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Design and optimal placement of a Standalone Photovoltaic Electric Vehicle Charging Station in Rwanda

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DECLARATION

I, declare that this thesis is the result of my own work, and has not been submitted for any other degree at University of Rwanda or any other institution. All sources of materials that will be used for the thesis work will have been fully acknowledged

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ABSTRACT

Nowadays, there is notable advancement in the production and utilization of electric vehicles, which provide benefits such as zero emissions, high efficiency, reduced noise, and minimal maintenance requirements. However, the existence of charging stations required for recharging electric vehicle batteries adds to a significant energy demand on the power grid and also the selection of optimal locations of that charging stations still have challenge. One approach to ease this pressure on the grid involves utilizing renewable energy sources like solar power. The utilization of standalone charging stations represents good support to the utility grid. Nevertheless, the electrical design and placement of these systems has different techniques and is sometimes complex. Thus, this research set out to design and determine the optimal placement of a standalone PV EV charging station in Kigali by integrating renewable energy generation, battery storage, and EV charging infrastructure. Using locally relevant solar irradiance data and simulated for EV, the design framework incorporated key system parameters such as the number of PV panels, the size of the energy storage system (ESS). The suitability analysis using geographic information system (GIS) data was conducted to provide the information on the optimal placement of standalone photovoltaic swap charging stations in Kigali.

In the design of standalone PV-EVCS the appropriate components for the system was selected, PVSyst and HOMER pro softwares were used in simulation of the system. The simulation results show that the system had a capacity of 78.75 kWh/day and cost of energy which is \$0.23/kWh. The standalone photovoltaic swap charging station is a good alternative for charging station in sub-urban and rural areas because it is cheaper and beneficial to energy independence.

Keywords: Electric vehicle charging station, Standalone PV system, Solar energy, GIS, PVSyst and Homer software

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LIST OF ABBREVIATIONS

EV	Electric vehicle
EVCS	Electric vehicle charging station
ICE	Internal combustion engine
GHG	Greenhouse gas
kW	Kilo Watt
AC	Alternating current
DC	Direct current
PV	Photovoltaic
GDP	Gross domestic product
PSO	Particle Swarm Optimization
MPPT	Maximum power point tracking
IEC	International Electrotechnical Commission
LCOE	Levelized cost of energy
NST	National Strategy for Transformation

CHAPTER 1: INTRODUCTION

1.1. Background

With the escalating concerns regarding environmental issues worldwide, the adoption of using electric vehicles is being viewed as a viable approach to reducing carbon emissions within the transportation sector.

The predominant mode of transportation in Rwanda relies heavily on internal combustion engine (ICE) vehicles, which have been associated with detrimental environmental effects such as air pollution that poses health risks, the release of greenhouse gases contributing to climate change, and noise pollution, among other issues[1].

Consequently, Rwanda heavily relies on the importation of petrol and diesel for its transportation needs, leading to an increased reliance on fuel imports that negatively impact the country's trade balance and expose it to the volatility of global commodity markets. This situation is deemed unsustainable and has significant implications at the macroeconomic level, notably by exacerbating the trade deficit[1].

The government of Rwanda is committed to ensure that the country's transportation infrastructure is both safe and ecologically beneficial for both passengers and goods, with the aim of fostering green development and innovation while also reducing the country's dependence on fossil fuels within the transportation sector. Rwanda's goal is to electrify 20% of buses, 30% of motorcycles, and 8% of automobiles by 2030. [1][2].

1.2. Statement of the problem

In Rwanda, the transportation sector heavily relies on road infrastructure, which significantly contributes to greenhouse gas (GHG) emissions because diesel-fueled vehicles are common use[1]. Addressing the effects on the environmental and dependency on fossil fuels, Rwanda is exploring alternatives like electric vehicles (EVs). However, while electric vehicles reduce dependence on fossil fuels, they still require electrical energy, which may contribute to GHG emissions if sourced from non-renewable energy.

With the anticipated increase in EV adoption, EV Charging stations are still a problem in Rwanda, in addition developing charging station is expensive because most of them are grid-connected in Rwanda and also the strategic placement of charging stations becomes essential. These stations must be conveniently located within the driving range of EVs and widely dispersed across cities to ensure access. However, the increased demand for electricity from EV charging could disrupt grid stability, leading to issues like harmonic distortion and voltage instability.

The use of renewable energy sources can mitigate these challenges, solar energy is proposed. Installation of standalone photovoltaic (PV) electric vehicle charging stations may provide a solution. These stations generate electricity independently from the grid through PV systems, which include a photovoltaic generation system, battery energy storage system, and the charging station itself. The system stores excess energy generated by the PV panels in batteries, which can then be used to charge EVs when PV production is insufficient, ensuring a stable and renewable energy supply for EVs.

1.3. Objectives

The main objective of this research is to design and optimal placement of a Standalone Photovoltaic Electric Vehicle Charging Station in Rwanda.

1.4. Specific objective

The specific objectives of this thesis are:

1. Assessment of current EV charging station in Kigali city
2. Placement optimization of the charging station in Kigali city
3. Design a standalone PV charging station

1.4. Expected Outcome

At the successful completion of this research, it is expected that:

- Potential locations of a standalone PV charging station
- Size of standalone PV charging station
- Optimized place for charging station
- Accessibility, efficiency, and economic viability of charging station

1.5. Scope of the study

This thesis focuses on the design and strategic placement of standalone photovoltaic (PV) swap charging stations for electric vehicles (EVs) in KIGALI City. The research covered several key areas: an analysis of Kigali's solar energy potential, including seasonal variations and geographic disparities; an assessment of current and projected EV adoption rates and their spatial distribution in KIGALI; and an evaluation of existing infrastructure to identify optimal locations for PV charging stations.

1.6. Organization of the Study

This thesis covers Seven chapters. Chapter one gives a brief introduction and motivation of this project and also describes the goal and the problem statement of this research. Chapter two is literature review. It briefly discusses the related literature. The chapter three is research methodology. It provide overview of the research steps, starting from the location to collect data, the data to be collected and method to analyze them targeting the objective of the research. Chapter four is Current EV charging station in Rwanda/Kigali city. It briefly discusses overview of EV charging station in Kigali city. The chapter five Placement optimization of the charging station in Rwanda which discusses on the technique used to place optimally charging station in Kigali city. The chapter six is design of a standalone photovoltaic charging station for the semi-urban areas in Kigali city. The last chapter will cover conclusion.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This chapter presents the theories and researches done on Electric vehicle. It provides information on the background theory of EV, PV system, the battery system and charging station components and the researches done on the area. It is divided in the following sub-sections: Theoretical Background on Electrical vehicle, Photovoltaic systems, battery systems and charging system functioning and efficiency and related research done on Electric vehicle charging stations.

The worldwide movement towards sustainable energy has raised interest in integrating renewable energy sources into transportation systems. Photovoltaic (PV) technology has emerged as a viable option for powering electric vehicle (EV) charging stations due to its ability to harness abundant solar energy[3]. In Rwanda, where solar irradiance is favorable, the development of standalone PV-powered EV charging stations presents an opportunity to support the growing adoption of electric vehicles while addressing the country's energy and environmental challenges. This literature review explores the current state of PV technology in EV charging, with a focus on design considerations and optimal placement strategies for such infrastructure in Rwanda[3][4][5].

2.2. Theoretical Background on Electrical vehicle

Electric vehicles (EVs) are vehicles that use electric motors for propulsion. Even though by definition, motorcycles, trains, ships, or airplanes that are powered by electricity can be categorized as EVs, most often EVs refer to road transport vehicles, e.g., electric cars, motorcycle, buses and trucks[6][7][5].

2.2.1. Various electric car types

There are different kinds of EVs which are divided into three categories which are Battery Electric Vehicle (BEV)[5][6][8], Plugin Hybrid Electric Vehicle (PHEV)[5][6] and Hybrid Electric Vehicle (HEV)[5][6][7] described in more details below[6][7][8][5].

i. Battery electric vehicle (BEV)

It is driven by a DC electric motor supplied from battery and plugged into the grid to recharge its battery. The drive of BEV works independently from the traditional internal combustion engine and its battery is allowed to be recharged through a regenerative braking to recover some of the energy wasted during braking[6][5].

ii. Plug-in hybrid electric vehicle (PHEV)

In contrast to BEV, PHEV is driven by electric motor supplied from a battery but requires a support of an IC engine to charge the battery and /or to drive the system when the battery is about to die which results in fuel cost savings when compared with IC engine drive alone[5][6].

iii. Hybrid electric vehicle (HEV)

HEVs function by combining an electric motor with a battery drive system and a gasoline engine with a fuel tank. Transmission can be turned simultaneously by both the electric motor and the engine which in turns the wheels. HEVs cannot be recharged from utility instead all the energy to be used, comes from gasoline and from regenerative braking[6][5].

2.2.2. Electric vehicle charging

Similarly, to internal combustion engine vehicles, EVs also need the points of refueling which called charging stations. Those charging station deliver the electrical energy form a source to an EV battery throught physical equipment. Charging stations can be classified according to their process type and power [5][9].

2.2.2.1. Methods of Charging

Chargers are devices that deliver energy to batteries. Typically, they work as rectifiers that transform AC power into DC power needed for charging. Battery charging methods are generally categorized into three types: conductive, inductive, and battery swapping[5][9][10][11], [12].

i. Conductive Charging

The most widely used method is conductive charging, which transfers electricity through direct physical contact. In this process, a conductor carries electricity from the source to the battery, making it a simple and high efficiency. Today's electric vehicles like the Nissan Leaf and Tesla models offer two options for conductive charging. For low-power needs, an onboard charger connects directly to the AC grid using a control device, whereas high-power charging is achieved with an external charger that bypasses in-car conversion, delivering power straight to the battery [5][11][12].

ii. Inductive Charging

Inductive charging, often called wireless charging, delivers power to a battery using an electromagnetic field instead of cables. This method offers increased safety in all weather conditions and simplifies the charging process vehicles can simply park over a wireless charging spot to recharge. Several EV manufacturers, including Audi, Mercedes, and Porsche, have indicated that future models may support wireless charging due to its convenience. Moreover, this charging approach is drawing interest from research institutions for public transportation applications, such as electric bus charging. For example, a project at KTH Royal Institute of Technology explored wireless charging for parked buses, while the FABRIC16 project examined advanced on-road charging solutions. In Sweden, Scania and Siemens have tested a wireless charging roadway, where a series of strategically arranged chargers would allow vehicles to recharge while in motion, potentially reducing the need for large batteries. Similar initiatives are underway around the world [5][11], [12].

iii. Battery Swapping

Battery swapping is the process of replacing fully charged batteries with depleted ones at swap charging stations. This strategy offers benefits such as extended battery lifespan, rapid recharging, and a reduced impact on the power grid. Because many batteries remain connected and can be charged continuously, the system helps avoid peak demand periods. However, high management costs and other challenges have limited its broader adoption. Although Tesla once implemented battery swapping for the Model S, the initiative was discontinued. Today, China leads the world in the number of battery swapping stations [5][11], [12].

2.2.3. Charging Levels

Network standards and characteristics for each country has a different specific power configuration. Thus, Electric vehicle charging is classified in various ways. In North America, the Electric Power Research Institute (EPRI) and the Society of Automotive Engineers (SAE) categorize charging into AC Level 1, AC Level 2, and DC Level 3. In contrast, European standards specifically, the International Electrotechnical Commission's IEC 61851-1 Committee define four distinct modes based on factors like power type, voltage, protection devices, and the presence of grounding or control lines[5][8], [9][11].

Conductive charging involved an electric connection between the charging inlet and the vehicle which follows three charging levels such as Level 1, Level 2, and Level 3 depending on the power level as shown in **Table 1**. Level 1 and Level 2 charging are used in onboard chargers with AC power and follow the same set of standards. The Level 1 charger uses a 120 V single-phase AC power supply and has the slowest charging speed which is generally used in domestic with low power levels (up to 1.92 kW) without any additional infrastructure. Therefore, Level 1 charging is appropriate for long-time or overnight charging. Level 1 chargers generally required about 12-24 hours for 1.9 kW charging power for a 16-50 kWh EV battery. Level 2 chargers are the primary charging choice for both public and private facilities because of their comparatively quick charging speeds. The charging time of Level 2 is 3 to 5 times faster than Level 1 chargers due to high power usage. Level 2 charging can provide power up to 19.2 kW for both single phase and split-phase with 208 Vac or 240 Vac voltage. Dedicated components and installations are required in Level 2 chargers for high power transfer through the onboard charger. The charging time range is 2 - 5 hours for 19.2 kW with an EV battery capacity of 30 -50 kWh. Level 1 and 2 charging connectors follow the IEC62196-2 standard in Europe, SAEJ1772 and Tesla superchargers in the USA The DC fast charging or Level 3 charging uses AC and DC power to deliver high voltage DC power to the EV battery. The Level 3 chargers can handle a high-power range between 20 kW to 350 kW to supply DC voltage of around 480 Vdc and above in offboard chargers. DC fast chargers are directly connected to the vehicle via off-board chargers to the three-phase power grid. Charging time of 90 kW or larger Level 3 charger is range 0.2 - 0.5 hours which is faster than Level 1 and 2. However, low-power chargers including Level 1 and Level 2 have the lowest negative impact on the power network during peak time. The local distribution grid may become overloaded by the level 3 chargers due to high power usage during peak times[5][8], [9].

