:

- Eshe is 29 years old and holds a bachelor’s degree in teaching.
She completed the questionnaire on May 2, 2024.
- Tanishia is 27 years old and holds a diploma in teaching.
She completed the questionnaire on June 6, 2024.
- Walidah is 25 years old and holds a diploma in teaching.
She completed the questionnaire on June 1, 2024.

The introduction to the questions, the questions, and the directly quoted answers are presented below:

Before, there was neither a solar PV system nor an InfoSpot.

Now, there is access to continuous electricity, Wi-Fi, and a local server with information. How have these new circumstances influenced:

1. the empowerment (autonomy and self-determination) of the teenage mothers?
 - Eshe: “The teenager mothers empowered by learning through visual, sounds, and practical which incorporate modern device which use power or electricity”
 - Tanishia: “The young mothers are really feeling empowered unlike past days due to the improved learning environment and is valid due to the presence of constant availability of electricity”
 - Walidah: “The teenage mothers feel to be empowered hence they can have high level of personal dependence on their studies these changes are influenced by improvements done in our school compound this is installations of continuous electricity.”
2. your feeling of empowerment as a teacher?
 - Eshe: “I am feeling now as a modern teacher, since I am using modern teaching devices like projector and computer.”

- Tanishia: “Before the installations of the system the life is used to be hard at work so currently, I feel so empowered because of presence of power and internet that help me to use it as tools in my teaching activities.”
- Walidah: “As a teacher I feel to empowered and because the way of performing my tasks looks so cleared due to the presence of some factors that modify and simplify my task like not back days.”

3. the teaching environment and resources at Tumaini Open School?

- Eshe: “Through continuous electricity and presence of internet, now days we are using visual aid in teaching”
- Tanishia: “Teaching environment currently are better compared to the time before installation, working environment are suitable for my tasks and assigned tasks, system installations come to make difficult things to be easier.”
- Walidah: “School environments are well improved and are so supportive for my teaching activities”

4. your digital literacy (skills) and internet literacy?

- Eshe: “Now days we are familiar with navigating in difference learning platform such as yeboo.com and other digital transformation platform”
- Tanishia: “There is high increase on my digital literacy because nowadays am becoming so closer to the computers and other digital devices that helps me to learn more on digital literacy”
- Walidah: “Every day after installation of the system and internet contributed to raise my literacy skill, unlike before when were not had an internet my digital literacy was like stagnated due to the unavailability of internet and insufficient electricity.”

5. your teaching methods and classroom activities??

- Eshe: “Through that method new technologies, now day we are using film showing-discussions audiovisual and video as a teaching
- Tanishia: “Nowadays my teaching methods are shifted highly unlike past days where I just applied normal teaching methods but currently in my teaching methods, I always involve technological techniques to deliver lessons to my students it involves use of videos for demonstrations”
- Walidah: “Not like back days when we had no insufficient power and internet nowadays, I can apply modern ways in teaching this I because there are facilities that helps me to facilitate the teaching process.”

6. the effectiveness of preparing a class session?

- Eshe: “The new technologies helped us as a teacher in time management when conducting teaching plan.”
- Tanishia: “The presence of internet and electricity gives me an opportunity to get enough time for preparing my class session because nowadays there is no restrictions of circumstances like electricity and unavailability of internet.”
- Walidah: “Nowadays I can prepare my class session in short period of time with accuracy and effectiveness because the assurance of getting power is always good also, I can access teaching materials from different sources.”

7. the effectiveness of conducting class sessions?

- Eshe: “the new technologies helped we as time management when conducting teaching plan.”
- Tanishia: “The presence of both electricity and internet helps me greatly in conducting all of my class sessions to be very effective hence I can teach with application of technology.”
- Walidah: “Nowadays I am conducting my class sessions on so planned and organized ways so all my lessons are being so helpful to my students hence I can use understandable teaching ways such as use of pictorial and videos for demonstrations.”

8. the quality or variety of instructional materials available to you?

- Eshe: “Through the presence of internet and continuous electricity, we have a wide chance in select instructional materials which attract motivate and facilitate learning process.”
- Tanishia: “Due to the presence of internet and continuous electricity, I can prepare and access different learning and instructional materials that are quality and suitable for me to learn.”
- Walidah: “Instructional materials and other teaching resource are so quality hence I get a chance on preparing my lesson plan.”

9. your understanding of renewable energy and sustainability?

- Eshe: “Understanding comes from experience, through the experience of using solar PV system, now we have advanced knowledge about solar energy.”

- Tanishia: “The rate awareness comes from experience we get on what we use nowadays so community is really aware about renewable energy and sustainability this is because of presence of PV solar system.”
- Walidah: “Understanding on use of renewable energy is highly light up because we are the primary beneficiaries of the solar energy installed in our school, so we are currently aware on the use of renewable energy.”

10. your motivation, engagement, and overall satisfaction with your job?

- Eshe: “We as teachers we are motivated and satisfactory due to new technology facilities installed in our school.”
- Tanishia: “As a teacher I feel encouraged and satisfied due to the presence of new technology facilities installed in our school.”
- Walidah: “I do feel well motivated unlike before where we had no continuous electric power and internet in our school.”

11. the student’s engagement, performance, learning outcomes, and skill development?

