Standalone Solar-Based Power Supply for Electric Mobility in Rural Areas of Developing Countries

Based on a case study in Kenya

vorgelegt von

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Executive Summary

Transportation is a vital sector in Sub-Saharan Africa (SSA), contributing to the social and economic development of the region. However, transport activities, particularly the use of conventional fossil-fuel vehicles, contribute significantly to air pollution and greenhouse gas emissions, leading to serious environmental and health challenges. The region also faces challenges with frequent fuel scarcity, lack of constant electricity, and high rising fuel costs, which limit the ability of people to access affordable and reliable transportation services.

To address these challenges, this research designed an off-grid photovoltaic (PV) system that provides sustainable energy for charging electric mobility and non-electric mobility loads in SSA. The system was designed to leverage the potential solar energy in the region and provide a cost-effective and reliable solution for powering transport infrastructure.

The PhD research project has provided a sustainable off-grid model based on solar PV technology for charging battery-powered electric mobility and other non-mobile electric loads. The PhD research utilises a Water Energy (WE) Hub (i.e. a 30kWp off-grid PV standalone system) owned by WeTu Limited in Mbita which is used to supply sustainable power for charging electric fishing lamps and water treatment devices. The integration of the electric mobility concept into the current infrastructure of the WE Hub helps to increase the operational region of the WE Hub and to provide new avenues for the power generated. Electric cargo bikes and motorbikes (for delivering treated drinking water, transportation of products, and services) are among the mobility alternatives considered in this study.

A field measurement investigation was also conducted on the energy consumption of e-bikes using the rider's driving style as a basis. A load management algorithm for load prioritisation, scheduling, and optimization was developed to maximise the utilisation of the PV power production and decrease energy deficit without necessarily enlarging the PV module, battery size, or using a diesel generator. Computer-standalone *MATLAB App* was developed to serve as a technical tool for off-grid PV system designs employing electric mobility options at any given location.

Findings

Mbita Water Energy *(WE) Hub*

Mbita WE Hub, located around Lake Victoria, provides sustainable electricity for charging electric fishing lights, water purification and other electric activities. To satisfy future electric demands, the WE Hub's hardware was upgraded from 15.8 kWp PV with a 70-kWh central battery capacity to 30.24 kWp with a 104-kWh central battery system. The fishing lanterns demand increased from 300 to 450 lanterns daily. Similarly, at the WE Hub, electrically driven bikes were recognised as potential electric consumers. These include e-Anywhere Berlin freight bikes, e-OpiBus bikes, and e-BodaWerk bikes.

Measurement Investigation

The measurement investigation formed the basis for a comprehensive design and simulation of the technological infrastructure (size of PV field, battery storage capacity, etc.) of the WE Hub. Energy loggers, multimeters, and GPS trackers were selected as acceptable measuring tools for monitoring and estimating the electric bikes' electricity usage during operation and charging. The factors considered during the measurement were the battery state of charge (SoC), average speed travelled, distance travelled, payload weight, terrain type, charging rate, power consumption during operation and charging etc.

Anywhere Berlin cargo bike measurement investigation

it was discovered that a 100 km journey would require at least three battery swaps for an Anywhere Berlin cargo bike with a 1.1 kWh rechargeable battery, an average load weight of 102 kg, and running at an average velocity of 22.9 km/h on both tarmac and non-tarmac terrains.

OpiBus bike measurement investigation

It was discovered that an OpiBus bike with a 2.16 kWh battery capacity, running on both tarmac and non-tarmac at an average speed of 47.8 km/hr and an average payload weight of 129 kg would require at least two battery swaps to travel 100 km.

BodaWerk bike measurement investigation

It was discovered that a BodaWerk bike operating on tarmac terrain with an average load weight of 74 kg, average velocity of 39 km/h, and 2.2 kWh battery capacity would need at least one battery swap to complete a 100 km journey.

Development of a simulation model

A simulated design scenario at Mbita WE Hub employed a 104-kWh lead-acid central battery capacity and a 30kWp PV array size. Based on holidays (full moon phase days) and workdays (non-full moon phase days), daily and annual load profiles were developed.

Workdays are days with no moon or with low moonlight brightness, and this is exclusively determined by *Mbita's* lunar calendar. Lake Victoria has a naturally high fishing catch these days. As a result, it was estimated that every day at the Mbita WE Hub, auxiliary equipment (such as water purification, laptops, light bulbs, etc.), 450 fishing lanterns, and 25 batteries for electric bikes would be charged.

Holidays are days with a full moon or high moonlight brightness, which depend on Mbita's lunar calendar. These days, Lake Victoria has a naturally poor fishing catch. As a result, all other loads are charged, except that half of the number of fishing lanterns required during workdays are charged (i.e. 225 lanterns).