Table 1: Charging levels[5][8], [9][6]

Level	Voltage	Current	Power Output	Charging Time
Level 1	120V AC, Single phase	12 A – 16 A	1.4-1.9 kW	12-24 hours
Level 2	240V AC, Single phase/Three phase	12A - 80A	3.6-19.2 kW	2-5 hours
Level 3 (DC Fast Charging)	240 AC, Three phase/480V DC	250-500A	20-350 kW	20-60 minutes

2.2.4. EV Charging stations

Based on their power sources, electric vehicle (EV) charging stations classify into three primary categories: hybrid, grid-connected, and standalone solar-powered systems.

- i. Grid-connected EV charging stations** are the most common and rely entirely on electricity from the local power grid. These stations are typically easy to install and maintain, offering consistent power supply. However, their environmental impact depends on the energy mix of the grid; if the grid relies heavily on fossil fuels, the charging process may not be entirely eco-friendly.

- ii. Solar-powered EV charging stations** use photovoltaic (PV) panels to generate electricity from sunlight, making them a sustainable and renewable energy option. These stations are ideal for reducing carbon footprints and operating costs over time, as they harness free solar energy. While they offer energy independence and zero operational emissions, their charging capacity can be limited by weather conditions and available sunlight, that’s why these stations should include battery storage systems to maintain charging capability during cloudy weather or nighttime.

- iii. **Hybrid EV charging stations** combine grid electricity with solar power, offering a balanced solution. They use solar energy as the primary source and switch to the grid when solar power is insufficient, ensuring uninterrupted charging. This hybrid approach maximizes sustainability while maintaining reliability, making it a practical choice for areas with variable sunlight or high energy demands. To increase efficiency even more, extra solar energy can be fed back into the grid or stored in batteries.

2.3. Similar Works and Gaps

Several studies have investigated the design and implementation of PV-powered EV charging stations globally. Research has primarily focused on integrating PV systems with existing grid infrastructure, assessing the technical and economic feasibility of such systems, and optimizing the size and configuration of PV arrays and storage systems to meet varying energy demands. For instance, studies in urban environments have explored the potential of rooftop PV installations to power EV chargers, highlighting challenges related to space constraints and shading effects. Other research has examined standalone systems in remote or off-grid areas, emphasizing the importance of reliable energy storage and efficient load management. From the studies, various results have been published as follows:

Hanumantha Hanumantha Reddy and Santosh Santosh Kumar[13]in their research “Solar Off-Grid Electric Vehicle Charging Station” Main objective was exploring the idea of independent solar-powered EV charging stations as a way to assist the utility”. Results was simulated using a Cayenne Software, and it show that the charging process of the electric vehicle battery is precisely steady for all the PV insolation disturbances. Furthermore, the energy storage battery's charging and discharging processes react flawlessly to store and offset changes in PV energy. [13].

Mohamed Ahmed Mohamed and al.[14]in their research “Design and Simulate an Off-Grid PV System with a Battery Bank for EV Charging”. The main objectives were design a model of a charging station for electric vehicles in remote areas using an off-grid system with a battery bank, design DC-DC converters to ensure optimal performance for the charging station, and evaluate the performance of lithium-ion and lead-acid batteries as energy storage systems for the charging station. The proposed system has been designed and simulated in the MATLAB-Simulink environment. The effective performance of the proposed station for EV battery charging is achieved through the simulation results[14]

Abdelfatah Ali and al. in their research[15]” Optimal Sizing and Placement of Multiple Photovoltaics Considering Electric Vehicles Charging Stations” research proposed an optimization planning model for optimally allocate PV to accommodate EV charging stations in distribution systems, which can determine the best PV locations and sizes to reduce the electrical energy losses in the distribution system, considering voltage and power flow boundaries[15].

Naresh Kumar Golla and al.[16]in their research “Optimal Placement of Electric Vehicle Charging Station in Distribution System Using Meta-Heuristic Techniques” It focuses on the significance of Electric Vehicles (EVs) in the road transportation system and the impact of their increasing adoption on the power grid, the primary objective is to select the optimum location for EVCS in the power grid. The analysis conducted in the paper involves utilizing the Loss Sensitivity Factor (LSF) and power flow by the Newton Raphson method for the IEEE 33 BUS system and A comparison is made between the results obtained from the proposed approach and conventional methods like Particle Swarm Optimization (PSO) and Harris Hawks Optimization (HHO) algorithms[16].

R. Ragul, and al.[17] in their research “PV Based Standalone DC -Micro Grid System for EV Charging Station with New GWO-ANFIS MPPTs under Partial Shading Conditions” The main objectives were to utilize MPPTs to extract maximum power from the best configuration or combination of renewable resources and energy storage systems in an off-grid setup for electric vehicle charging and implement and demonstrate the effectiveness of the proposed off-grid station for Electric Vehicles (EVs) battery charging through MATLAB-Simulink simulations and experiments[17].

Saeed Al-Muhammad, and al[18].in their research “Optimizing Electric Vehicle Charging Infrastructures: A Microscopic Review” The main objectives were explore the optimization of electric vehicle (EV) charging stations through a comprehensive literature review, Identify the critical factors influencing the location-allocation problem for EV public charging stations, including understanding demand, assessing needs, identifying possible locations, and selecting an optimization model for facility location. Methods for estimating EV charging demand using population distribution, demographic data, vehicle ownership data, and traffic volume data were explored to understand the challenges and approaches in predicting demand accurately. However, the results obtained from the optimization process highlighted the significance of factors such as

income level, education, access to home charging, government policies, population density, GDP per capita, urbanization, and daily driving distances in influencing EV adoption and charging infrastructure requirements[18].

I.Anose and al.[19] in their research “Design and Implementation of Renewable Based EV Charging Station” The main objectives were to propose a renewable energy solution for electric vehicle (EV) charging stations and to develop a photovoltaic (PV) system with a Neuro Fuzzy-based Maximum Power Point Tracking (MPPT) algorithm and a Switched Z source Boost converter[19].

Despite these advancements, gaps remain in the literature, particularly concerning the contextual factors unique to different regions. In the case of Rwanda, specific research on the optimal placement of standalone photovoltaic electrical charging stations is limited. Most existing studies are concentrated in developed country with different solar irradiance profiles, urban planning standards, and electric vehicle adoption rates[3], [6]. Additionally, there is a lack of detailed analysis on the socio-economic and environmental impacts of deploying such infrastructure in Rwanda. Addressing these gaps is essential to developing tailored solutions that maximize the benefits of PV technology in supporting sustainable transportation in Rwanda.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter includes techniques and methods that used for conducting this research. The research methodology designs to address the specific objectives of the study, it involves a multi-phase approach that includes documentation, data collection, data analysis and design method. Each phase was critical to ensure the feasibility, efficiency, and sustainability of the proposed solution.

3.1. Research design

This research design aims to develop a comprehensive framework for optimizing the location and configuration of EV charging infrastructure by considering multiple factors. It comprises by interlinked Activity (see **Figure 1**)

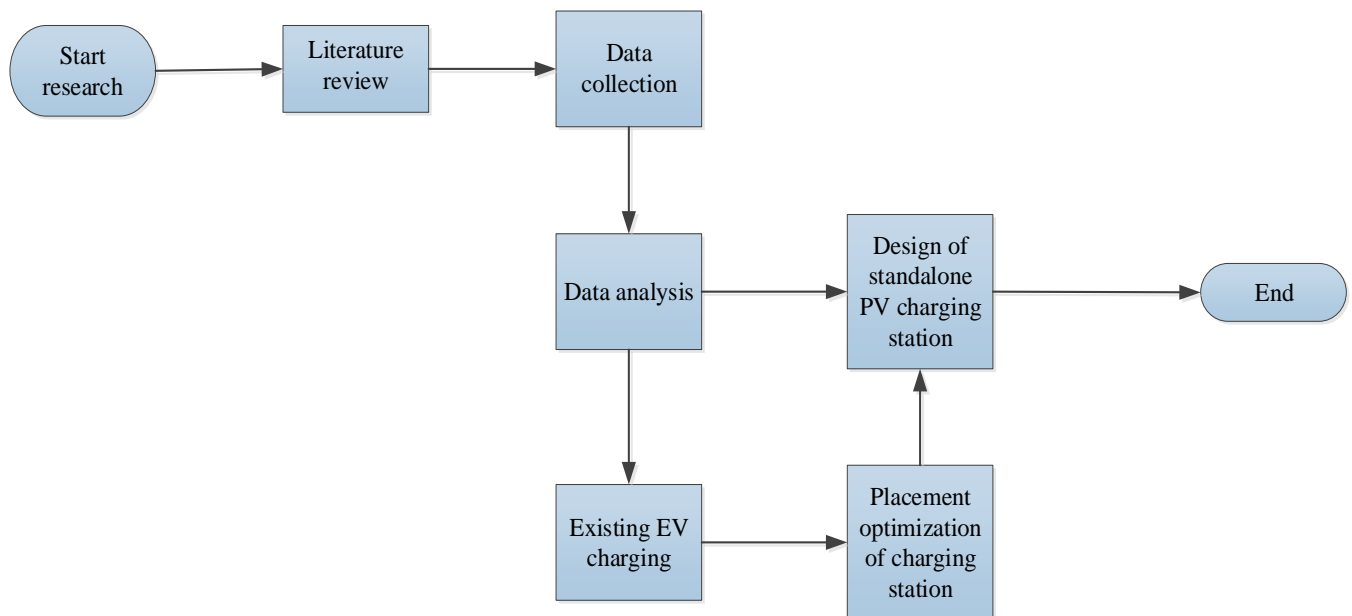


Figure 1:Flow chart for research design

3.2. Documentation

The research was beginning with an extensive review of existing literature, reports, and case studies on standalone photovoltaic (PV) systems and electric vehicle charging stations. This documentation phase provided a good understanding of latest technologies, deployment strategies, and optimization methods used globally. It was also involve gathering different on EV charging

station information in Rwanda to ensure that the design and placement of the PV charging stations are contextually relevant and effective.

3.3. Data collection

The preliminary stage of this research was data collection. This was included assessment of standalone PV charging station in Rwanda.

i. Primary data

Primary data are those data that researchers collect directly from the main sources and happen to be original in character. These data have a big impact on the outcome of the results therefore; care must be taken when collecting them. There are several methods of collecting primary data and in this research, field survey and open sources were used to assess and understand the existing swap charging station and charging needs in Kigali. The materials in this thesis are electrical motorbikes swap charging station in Kigali city.

ii. Secondary data

Using PVSyst and HOMER pro softwares, those techniques were utilized to determine the sun radiation of the chosen location by selecting location which is Kigali city and then downloading the data from that location including data of irradiation, temperature and clearness index. Reports, scholarly journals, and other scientific publications were reviewed in order to obtain more material pertinent to the study.

3.4. Study area: Kigali city

City of Kigali is located in near central of Rwanda at Latitude of 1°56.6'S and Longitude of 30°3.7'E and extends from the elevation between 1300 to 1800 m above the sea with 730 km²(**Figure 2**), and according to the fifth Rwanda Population and Housing Census (RPHC5) of 2022 conducted by NISR, Kigali had 1,745,555 population[20].

The city of Kigali is a rapidly growing urban hub with a rising population and expanding infrastructure, making it a focal point for sustainable development initiatives. Kigali's transportation system is heavily reliant on two-wheelers and buses, which presenting significant opportunities for electric vehicle adoption, especially in light of government policies promoting renewable energy and electric mobility.