- Eshe: “Students are more engaged, increased the performance and three skills developed due to attractions and motivation from teaching techniques like simulations.”
- Tanishia: “Actually, the learning outcomes and performance of students is increased highly because of well and improved learning environment unlike the past days.”
- Walidah: “The engagement to my students is so highly because they get quality learning materials and are well guided to attain best performance.”

12. your expectations for the teenage mothers’ future studies, employment and/or economic opportunities?

- Eshe: “Now days all activities involve technology skills, my expectations are to see teenage mothers are involved in various technology sector such as digital market in business.”
- Tanishia: “I expect great risen of young mothers to be young leaders in technology and other important areas hence the nature of school they are used to be equipped and helped them enough under good environment how to lead the world in different opportunities.”
- Walidah: “The future of girls looks so lucrative hence students are well prepared to conquer different economic opportunities and to master it this I well influenced because of presence of modern learning environment.”

Appendix 1C – The questionnaire for the leaders/volunteers, and the response

A short description of the male volunteer respondent, along with the date he completed the questionnaire:

- John is 27 years old and holds a bachelor's degree in human resource management. He completed the questionnaire on May 4, 2024. On June 12, 2024, he elaborated on questions 1 and 10 at the author's request (The elaboration is provided directly below the initial response to the question).

The following text presents questions along with his exact quoted answers:

1. Have there been any unexpected benefits or challenges arising from implementing the solar system and the InfoSpot?
 - “Yes, we are really witness more unexpected benefits from the implementation and use of PV solar system and the internet and some of those unexpected.”
 - “We didn't expect to have sufficient power for Our school and our students all days, all times. Are not our expectations to have a free internet service to our school, this comes to soften the process of learning and is acting as a main tool for our students and teachers, this benefit is meaningful to Tumaini open school. Also, We didn't expect to an alternative Energy system that will help us to conduct different entrepreneurship programs this also come up with a lot of employment opportunities to our teenager's mother's also they can learn on entrepreneurship activities. Now, we have Poultry project that is started immediately after installation of the system. We didn't expect to have the benefits of such kind before.”
2. How do you envision these technologies to contribute to the school's long-term development?
 - “Installations of this technologies comes to us with very big envision in achieving our future and long-term plan to our institute hence comes to show simplicity of accomplishing our daily goals, so the technologies come with highly contributions on showing possibility of achieving goals.”
3. Are there any noticeable changes in community engagement or involvement with the school since implementing the solar system and InfoSpot? If so, please elaborate.
 - “Yes, the community involvement in our school is really increased hence community comes to learn about technology also the perception of community

towards our school is well now hence they believe the presence of TUMAINI OPEN SCHOOL can be source of community development.”

4. Are there plans to introduce new energy-intensive equipment or equipment dependent on continuous energy consumption? If so, why?

- “Yes, we have a plan to introduce new energy intensive equipment such as incubators, water pump machines in order to use the available energy in very productive means hence we can make a profit which will help us in running school activities.”

5. Are there any plans to increase the existing solar system by adding batteries, solar panels, or both? Are there any personal or local requirements to consider when planning?

- “Yes, we actually have a plan of expanding our system by adding batteries and solar panels and batteries in order to meet the need of energy needed in our daily school uses but also in operations of different equipment such as incubators.”

6. Are there any plans to install a similar solar system for another building? Are there any personal or local requirements to consider when planning?

- “Yes, in the future but currently we just have a plan for expanding the system by adding solar panels and batteries but the plan of installations for other building depending on the demand of energy that will be required in our compound.”

7. What do you consider the building blocks for empowerment in rural settings?

- “We real have desires to share the changes that we a getting from the technologies in our school compound, we do expect to have a block for empowering rural setting basically on sharing of technologies.”

8. In what ways do you see access to renewable energy and digital content contributing to the empowerment of teenage mothers in your community?

- “The use of renewable energy and digital content has a full of influence in pushing forward the development of teenage mothers hence the learning environment for our students are well improved also teaching environments for our teachers are well improved so they can facilitate learning process.”

9. How do you think solar energy and access to information influence the education of teenage mothers?

- “The solar energy and access of information influence and real facilitate learning of teenage mothers hence the get electric power which support them in their learning process, so the coming of these technologies to our school come with shining light to their education way.”

10. What prospects exist for employment and economic opportunities for teenage mothers, and for the Tumaini Open School? Have some of these opportunities changed since installing a solar system and an InfoSpot?

- “The future of a girls in our school is well structured so they can capture different economic opportunities and this is by building capacity and entrepreneurship skills so they can hand to capture economic opportunities and There are many economic opportunities and employment channel which arisen at Tumaini open school after installation of the system and we expect to prepare very useful labor and expert from our institute.”
- “Now we are really active on Teaching our students about Computers and impacting them with digital literacy. This Help to raise an opportunity for girl to have digital skills also they can employ on capturing different digital employment such as Digital marketing, Provisions of secretarial services, And other digital services. But also, we have an entrepreneurship classes, this classes are raised by the influence of presence of non stop electricity to our compound, so we are learning on entrepreneurship activities like Poultry keeping, also we are thinking on Establishing simple Fish keeping Programs, also Bakeries this is due to the presence of sufficient Power to our compound.”