Similarly, results obtained from the simulation of the Mbita WE Hub charging infrastructure model show 27,200 kWh as annual electricity demand and photovoltaic (PV) electricity generation of 37,700 kWh with an electricity deficit of 375 kWh. From the aforementioned annual results, it is clear that the PV production is greater than the electricity demand which in turn should lead to no electricity deficit. However, the results are not reflected in hourly resolution, thus neglecting the effect of weather variability on PV production. Therefore, in later chapters of the thesis, hourly resolution results are presented to understand the electricity deficit.

Load optimisation

To best integrate electric mobility options into the WE Hub as well as utilise the maximum PV production and reduce electricity deficit, a load optimisation algorithm was designed using the MATLAB Non-Linear Programming (NLP) solver. The maximum variable solar energy was captured by the load optimisation algorithm, which then schedules, sizes and charges a limited number of devices.

Following intra-day PV production, the system using the NLP algorithm was able to plan, prioritize, and optimize the major loads' demand (such as electric bikes and fishing lanterns). This is demonstrated by the simulation-based results for the optimized load profile. Based on the moon phases and the seven-day solar prediction at the Mbita WE Hub, the system with the NLP algorithm was also able to shift the electric loads from days with potential energy deficits to days with surplus energy.

By maintaining the 30 kWp PV capacity and reducing the central battery capacity from 104 kWh to 90 kWh, it was also discovered that the annual electricity deficit was decreased from 375 kWh to 50 kWh using the NLP algorithm load optimization algorithm, and the annual energy consumption was increased by 11% (31,300 kWh), which for example is enough to charge 4 more e-bikes batteries daily. Hence the NLP-based algorithm assisted in optimally integrating electric mobility solutions into the WE Hub in an economical manner.

Development of an optimisation design tool

A standalone computer application using *MATLAB App* was developed to allow the user to simulate the size of a PV and battery system based on the available loads (i.e. fishing lanterns or electric vehicles). It also incorporates the developed *MATLAB NLP* load scheduling, shifting, and optimisation algorithm, thus allowing the most cost-effective integration of electric mobility solutions into any rural off-grid PV system.

Techno-economic analysis

The Levelised Cost of Electricity (LCoE) of the system with and without NLP load optimisation was calculated. It was found that the system with the NLP algorithm has an LCoE of 17.07 €-Ct/ kWh compared to 18.24 €-Ct/ kWh for the system without the non-NLP algorithm. This is because the NLP system had a reduction in the central battery capacity from 104 kWh for the non-NLP system to 90 kWh. Hence, for example, to fully charge a 2.2 kWh e-bike battery, the user is required to pay 37.55 €-Ct and 40.13 €-Ct for NLP based system and a non-NLP system respectively.

The sociological impact of the research

Siemens Stiftung and WeTu Limited have launched a business model centred on sharing economic approaches that are practical for e-mobility transportation adaption. These include providing faster, more cost-effective access to e-mobility with less maintenance, as well as the construction of workshops for e-motorcycle training and maintenance, hence increasing local job opportunities in the Lake Victoria region where the WE Hubs are located.

A study conducted by Siemens Stiftung on the willingness of existing gasoline-powered boda-boda riders to switch to e-motorbikes shows that the most significant challenges for motorbike taxi drivers are high fuel costs and excessive motorcycle fuel use. Riders who wish to avoid high gasoline expenses appreciate the notion of an e-bike, and if given enough financial assistance, nearly 85 % of riders would switch to e-motorbikes. Approximately, 30 % of motorcycle riders prefer to buy the e-bike outrightly, whereas around 8 % would be willing to buy it on loan.

WeTu Limited intends to install more than 30 charging stations for e-bikes at each location. To guarantee ecologically responsible e-bike battery disposal, plans are in the works to establish collection terminals at We Hub sites around Lake Victoria.

Similarly, a secondary school student reported preferring electrically propelled motorcycles to gasoline-powered ones because of their distinctive feel, absence of noise, and smoke traces, according to a survey done by Siemens Stiftung. He expressed interest in utilizing the e-cargo bikes rather than traditional wheelbarrows to deliver his father's building supplies to a construction site.

In another survey, a lady trader who sells groceries mentioned that she had a special feeling during her first encounter with e-bikes. She claims to have never seen anything move so quickly without gasoline and is pleased that it offers a less expensive way to get food from the market and farms to her business location. She adds that her husband transports water and goods between wholesale and retail stores on the e-cargo bike.

Another study indicates that a boda boda operator who currently uses a petrol-fuelled motorcycle is contemplating switching to an e-bike as it could offer a more affordable means of supporting their family.