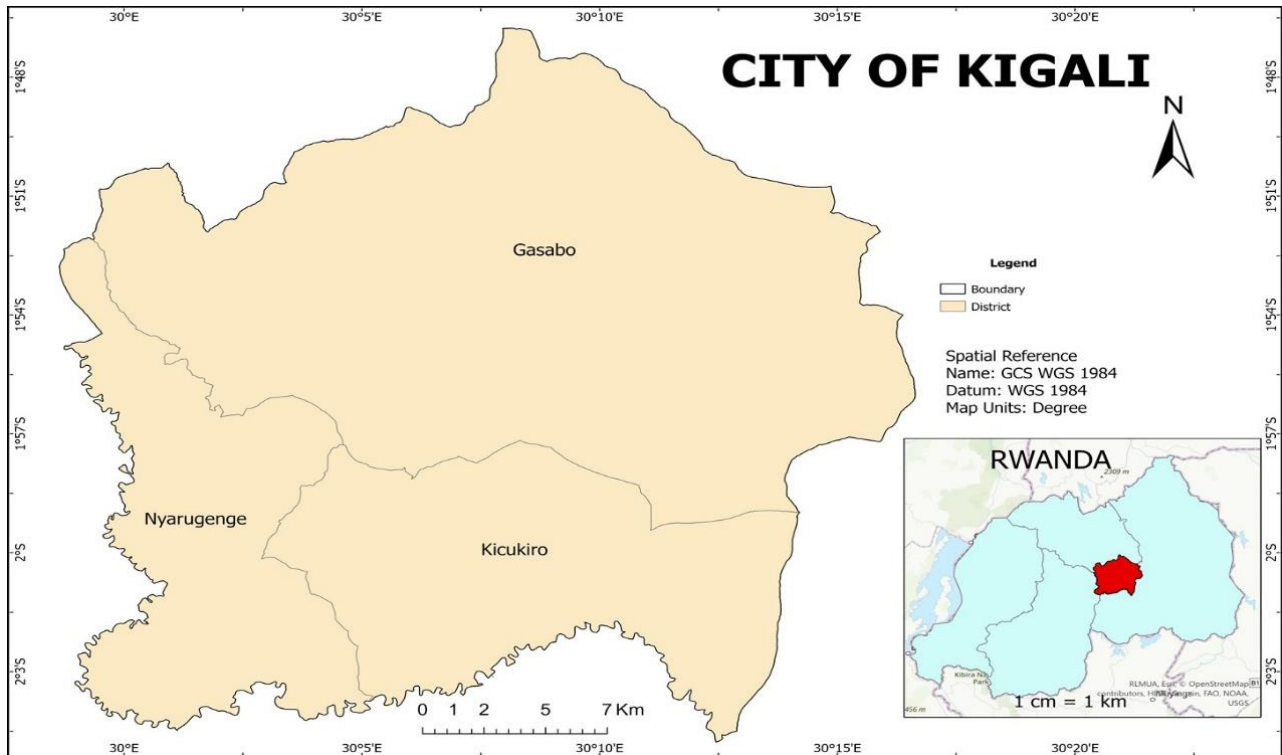


Figure 2:Kigali city map

3.5. Data analysis

Data analysis of EV charging stations involves gathering, processing, and interpreting data to optimize their placement and efficiency. One key method of data collection was using geographic information systems (GIS) tools (Google Earth and Google Maps). These platforms provide high-resolution imagery and location-based data that help identify existing infrastructure. And analysis of placement of EV charging stations involved modeling various parameters to optimize their placement, efficiency. Geographic Information System (GIS) tools (ArcGIS) played a crucial role in this process by enabling spatial analysis and decision tree analysis was used in optimal placement of charging station locations. ArcGIS, used to analyses the input and geospatial data, such as road networks, population density, energy demand, and solar potential for standalone PV-based stations. This tool allows for multi-criteria analysis, where different factors are weighted to identify optimal locations. By analyzing historical and real-time data from these sources, help to assess potential locations for new charging stations, ensuring accessibility and convenience for EV users.

3.6. Design

The design phase involved developing a detailed for the EV PV charging stations. This was include selecting appropriate PV panels, energy storage systems, and charging infrastructure to match the local conditions.

CHAPTER 4. CURRENT EV CHARGING STATION IN RWANDA

4.1. Overview of electric vehicle charging stations in Rwanda

Electric vehicles are gaining attention in Rwanda as the country seeks sustainable transportation options and aims to reduce carbon emissions. The government, in line with its Vision 2050 and National Strategy for Transformation (NST1), has prioritized green growth, which includes fostering the EV industry. Rwanda's EV development has focused on both electric motorcycles and cars, with incentives in place to encourage adoption[2][1].

Rwanda's government has introduced several incentives to promote EV adoption, including import tax exemptions for EVs and their components, VAT exemptions, and reduced electricity tariffs for EV charging stations. These policies aim to make EVs more affordable and encourage infrastructure development[1][21].

Charging infrastructure is still in the early stages but is growing steadily. Companies like Ampersand, Spiro, Rwanda Electric Mobility, Kabisa, EVP, BasiGO, Volkswagen's mobility solution, and others have been setting up charging stations around Kigali and other areas. The government has also expressed interest in renewable energy-powered charging stations to ensure a sustainable EV ecosystem[2][22].

Rwanda has attracted several private players in the EV sector. Ampersand, Spiro for examples, focuses on electric motorcycles, which are widely used as taxis across Rwanda. BasiGO introduced bus, Kigali's first 100% Electric Bus. Volkswagen introduced an electric car-sharing service, operating a fleet of e-Golfs in Kigali. Other players, like Vivo Energy, Kabisa in partnership with SP are investing in EV infrastructure[22].

With a large number of motorcycles used in public transportation, electrifying this sector has been a key focus. Ampersand and other companies have successfully deployed electric motorcycles and established battery-swapping stations, which have gained popularity among drivers for their cost-effectiveness and reduced maintenance compared to gasoline-powered motorcycles[21], [22].

Rwanda's push towards EVs aligns with its commitment to climate goals, including reducing air pollution in urban areas. Electric mobility is seen as a way to combat urban air pollution, particularly in Kigali, where traffic emissions are a concern[2].

While there is significant progress, challenges remain, including the high cost of EVs, limited charging infrastructure, and reliance on imported vehicles and components. However, with continued government support, expanding infrastructure, and a focus on renewable energy integration, Expected growth in Rwanda's EV industry will pave the path for future transportation that is more environmentally friendly. [21].

The Rwandan government has declared that, as part of a significant move toward sustainable mobility, it will forbid the registration of motorbikes with gasoline engines for use in public transportation in Kigali beginning in January 2025. The only motorcycles that can be registered for commercial usage are electric motorcycles.

4.2. Existing physical plan of electric vehicle charging stations in Rwanda

Despite the growing adoption of electric vehicles in Rwanda. Currently, there is no existing physical plan for EV charging infrastructure. The deployment of charging stations is still mainly disorganized, despite the fact that a number of stakeholders, including both public and private sector organizations, have started initiatives to encourage e-mobility. There is no officially designated framework outlining the optimal locations, capacity, or integration of charging facilities within the national transport network. As a result, charging infrastructure development has been occurring in an ad hoc manner, often driven by individual projects rather than a strategic national plan. This gap presents challenges in ensuring widespread accessibility, efficiency, and sustainability of EV charging stations, particularly as Rwanda aims to transition towards a cleaner and more energy-efficient transportation system.

Addressing this issue, the Rwanda's Ministry of Infrastructure (MININFRA) is developing a master plan for electric vehicle charging stations, with focus on increasing such infrastructure upcountry to ensure that no car travels more than 50 kilometers without coming across a charging station. The master plan includes identifying the necessary number of charging stations nationwide by focusing on high population density, traffic areas, energy availability, land use, and user demand, as well as leveraging existing petrol stations and commercial buildings.

A preliminary geospatial analysis identified over 226 potential sites for EV charging infrastructure across the country. As of August 2024, there were 24 public charging stations for vehicles (AC and DC-based charging facilities), 4 stations for direct chargers for motorcycles, and 49 stations for chargers coupled with swapping stations all over the country as per data from the ministry[23].

4.3. Assessment results of current operational electric vehicle charging stations in Rwanda

Refer to **figure 3**, Kigali currently has a limited number of swap charging stations, most of which are located in major urban areas with convenient access to the power grid and roads. To support a large number of electric vehicles aligned with the government’s target, more charging stations are needed in urban, and rural areas, including in areas without access to the electric grid.

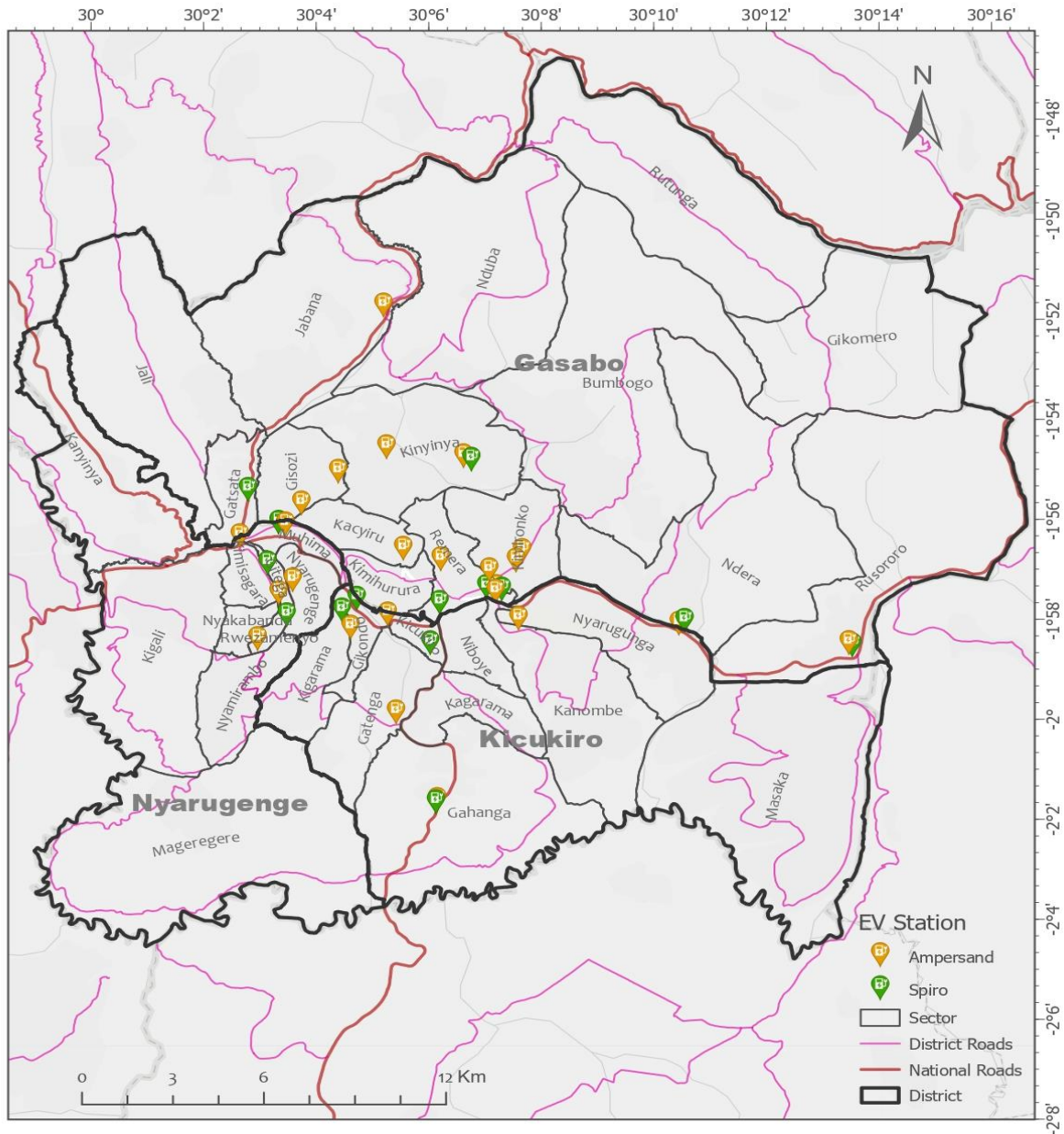


Figure 3: Existing swap charging station in Kigali

This map (**figure 3**) illustrates the assessment results of current operational electric vehicle swap charging stations in Kigali. It provides a comprehensive overview of the distribution and density of these facilities across various districts. The data and analysis indicate that the stations are primarily concentrated in central; These areas have higher EV penetration due to population density, roads accessibility, increased economic activity, and easy access to infrastructure, making them strategic locations for EV charging infrastructure.

This research conducted on swap e-motorcycle charging station where it focused on Ampersand, Spiro and REM swap charging station.

Ampersand appears to have a wider coverage, with more stations dispersed across various districts, while Spiro stations are more concentrated in central areas, possibly indicating a phased expansion strategy, and REM using centralized charging station then distribute the batteries. Additionally, the distribution of stations along major district and national roads reflects a deliberate effort to ensure accessibility and convenience for EV users. This positioning aligns with the transport corridors used by electric motorcycle taxis, one of the primary user groups for swap stations.

Despite the evident progress, gaps in coverage remain, particularly suburban and rural areas show fewer or no EV stations, indicating lower EV adoption in these regions, where fewer stations are available. This map show that EV infrastructure development is still in its early stages, with a focus on urban centers where the immediate need and potential for EV usage are higher. The presence of national and district roads in these areas further supports the rationale for placing charging stations along major transportation routes, facilitating long-distance travel and reducing range anxiety for EV users. Integrating standalone photovoltaic (PV) swap stations in that area could further improve their sustainability and reliability, especially in areas with limited grid infrastructure.

4. 4 Conclusion

The current infrastructure layout appears to prioritize commercial viability and high-traffic locations, which is logical for initial implementation. However, as EV adoption grows, a more comprehensive coverage strategy is necessary to support sustainable transportation goals across the entire city. This might include establishing minimum distance standards between stations and ensuring all areas both urban and rural area have reasonable access to charging facilities.

Build new more charging stations which are powered by distributed solar photovoltaic technology might be an encouraging solution. The solar technology means the charging stations won't need to rely on a national electric grid. They can also installed in isolated areas with limited or challenging access to energy.

CHAPTER 5. PLACEMENT OPTIMIZATION OF THE CHARGING STATION IN KIGALI

As discussed in the previous chapter, the strategic placement of electric vehicle charging stations in Kigali, Rwanda's capital city, represents a critical infrastructure challenge as the city embraces sustainable transportation. With Rwanda's commitment to reducing carbon emissions and promoting electric mobility, optimizing the locations of charging stations across Kigali's diverse urban landscape requires careful consideration of multiple factors. These include population density, traffic patterns, land availability, and accessibility from major roads and commercial centers. The optimization process must balance the needs of both personal and commercial electric vehicles while accounting for Kigali's unique topography, characterized by its hilly terrain and distinct business, residential, and industrial zones. This chapter explored optimal placement strategies for standalone photovoltaic EV charging stations, with a particular focus on swap battery charging stations, to enhance sustainability and accessibility in Kigali's evolving transportation ecosystem.

5.1.Suitable location of standalone PV electrical vehicle charging station

5.1.1. Analysis of suitability

Suitability Analysis is a spatial analysis technique used to identify the most appropriate locations for specific purposes, based on a set of criteria. This method involves overlaying multiple layers of geographic data, such as land elevation, soil type, vegetation, climate, and infrastructure, to pinpoint locations that meet the requirements of the intended project or activity. The analysis typically utilizes weighting and scoring systems to assess the suitability of each factor, leading to a comprehensive suitability map. This map can highlight areas most conducive to an objective, such as determining the best site for a new school, farming operation, or conservation effort. Suitability Analysis is crucial for optimizing land use, maximizing resource efficiency, and minimizing environmental impact.

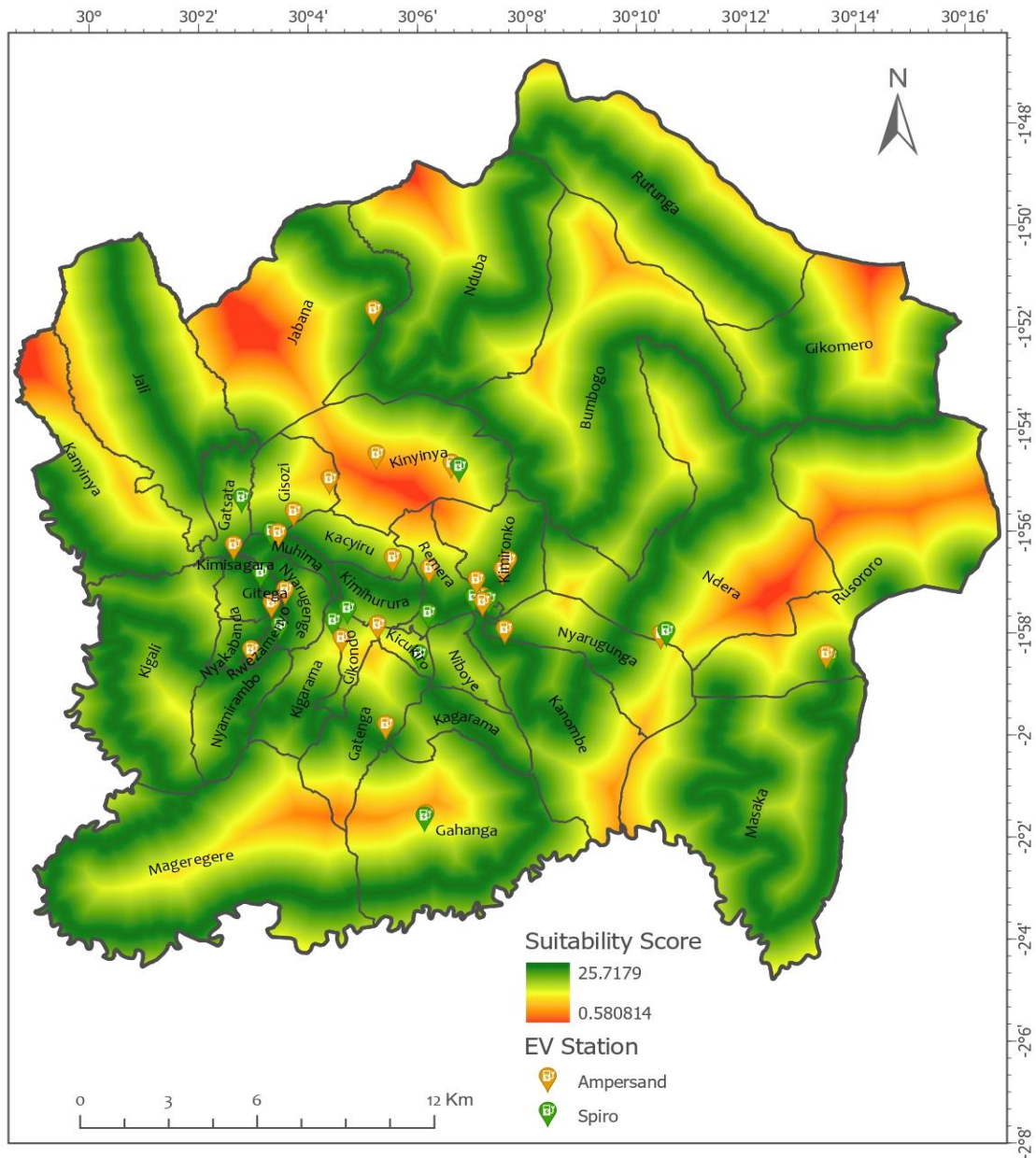


Figure 4: Suitability location of EV charging station in Kigali

The map (Figure 4) presents a comprehensive suitability analysis for electric vehicle charging stations across Kigali, showcasing both existing infrastructures operated by Ampersand and Spiro, as well as potential locations for future stations. This analysis employs a sophisticated multi-criteria evaluation approach that considers different critical factors shaping the optimal placement of charging infrastructure.

- 1. Road accessibility:** Road accessibility serves as a fundamental criterion, ensuring that potential charging stations are strategically positioned near major transportation arteries and intersections, maximizing convenience for EV users.
- 2. Land Use and land cover:** The analysis also carefully considers land use and land cover patterns throughout Kigali, examining various zones including commercial, residential, wetland, sloping land, and industrial areas to identify locations that not only comply with local regulations but also align with existing urban development patterns.
- 3. Traffic Density:** Traffic density patterns play a crucial role in the evaluation process, as areas with higher motorcycles movement typically indicate greater potential demand for charging services. This data helps ensure that new stations are positioned where they can serve the maximum number of users efficiently.

A comprehensive analysis of these factors is performed and a scoring system is developed to evaluate the contributing impact of each factor on the charging station. The analytical process began with extensive data collection, gathering detailed spatial information about roads networks, land use and land cover patterns, and traffic flow throughout Kigali. This data was then processed through a weighted overlay analysis, where each factor was assigned a relative importance score (**Table 2**) [24]. To prevent any of the input factors from dominating the scoring system, a uniform weighted system is developed to distribute weight to each input demand factor. This systematic scoring method provided the necessary input parameters that were utilized during the analysis to determine suitable and unsuitable areas for EV charging stations. The analysis was conducted using Geographic Information System (GIS) technology, which allows for the layering and analysis of spatial data. By inputting data layers for road networks, land use and land cover classifications, and traffic patterns, the GIS software generate a suitability map (**figure 4**) that highlights suitable locations for charging stations in Kigali.

Table 2: Layer weighting [24]

Layer	Weight
Roads	35%
Land use and land cover	25%
Trading centers	15%
Traffic density	25%

As seen in the map, the suitability study identifies regions with differing degrees of viability for the location of EV stations:

- **High Suitability Areas:** These are locations that are perfect for EV stations because they combine infrastructural support, demand, and accessibility.
- **Low Suitability Areas:** These areas are constrained by factors like less commercial activity, a lower population density, or poor road connectivity.

The suitability score mentioned 0.580814 to 25.7179 represents a quantitative assessment of how well each location meets the criteria based on the factors above. Higher scores indicate locations that are more suitable for placing EV charging stations.

The final result, as seen on the map, offers a clear roadmap for future infrastructure expansion, guaranteeing that new charging stations are placed to enhance the current network while optimizing their usefulness and accessibility. Kigali's continuous shift to electric mobility is supported by this scientific approach to charging infrastructure design, which makes sure that the city's charging network expands strategically and effectively.

5.2. Range of the battery in terms of distance

The range of an electric motorcycle in terms of distance can vary significantly depending on several factors.

Factors Affecting Range:

1. **Terrain:** Rwanda is Land of a Thousand Hills, and the hilly terrain can reduce the range as the motor works harder to climb hills.
2. **Road Conditions:** Poor road conditions can also reduce efficiency, as more energy is used to navigate rough or uneven surfaces.
3. **Riding Style:** Aggressive acceleration and braking can reduce the range, while smooth, consistent riding can help maximize it.
4. **Battery Age and Health:** Over time, the capacity of the battery can degrade, reducing the overall range.
5. **Weight:** Carrying heavy loads or multiple passengers will also reduce the range.

In Rwanda, where the terrain can be hilly and roads may vary in quality, these factors can have a notable impact on the range.

On average, electric motorcycles can travel between 50 to 100 kilometers per charge. For example, Ampersand motorcycles typically offer a range of 60 to 90 kilometers per battery, while Spiro motorcycles can cover 70 to 90 kilometers before requiring a battery swap or recharge[25], [26].

5.3. Optimal placement of new standalone photovoltaic electric vehicle charging station in Kigali

From the assessment of the existing swap charging station(Figure 3),the stations are concentrated in central urban areas where it easy to access the infrastructure;in suburban and rural areas show fewer or no EV swap stations. In this research, the optimal placement of new standalone photovoltaic electric vehicle charging stations was focus on suburban and rural areas of Kigali. This strategic placement was address the current gap in charging infrastructure and expand EV accessibility beyond the urban center, creating a more balanced charging network throughout the region.

Based on the comprehensive suitability analysis detailed in the previous sub-chapter, this section explores the optimal placement of a new standalone photovoltaic electric vehicle charging station in suburban Kigali. Using a decision tree analysis (**Figure 5**), the study integrates critical factors

which are battery range, distance to travel, and road conditions to systematically evaluate potential sites. This approach not only refines the spatial evaluation process but also reinforces the earlier findings, ensuring that the selected location maximizes both operational efficiency and accessibility.

5.3.1. Algorithm for placement of new standalone photovoltaic Swap charging Station in Kigali

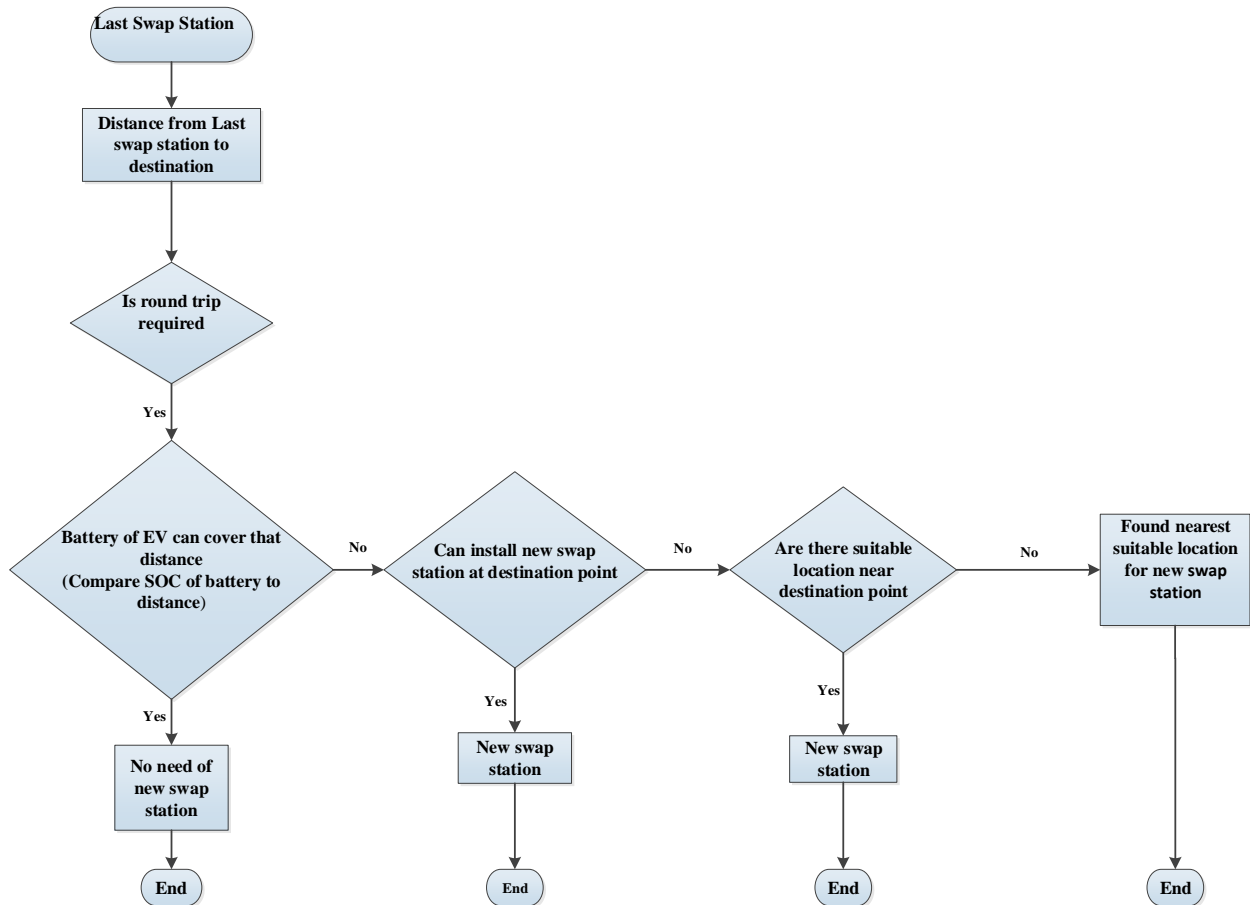


Figure 5: Algorithm for optimization of battery swap station

The algorithm (**figure 5**) is designed to determine the optimal placement of a battery swap station for Electric motorbike in Kigali, it designed by considering the following condition: the battery capacity, distance and suitable location.