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List of publications

The following peer-reviewed papers have been prepared and published during the Ph.D. research:

A. Bugaje, A., Ehrenwirth, M., Trinkl, C., Zoerner, W., Investigating the Performance of Rural Off-Grid Photovoltaic System with Electric-Mobility Solutions: A Case Study Based on Kenya, 2020 J. sustain. dev. energy water environs. syst., 1090391, DOI: https://doi.org/10.13044/j.sdewes.d9.0391
B. A. Bugaje, M. Ehrenwirth, C. Trinkl, K. Baer and W. Zoerner, "Development of a Load Management Algorithm Using Nonlinear Programming (*NLP*) for Optimum Integration of Electric-Mobility Solutions into Rural Off-Grid PV Systems," NEIS 2020; Conference on Sustainable Energy Supply and Energy Storage Systems, Hamburg, Germany, 2020, pp. 1-6.
C. A. Bugaje, M. Ehrenwirth, A. Yadav, K. Mehta, F.Ojinji, C. Trinkl and W. Zoerner, "Off-Grid Solar Photovoltaic Power Forecasting Using Artificial Neural Networks," NEIS 2021; Conference on Sustainable Energy Supply and Energy Storage Systems, Hamburg, Germany, 2021, pp. 1-6.
D. Bugaje, A.; Ehrenwirth, M.; Trinkl, C.; Zörner, W. Electric Two-Wheeler Vehicle Integration into Rural Off-Grid Photovoltaic System in Kenya. Energies 2021, 14, 7956. https://doi.org/10.3390/en14237956

The following conferences were attended during the Ph.D. research:

A. Aminu Bugaje (2021) “Influence of Input Parameters on Artificial Neural Networks for Off-Grid Solar Photovoltaic Power Forecasting”. NEIS 2021 Conference on Sustainable Energy Supply and Energy Storage Systems, Hamburg Germany. Available https://neis-conference.com/wp-content/uploads/2021/09/NEIS-2021-Final-Program.pdf (page 5)
B. Aminu Bugaje (2021) “Integration of Electro - Mobility Solutions into Off-Grid PV Systems for Sustainable Development of Rural Areas in Sub - Sahara Africa”. 3rd International Conference on Solar Technologies & Hybrid Mini Grids to improve energy access September 15-17, 2021. Available

https://agenda.uib.es/_files/_event/_33167/_editorFiles/file/BOOKOFABSTRACTS/Book%20of%20Abstracts%20S-@ccess%202021%2021_09.pdf (page 27)

C. Aminu Iliyasu Bugaje (2020) *"Electric Battery Storage Simulation with Solar-PV".* CARNOT Toolbox user meeting at Hochschule Biberach, Germany. Available online https://www.gomatlab.de/download,id,14677.html (page 1)

D. Bugaje (2020) "*Development of a Load Management Algorithm Using Nonlinear Programming (NLP) for Optimum Integration of Electric-Mobility Solutions into Rural Off-Grid PV Systems"*. NEIS 2020 Conference on Sustainable Energy Supply and Energy Storage Systems, Hamburg Germany. Available online https://neis-conference.com/wp-content/uploads/2020/09/NEIS2020_Final_Program.pdf (page 6)

E. Aminu Bugaje (2020) "*Investigation of Rural Off-Grid PV System with Electric-Mobility Solutions Using MATLAB / Simulink CARNOT TOOLBOX"*. 15th SDEWES Conference, Cologne, Germany. Available online https://www.cologne2020.sdewes.org/programme

F. Aminu Iliyasu Bugaje (2019) *"Electromobility for sustainable development in rural areas"* DAAD-scholarship holders meeting. Ulm University, Germany. Available online https://www2.daad.de/medien/der-daad/presse/downloads/programmheft_stipendiatentreffen_ulm.pdf (page 9)

G. Aminu Bugaje (2019) *"Electro-Mobility for Sustainable Development in Rural Areas"* Young BRAIS Kick off Meeting Bayreuth Universität Würzburg, Germany. Available online https://www.brias.uni-bayreuth.de/pool/dokumente/Short-presentations.pdf (page 1)

List of abbreviations

kWh	Kilowatt-hour
kW	Kilowatt
kWp	Kilowatt-peak
$MtCO_2$ e	Million tonnes of carbon dioxide equivalent
kWh/a	Kilowatt-hour per annum
GHG	Greenhouse Gas
m^2	Meter square
P_demand	Power / electric demand
P_deficit	Power deficit
P_{PV}_real	PV power produced
η_{PV}	Efficiency of solar panel
PV	Photovoltaic
SoC	Battery state of charge
DOD	Battery depth of discharge
T_t	Ambient Temperature
G_t	Irradiance
A	Panel area
Gh	Global horizontal irradiance
STC	Standard test conditions
ηnom	Efficiency of panel at STC
CG	Irradiance coefficient
^{o}C	degree celsius
KEMP	Kenya Electricity Modernization Project
KEEP	Kenya Electricity Expansion Project
RECP	Renewable Energy Cooperation Programme
REMP	Rural Electrification Master Plan
RECP	Kenya Renewable Energy Potential
GRSF	Global Road Safety Facility