Here are key data points needed to run the decision-making algorithm for optimal placement of battery swap stations in Kigali:

Battery Specifications:

- **Capacity (kWh):** Total energy storage of the battery when its full charged
- **Range (km per charge):** How far the EV can travel on a single full charge.

Distance,location and route Information

- **Distances Between Stations and destination:** The distance from the last known swap station to the next station or destination.
- **Potential suitable location:** Locations or stops along the way where installing a station is suitable (commercial center, road intersection,land availability).

Algorithm Logic

This algorithm determines whether a new battery swap station is needed for an electric vehicle traveling from its last swap station to the next destination. First, it checks if the current SoC of battery can complete its trip (or round trip). If it can, no new station is required. Otherwise, it looks for the possibility of placing a new swap station at the destination or, if that's not feasible, at a suitable location nearby. If such a location is found, a station is installed.

Optimal placement flow chart analysis

1. **Start from the last swap station:** The process begins at the most recent battery swap or charging station.
2. **Measure distance from the last station to the destination:**This is the one-way distance you must travel before possibly needing to charge again.
3. **Check if a round trip is required:**
 - If the vehicle only needs to travel one way (last station to destination), the decision process is simpler.
 - If the vehicle must return to the original point (last station), you must account for the total distance (destination to back to the start).

4. Compare battery State of Charge (SOC) to the required distance

- The battery's range is compared to the total distance that needs to be covered (one-way or round trip).
- If the battery can cover the distance without needing another station, no new station is required.
- If the battery cannot cover the distance, then you must consider installing a new swap station.

5. Check if a new station can be installed at or near the destination

- If yes, you install a new station there (If the destination meet the suitability condition for new station).
- If not, you check for any other suitable locations nearby. You would place the station at the nearest feasible location that ensures the vehicle can travel from the last station to the new station, and from the new station to the destination and back if needed.

5.3.2. Mathematical Model for placement of new standalone photovoltaic Swap charging Charging Station in Kigali

Based on the decision tree analysis(**figure 5**) detailed in the previous part, this section explores the optimal placement of a new standalone photovoltaic electric vehicle charging station in suburban Kigali, using a mathematical model, which integrates critical factors :battery range and distance to travel, to systematically evaluate potential sites.

The model defines the battery range as the distance an EV can travel on a full charge.

$$R = \frac{E_{max} * 1000}{C} \text{ (km) ;} \quad \text{Eq.(1)}$$

Where: E_{max} : Maximum battery capacity (kWh), C : Vehicle's energy consumption rate (Wh/km).

From these, we get the maximum driving distance for a full battery,

In this mathematical model, we consider the latest swap station as node, indexed by i and trajectory to destination point call it set of node, indexed by j .

i.Distance formulation

The distance between a node i and a candidate location j . This helps in assessing whether a station is within reach given an EV's battery range. d_{ij} : Distance (km) from latest swap charging station i to destination point j .

ii.Coverage Requirement

Form the decision tree, a demand point is considered as covered if there is at least one station within the battery range it mean if $d_{ij} \leq \text{Battery Range}$. This ensures that EV users can reach a station before depleting their battery.

iii.Decision Variables and Constraints

- The Station Placement :

$$X_j \in \{0,1\}, \quad \forall j \in J; \quad \text{Eq.(2)}$$

Form the eq 1, $X_j=1$ if a new charging station installed at destination point j ; 0 otherwise

- Node Coverage (ensure each node is covered)

$$Y_i \in \{0,1\}, \quad \forall i \in I; \quad \text{Eq.(3)}$$

Form the Eq.1, $Y_{ij}= 1$ if route $i \rightarrow j$ is covered (stations $\leq R$ km apart), 0 otherwise

To ensure that the node i is covered only if at least one station j within the battery range is built, we can write:

$$Y_i \leq \sum_{j: d_{ij} \leq R} X_j, \quad \forall i \in I; \quad \text{Eq.(4)}$$

If $d_{ij} > R$, station j cannot serve demand i because it is beyond the EV's maximum range, so j is omitted from that sum.

As discussed above, this research was focus on the optimal placement of new standalone photovoltaic electric vehicle charging stations suburban and rural areas of Kigali. The **table 3** shown the distance from latest charging station to the suburban and rural area in Kigali using different route, energy required and decision to schedule the trip.

Table 3: From latest swap station to destination

SN	From latest swap station to destination	Distance(Km)	Return (Km)	Required energy for the trip(kW)	Decision to schedule the trip
1	Nyabugogo to Kanyinya	11	22	2	Yes
2	Kabuga to Rwamagana border	13	26	2.36	Yes
3	Kabuga to Gikomero	24	48	4.36	Yes
4	Kabuga to bugesera border via Masaka	14.2	28.4	2.58	Yes
5	Kinyinya to Rutunga	35	70	6.36	No
6	Kimironko to Rutunga	28	56	5.09	No
7	Murindi to Gikomero	17	34	3.09	Yes
8	Nyacyonga to Gicumbi border	6.1	12.2	1.1	Yes
	Nyamirambo to Mageragere	21	42	3.8	Yes
9	Nyamirambo to Kigali sector	13.1	26.2	2.38	Yes
10	Gatsata to Jali	10.3	20.6	1.87	Yes

Trips 5 and 6 exceed the battery capacity which is 5.4 kWh and require a mid-trip swap station. All other trips are within the 5.4 kWh limit and can be scheduled.

Based on the process described in optimal placement flow chart analysis and mathematical model, this research further analyzed those potential locations based on suitability analysis (**Figure 5**),

battery capacity and distance (**Table 3**) to find out how efficiently and effectively they would satisfy the EV charging demand in Kigali, in **Figure 6** show optimal placement of new standalone photovoltaic electric vehicle charging station.

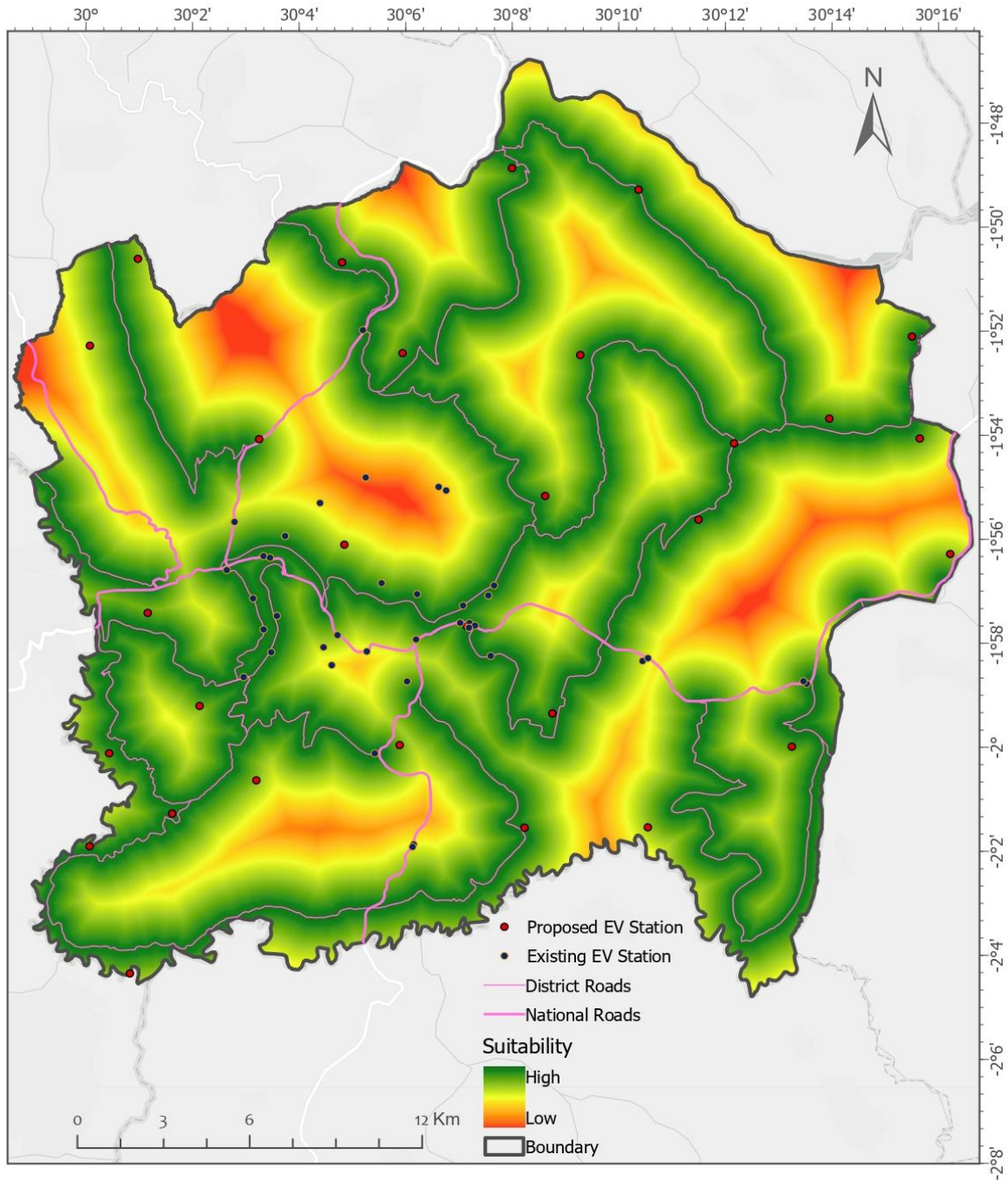


Figure 6: Optimal placement of EV charging station in Kigali

In summary, this chapter was identified new standalone EV charging station locations **figure 6**. The suggested sites are spread across the study area, predominantly in semi-urban regions where the conditions are favorable, partly due to the concentration of charging infrastructure in the city center. To determine the best locations for new, standalone EV charging stations, a practical approach is employed that combines GIS-based spatial overlap analysis with decision tree analysis.

CHAPTER 6: A DESIGN OF A STANDALONE PV CHARGING STATION FOR THE SEMI-URBAN AREAS IN KIGALI CITY

The previous chapters reveals that more charging stations are required to increase the penetration level of EVs in Kigali. Since there is potential for solar energy in Rwanda, it is possible to install some stand-alone solar charging stations in Rwanda. This chapter aims at designing a stand alone solar charging station.

6.1. Potential of solar energy in Rwanda

Rwanda is located near to the equator, it receives abundant sunshine with an average daily solar irradiation of about 5.2 kWh/m² on tilted surfaces. Monthly averages vary from 4.8 to 5.8 kWh/m² per day, highlighting its significant potential for solar energy[27].

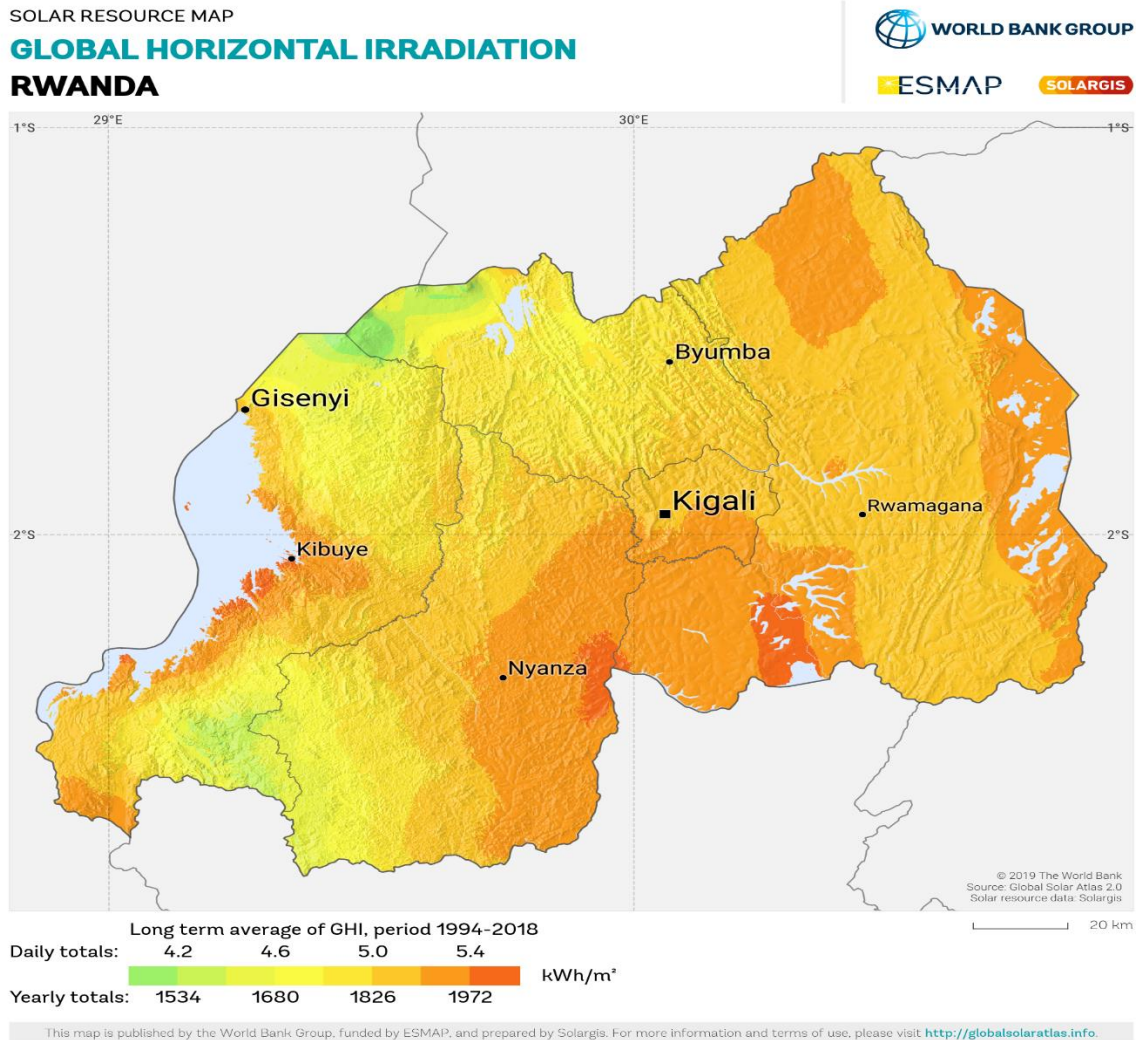


Figure 7:Rwanda Global horizontal irradiance

Due to Rwanda's great solar radiation potential, there is significant solar energy development, and two technologies solar PV and the solar water heater are currently taking place. The solar photovoltaic is more used to generate electricity either as on grid-connected or off-grid to supply communities in remote areas where government buildings, schools, and health institutions are more beneficial[28].

When carrying out the design of solar PV system, it is very important to determine insolation (solar radiations) of the specific location in which the system will be installed. Monthly average solar radiation and clearness index are obtained from NASA meteorology at Latitude of 1°56.6'S and Longitude of 30°3.7'E where solar radiations monthly values vary from 4.54 in November to 5.22 in February with an average of 4.88 kw/m² /day. Because of these variations in solar radiation, the energy generated from solar will vary also from January to December. Monthly Average Solar Global Horizontal Irradiance (GHI) data from Homer Pro are plotted in following figures 8&9 and **table 4**, including the daily radiation in kWh/m² /day, clearness index and temperature for every month.

Table 4:Solar radiation and temperature

Month	Clearness index	Daily radiation(kWh/m2/day)	Temperature (° C)
January	0.480	4.93	19.85
February	0.496	5.22	20.68
March	0.473	4.97	20.18
April	0.479	4.83	19.72
May	0.498	4.71	20.62
June	0.532	4.83	21.13
July	0.556	5.14	21.26
August	0.519	5.09	22.04
September	0.491	5.07	21.68
October	0.448	4.68	19.96
November	0.442	4.54	19.20
December	0.451	4.57	19.26
Annual average	0.488	4.88	20.47

According to Homer Pro data, the clearness index is 0.488 and the average annual sun radiation is 4.88 kWh/m2/day.

The above monthly averages of the daily radiation in Rwanda are presented in **figures 8 and 9**. The clearness is the percentage of solar energy that passes through the atmosphere and onto the earth's surface.

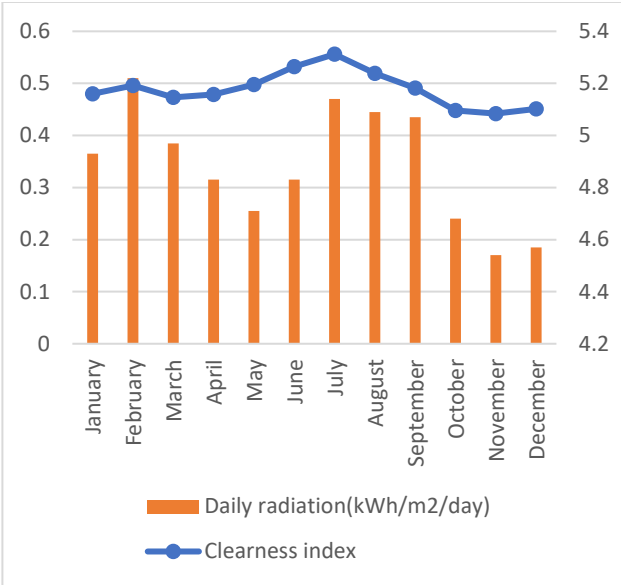


Figure 8: Monthly radiation and clearness index

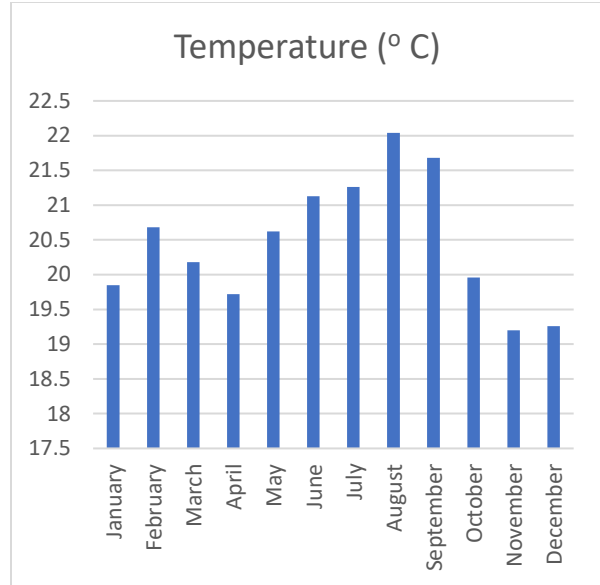


Figure 9: Monthly temperature

6.2 Design of a standalone PV charging station

The previous chapter identified several strategic locations in semi-urban areas of Kigali that are ideally suited for electric motorbike swapping stations. Building upon these findings, this section explores the design of standalone photovoltaic charging stations. By implementing solar-powered charging infrastructure in these strategically located semi-urban areas, This research address two critical challenges simultaneously: providing accessible charging options in areas with potentially weaker grid connections and promoting sustainable energy practices. This approach not only supports the optimal placement strategy developed previously but also creates a robust foundation for increasing EV bike penetration throughout Kigali by reducing range anxiety and demonstrating Rwanda's commitment to clean transportation solutions.

6.2.1. Configuration and Working Principle of the proposed System

The electric vehicle charging station system is an off-grid type that is powered by renewable energy and chooses solar energy that will be the main source. It is captured by a PV array that generates electrical energy for the electric vehicle charging station by falling radiation from the sun. However, the generated energy is unstable. Due to varying of output power from energy intermittence solar cells and environmental changes we install Energy Storage System by using batteries to store power in peak production from PV and later when needed. The output terminals

of the PV are connected to a boost converter to step up the voltage to the DC bus limit and help in utilizing the charge controller (MPPT) condition of the PV panel. The EV battery is connected directly to DC bus. In addition, the other converter namely bidirectional converters used in two ways, the first way using the converter as a buck converter to step down the voltage to charge the ESS battery (Lead-acid), and the second way using the converter as a boost converter to step up the DC voltage to energized the bus in regulating the DC bus voltage against the variations of the EV load and insolation level. **Figure 10** show the configuration of the system

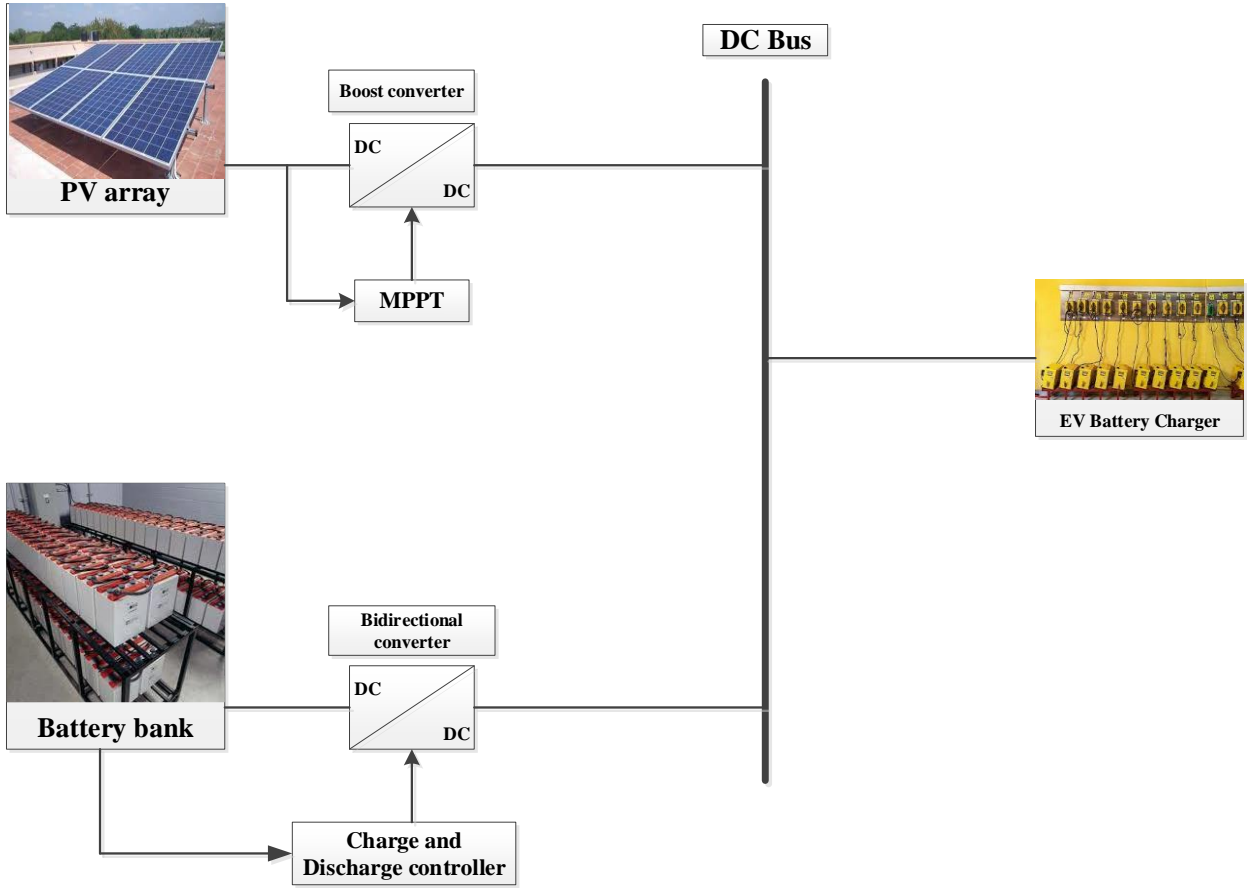


Figure 10:Layout of PV EV charging station

i. Operating of the standalone PV EV charging station

The performance analysis of this PV EV charging station was carried out by establishing three distinct operating cases, where:

In first case, once an EV is connected to the system, the charge level of the EV battery is first measured, and if the charge state is less than 100%, the charging operation for the EV battery begins. In this study, the charge rate of the EV battery was determined as 20% [29] and the system started to charge the EV battery.

In second case, backup batteries (battery storage system) are charged with the energy produced by the PV system. That is, if there is no EV waiting to be charged in the system or the EV battery is fully charged, the system controller charges the battery in the battery storage system.

In third case, once the PV system is unable to energy generation due to weather conditions or in the night, the EV battery is charged by the storage system's system controller via a bidirectional converter. The storage system battery began to discharge and the EV battery began to charge once the simulation was run. The storage system in discharged state and the EV battery in charging state.

ii. Mathematical Model for EV Charging Station Performance Analysis

The Mathematical Model for EV Charging Station Performance Analysis lays the foundation for a quantitative assessment of station performance. It introduces essential parameters and variables such as: P_{PV} : Power generated by PV system (W); P_{EV} : Power required by EV for charging (W); P_{BSS} : Power for charging or discharging the Battery Storage System (BSS) (W); E_{EV} : Energy stored in the EV battery (Wh); $E_{EV, max}$: Maximum energy capacity of the EV battery (Wh); SOC_{EV} : State of Charge (SOC) of the EV battery (%); SOC_{BSS} : SOC of the BSS (%); E_{BSS} : Energy stored in the BSS (Wh), $E_{BSS, max}$: Maximum energy capacity of the BSS (Wh); η_{ch} : Charging efficiency; η_{dc} : Discharging efficiency; t : Time (h)

Operating mode

1. EV is connected when $SOC_{EV} < 100\%$
2. PV system supplies power first to the EV, then to the BSS.

3. BSS discharges to supply the EV when PV generation is unavailable

First case : Direct EV Charging

When an EV is connected, and $SOC_{EV} < 100\%$ the charging power is:

$$P_{EV} = \min(P_{PV}, P_{EV, \max}); \quad \text{Eq.(5)}$$

Where:

$$P_{EV, \max} = \frac{0.2 * E_{EV, \max}}{t_{\text{charge}}} \text{ (20\% charge rate over the charging time) }; \quad \text{Eq.(6)}$$

The SOC of the EV battery updates as:

$$SOC_{EV}(t) = SOC_{EV}(t_0) + \frac{P_{EV} * \eta_{ch} * t}{E_{EV, \max}}; \quad \text{Eq.(7)}$$

Second case 2: PV Energy to Battery Storage

If no EV is waiting or $SOC_{EV} = 100\%$

$P_{BSS} = P_{PV}$ and SOC of the BSS updates as:

$$SOC_{BSS}(t) = SOC_{BSS}(t_0) + \frac{P_{BSS} * \eta_{ch} * t}{E_{BSS, \max}}; \quad \text{Eq.(8)}$$

Third case 3: Discharging BSS to Charge EV

If $P_{PV} = 0$ (e.g., at night or during adverse weather):

$P_{BSS} = P_{EV}$, SOC of the EV and BSS are updated as:

$$SOC_{BSS}(t) = SOC_{BSS}(t_0) - \frac{P_{EV} * t}{\eta_{dc} * E_{BSS, \max}}; \quad \text{Eq.(9)}$$

$$SOC_{EV}(t) = SOC_{EV}(t_0) + \frac{P_{BSS} * \eta_{dc} * t}{E_{EV, \max}}; \quad \text{Eq.(10)}$$

Conditions to Switch Between Cases:

Case 1: $SOC_{EV} < 100\%$ and $P_{PV} > 0$

Case 2: $SOC_{EV} = 100\%$ or no EV is connected

Case 3: $P_{PV} = 0$ and $SOC_{BSS} > 0$

6.2.2. Energy Demand

Understanding this energy demand is essential for designing efficient standalone photovoltaic charging stations, ensuring a reliable power supply while promoting clean transportation in the city. Electric motorcycles are becoming a key solution for sustainable urban mobility in Kigali. With a 5.4 kWh battery and an average range of 60 km per charge[25], [30], the energy demand per kilometer is approximately 0.09 kWh/km. Given that motorcycle taxi riders (moto-taxis) in Kigali travel an estimated 150–200 km per day, so average range is 175km per day, their daily energy consumption ranges from 13.5 to 18 kWh, requiring 3 to 4 battery swaps per day. The charging station will charge 5 batteries at the same. The daily energy demand will be $0.09\text{kWh/km} \times 175\text{km} \times 5 = 78.75\text{kWh/day}$.

i. Sizing of PV array

The peak power of the PV (P_{pv}) can be calculated from the following equation:

$$P_{pv} = \frac{E}{SPH \cdot \eta_s}; \quad \text{Eq.(11)}$$

Where: P_{pv} : peak power of PV; E: daily energy consumption; η : system efficiency; SHP: sun peak hour

With Sun peak hour =5hours and System efficiency =80%

$$P_{pv} = \frac{78.75}{5 \cdot 0.8} = 19.6875\text{kW}$$

$$\text{Number of PV panel} = \frac{P_{pv}}{\text{power rating of PV}}; \quad \text{Eq.(12)}$$

$$\text{No PV panel} = \frac{19687.5}{380} = 51.8 \sim 52 \text{ panels}$$

The total PV panels will be needed to supply this standalone charging station are 52 panels

$$\text{The number of modules per string (NS) in series, } NS = \frac{\text{System voltage}}{\text{module voltage}}; \quad \text{Eq.(13)}$$

$$NS = \frac{48}{48.05} = 0.999 \sim 1;$$

ii. Sizing of battery storage

The storage capacity of the battery block for such systems is considerably large. The ampere-hour capacity (Ah) and watt-hour capacity (Wh) of the battery block are important in the battery sizing. The number of days of autonomy (days without the sun) required for critical need which depends on the location of the system. In locations with relatively high average radiation, even during the worst part of the year, less storage is needed. Because of the target area almost has clear days (seasonal climate) during the year, we considered that the days necessary to cover the load demands for a period of one day without sun (one day of autonomy), the battery sizing is obtained as follows:

$$\text{Battery bank capacity} = \frac{E * DOA}{DOD * \eta * V_s} ; \quad \text{Eq.(14)}$$

Where: E: Daily energy consumption; DOA: Day of autonomy; DOD: Depth of discharge; η : battery efficiency; V_s : System voltage

With Day of autonomy=3 days, Depth do discharge =50%, Battery efficiency =85%, System voltage =48V

$$\text{Battery bank capacity} = \frac{78750 * 3}{0.5 * 0.85 * 48} = 11580.88 \text{Ah}$$

$$\text{Number of batteries string} = \frac{\text{battery bank capacity}}{\text{Battery rating}} ; \quad \text{Eq.(15)}$$

$$\text{No of batteries string} = \frac{11580.88 \text{Ah}}{200} = 57.9 \sim 58 \text{ batteries}$$

$$\text{Number of batteries series} = \frac{\text{System voltage}}{\text{Battery voltage}} ; \quad \text{Eq.(16)}$$

$$\text{No of batteries series} = \frac{48}{12} = 4 \text{ batteries}$$

Total number of batteries = $58 \times 4 = 232$ batteries

iii. Sizing of charger controller

The charge controller should be 125% (or 25% greater) than the solar panel short circuit current.

$$I_{CC} = I_{sc} \times \text{Number of PV strings} \times 1.25; \quad \text{Eq.(17)}$$

Where: I_{cc} : Charger controller current, I_{sc} : PV short circuit current

$$I_{CC} = 10.09 \times 1 \times 1.25 = 12.61 \text{ A}$$

6.3. Simulation and result

The PVsyst and Homer Pro softwares used in this study to simulate and analyze of optimization system.

6.3.1. Orientation

Rwanda is located near the equator and based on the landscape and weather of Kigali, the photovoltaic panels will be tilted at an angle of 15° to south at fixed position[31]. This orientation angle corresponds to earlier studies; maximum power is generated at the array output at this angle because it is where the optimal absorption of irradiance peaks. [31].

6.3.2. Horizon

The horizon line drawing of Kigali (**Figure 11**); it is a graph of sun's height compare to azimuth angle. The azimuth angle and the sun's height at particular times of the day are correlated[31].

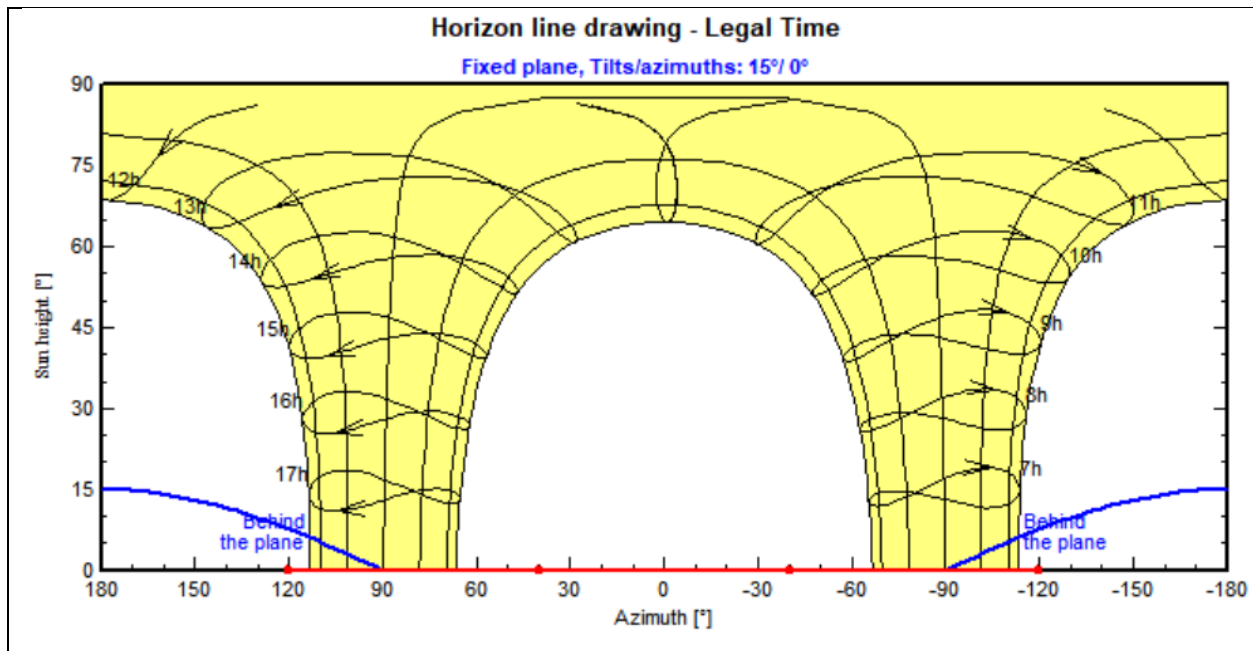


Figure 11:Horizon line drawing for Kigali [31]

6.3.3.Detailed losses

The PVsyst show the results of years of modeling and experimental study that produced standard figures for specific losses in solar power plants. These standard values can be changed according to the designers specifications. The following are some of the factors that influence losses in PV systems: thermal loss factor, ohmic losses, module quality and mismatch, soiling loss, IAM Losses, Ageing etc[31].

6.3.4.Normalized production (per installed kWp)

Figure 12 show normalized productions per each installed kilowatt power and it shows also other factors which are systems losses, collection losses, useful energy produced. Those are very useful indicators; which determines the performance of the system in terms of energy production. Photovoltaic systems rely on sunlight to generate electricity, and the heat energy from the sun has a negative impact on PV system performance [31][28].

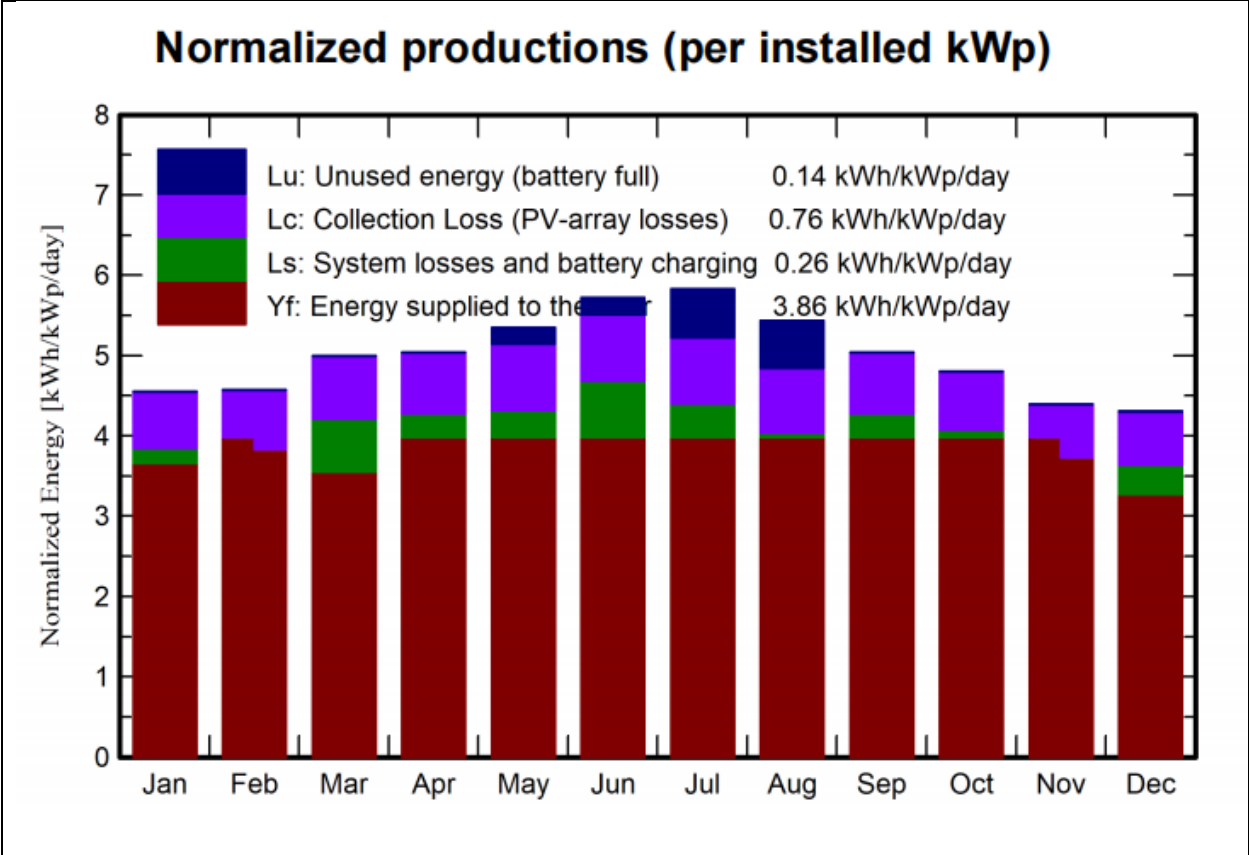


Figure 12: Normalized production

6.3.5. Performance ratio

Figure 13 show the performance ratio, which is the ratio of effective energy produced at the array output with respect to energy produce by an ideal PV system under the same conditions. Usually standard test conditions (STC) are used with the same amount of irradiance incident on global plane. The performance ratio of PV systems comprises of system and array losses. Array losses are wiring, mismatch, module quality, shading effects, photovoltaic conversion rate, IAM. From, the overall performance ratio of our system is 77.1%; there wasn't much difference in the monthly performance even though the system and collection losses for June and July were considerable high[31].

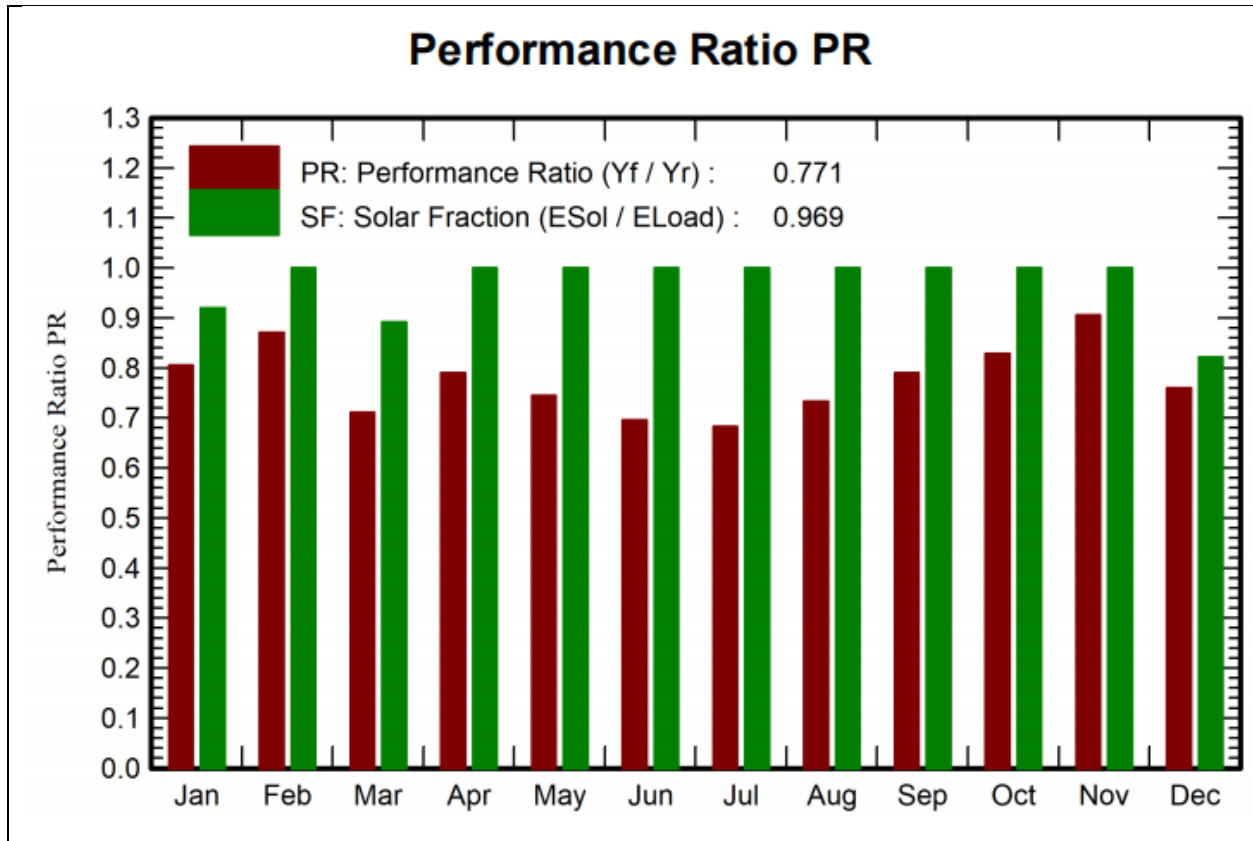


Figure 13: Performance ratio

6.3.6. Simulation result

System summary			
Stand alone system		Stand alone system with batteries	
PV Field Orientation		User's needs	
Fixed plane		Fixed constant load	
Tilt/Azimuth	15 / 0 °	3280 W	
		Global	
		28.73 MWh/Year	
System information		Battery pack	
PV Array		Technology	
Nb. of modules	52 units	Lead-acid, sealed, Gel	
Pnom total	19.76 kWp	Nb. of units	232 units
		Voltage	48 V
		Capacity	11600 Ah

Figure 14: Simulation result

6.3.7. Levelized cost of energy (LCOE)

Levelized cost of energy is the ratio of the total cost of electricity to the total amount of electricity produced annually. It represents the cost of generating one unit of electricity. The Levelized cost

of energy is used to make comparison of various energy system configurations which help to select the optimal system. The system which has a least cost of energy is the optimum one .

$$LCOE = \frac{\text{Total annualized cost of energy}(\$)}{\text{Total electrical consumption(kWh)}} ; \quad \text{Eq.(18)}$$

Based on the results of design and simulation of the system using PVsyst ,it was found that the total energy produced per annum is 27.8 MWh/Year. PVsyst software determines total installation Cost ,operation cost and used energy cost. As show **in Table 5**

Table 5: System cost

System summary	Cost(\$)
Total installation cost	86091
Operation costs	7320.56
Used energy cost	0.325
LCOE	0.23

The comparison of Energy price between existing system and proposed system

Currently the energy price for one battery is \$1.5[29] with the battery which has 5.4kWh, so the price per kWh for is $1.5/5.4 = \$0.27$ which is high than cost of energy for proposed optimal system (\$0.23/kWh).The price of utility (REG) is \$0.18[32] which is lower than the price of proposed system but this chapter focused on design of the standalone photovoltaic swap charging station in sub-urban and rural area where grid infrastructure is often expensive.

Based on the above discussion, the standalone photovoltaic swap charging station is the best solution for help the penetration of charging station in sub-urban and rural areas in compare to grid connected charging stations.

CHAPTER 7. CONCLUSION AND RECOMMENDATION

7.1. Conclusion

This research set out to design and determine the optimal placement of a standalone PV EV charging station in Kigali by integrating renewable energy generation, battery storage, and EV charging infrastructure. Using locally relevant solar irradiance data and simulated for EV, the design framework incorporated key system parameters such as the size of PV panels, the size of the energy storage system (ESS), and charging points.

This research was to develop a multi-factor methodology for identifying optimal locations for installing EV charging stations. A comprehensive geospatial analysis was conducted on multiple input demand factors to develop a scoring system and locate areas that are most frequently used by the driving public. This scoring system was able to calculate a composite score for each location and spatially classify influential factors to identify suitable locations for EV charging stations. The locations with high, moderate, and low suitability for installing EV charging stations was identified and spatially delineated. The hot spot map of suitable locations can assist decision-makers with developing a strong EV charging station infrastructure. Geospatial analysis plays a vital role in the comprehensive evaluation and determination of the scoring for each input demand factor and thereby identifying optimal locations for installing charging stations.

In the design of standalone PV-EVCS the appropriate components for the system was selected, PVsyst and HOMER pro softwares were used in simulation of the system. The simulation results show that the system had a capacity of 78.75 kWh/day and cost of energy which is \$0.23/kWh. The standalone photovoltaic swap charging station is a good alternative for charging station in sub-urban and rural areas because it is cheaper and beneficial to energy independence.

Finally, the findings confirm that a well-optimized PV EV charging station in Kigali is both technically feasible and strategically beneficial. Given Kigali's favorable solar resource and the rising demand for EVs, the proposed integrated design not only supports sustainable urban mobility but also offers a cost-effective solution for future expansion of the charging network.

7.2.Recommendation

Based on the findings of this study, it is recommended that the University of Rwanda (UR) strengthen its cooperation with private companies, government agencies, and other stakeholders to facilitate student access to reliable data. Such collaboration will enable students, particularly those at the postgraduate level, to conduct research that addresses existing societal challenges. In addition, UR is encouraged to provide research financial support to students in order to facilitate field data collection, which is essential for producing high-quality and impactful research. While this study focused on Kigali, future research should be expanded to other regions of Rwanda to gain a more comprehensive understanding of national EV charging infrastructure needs and to ensure balanced development between urban and rural areas. Finally, it is recommended that the Government of Rwanda integrate EV infrastructure planning into existing urban development frameworks, as this will maximize station utilization, minimize land-use conflicts and technical constraints, and align with the country's broader goals of sustainable mobility and clean energy transition.

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APPENDICES

1. Electrical swapping charging station in Kigali

Electrical charging station in Kigali (swap station)								
Ampers nd	Coordinate		Spiro	Coordinate		RE M	Coordinate	
Location	Latitud e	Longitu de	Location	Latitud e	Longitu de	Loca tion	Latitud e	Longit ude
Giporoso 1	1°57'42 .01"S	30° 7'11.30" E	Giporoso	1°57'39 .57"S	30° 7'17.96" E	Gipo roso	1°57'36 .47"S	30° 7'1.44" E
Giporoso 2	1°57'36 .54"S	30° 7'11.86" E	Murindi	1°58'17 .12"S	30°10'32 .84"E			
Kabeza	1°58'14 .56"S	30° 7'35.73" E	Kabuga	1°58'46 .62"S	30°13'31 .59"E			
Murindi	1°58'20 .46"S	30°10'26 .71"E	Kinyinya	1°55'3. 76"S	30° 6'45.54" E			
Kabuga	1°58'43 .75"S	30°13'27 .93"E	Kinamba	1°55'56 .23"S	30° 3'44.26" E			
Kimironk o 1	1°56'53 .34"S	30° 7'39.58" E	Muhima	1°56'19 .42"S	30° 3'19.91" E			
Kimironk o 2	1°57'4. 85"S	30° 7'33.04" E	Kimisagar a	1°57'8. 23"S	30° 3'8.12"E			

Kinyinya	1°54'59 .58"S	30° 6'37.11" E	Nyamiram bo	1°58'10 .35"S	30° 3'28.61" E			
Kagugu	1°54'48 .76"S	30° 5'14.97" E	Gikondo	1°58'4. 56"S	30° 4'27.52" E			
Gakinjiro Gisozi	1°55'18 .15"S	30° 4'23.55" E	Kicukiro Gatenga	1°58'43 .93"S	30° 6'1.57"E			
Kinamba	1°55'56 .23"S	30° 3'44.26" E	Gahanga	2° 1'54.91 "S	30° 6'7.73"E			
Muhima	1°56'21 .30"S	30° 3'27.16" E	Kicukiro Center	1°58'41 .01"S	30° 6'17.06" E			
Nyabugo go	1°56'35 .56"S	30° 2'38.52" E	Sonatube	1°57'55 .54"S	30° 6'11.67" E			
Kimisaga ra	1°57'44 .08"S	30° 3'20.01" E	Camp zaire	1°57'50 .54"S	30° 4'43.21" E			
Nyamira mbo	1°58'39 .02"S	30° 2'57.51" E	Gatsata	1°55'39 .95"S	30° 2'47.29" E			
Town	1°57'28 .48"S	30° 3'34.97" E						
Gikondo	1°58'25 .22"S	30° 4'36.75" E						

Rwandex	1°58'9. 41"S	30° 5'16.22" E						
Nyanza	2° 0'7.00" S	30° 5'25.17" E						
Gahanga	2° 1'52.09 "S	30° 6'8.97"E						
Kwa Rwahama	1°57'16 .43"S	30° 7'4.61"E						
Meridien	1°56'50 .57"S	30° 5'32.83" E						
Gishushu	1°57'3. 28"S	30° 6'12.83" E						
Nyaconga	1°51'58 .65"S	30° 5'11.76" E						

2. Module specifications

Table 5:Module specifications

Rated Maximum Power (Pmax)	380W
Open Circuit Voltage (Voc)	48.05V
Maximum Power Voltage (Vmp)	39.8V
Short Circuit Current (Isc)	10.09A
Maximum Power Current (Imp)	9.55A
Module Efficiency	19.2%
length	2000mm
Width	991mm
Depth	40mm
Weight	22.5kg

3.Battery specifications

Table 6:Battery specifications

Capacity	200Ah
Nominal voltage	12V
Lifetime @20°C	12years
Battery Efficiency	19.2%
length	558mm
Width	125mm
Depth	305mm
Weight	61kg