Chapter 1: Introduction

1.1 Motivation

Transportation using all kinds of passenger modes of transportation powered by fossil fuels (i.e. buses, boats, cars, motorcycles and rails), accounts for about a quarter of global CO_2 emissions. The rate of emissions is expected to increase significantly by 2050 when the number of all kinds of passenger modes of transportation is expected to more than double (Remeredzai Joseph, 2021). This increase is especially projected in low-income or developing nations, where regulations governing vehicle emissions are rarely implemented and where there is little financial investment in renewable energy sources (Remeredzai Joseph, 2021). However, some countries such as Germany, Norway, China, etc., have taken initiatives to reduce carbon dioxide emissions, by investing in renewable sources of energy, thus leading to global leapfrog to electric mobility (Remeredzai Joseph, 2021).

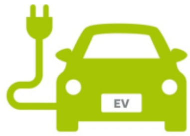
Electric mobility (E-mobility) is the use of electric vehicles (EVs) for transportation that is supported by a strong information and communication technology (ICT) infrastructure. In place of an internal combustion engine (ICE), electric vehicles (EVs) are propelled by one or more electric motors driven by rechargeable battery packs. EVs produce little or no emissions when in use, are quieter, and consume less energy than ICE-powered vehicles (Ministry of Transport and GIZ, 2019).

Similarly, the electric motor used by EVs converts around 80 % of their electrical energy to mechanical (Lluc Canals Casals *et al.*, 2016), thus making EVs a better alternative to conventional internal combustion engine (ICE) vehicles, which have an efficiency of less than 40% (Åhman, 2001). However, due to several impediments, the adoption of electric vehicles is not moving forward as swiftly as anticipated.

These impediments include their restricted range and long charging time (Kempton, 2016; Hardman *et al.*, 2016). Consequently, despite these impediments to their adoption, they still offer significant advantages such as lower cost of maintenance and much less energy usage than ICE vehicles (Alkawsi *et al.*, 2021).

Battery electrified buses, boats, cars, motorcycles and rails are all examples of EVs and are divided into three major groups (see **Table 1**) based on whether they use electricity as their main source of energy or to increase the economy of traditional vehicle designs in some way (Ministry of Transport and GIZ, 2019).

Table 1. Categories of Battery Electric Vehicles

			
Types	Hybrid Electric Vehicles (HEVs)	Plug-in Hybrid Electric Vehicles (PHEVs)	Battery Electric Vehicles (BEVs)
Description	HEVs are propelled by an electric motor that uses a battery to store electricity and an internal combustion engine (ICE). The ICE or regenerative breaking is used to charge the battery.	PHEVs are propelled by an electric motor that uses battery to store electricity and an internal combustion engine (ICE). The vehicle's battery can be charged by plugging the vehicle into an electric power source.	BEVs are propelled only by an electric motor that uses electricity from a battery. The vehicle's battery is charged by plugging the vehicle into an electric power source.
Components	ICE, petrol / diesel, electric motor, battery pack, regenerative breaking	ICE, petrol / diesel, electric motor, battery pack, regenerative breaking	Electric motor, battery pack, regenerative breaking

Numerous research institutions and energy supply companies are conducting studies on how to lessen the burden on local electricity networks due to the growing number of charge outlets for electric vehicles since the demand for electricity by EVs is rising quickly. One of the most efficient ways to address this issue concerning local electrical networks is to power the EV charging infrastructure using renewable energy systems (RES), such as wind and solar (A. Von Jouanne *et al.*, 2005).

RES may make a significant contribution to the growth of renewable energy penetration and the reduction of carbon emissions. The difficulties with deploying RES, however, lie in its varying characteristics, such as seasonal variations in wind and sunshine (Shukla *et al.*, 2019). As a result, it's crucial to properly design solar PV (photovoltaic) systems to prevent over or under-sizing, which would result in inadequate solar power generation or high capital expenditures (Patrick, 2014).

In terms of mobility, Africa is at an intersection since it continues to have one of the lowest rates of motorization worldwide while still seeing one of the fastest rates of vehicle expansion. Vehicle sales on an annual basis are increasing significantly, with most African countries reporting rises of over 10% as opposed to Europe's 4% (UNEP, 2018). Only one in ten of the vehicles brought into the continent are brand-new; the vast majority are pre-owned vehicles. This is an opportunity for African countries to cut back on vehicle emissions before further motorization takes off (Siemens Stiftung, 2020a).

Rapid urbanization, population growth, rising energy consumption, and economic expansion, particularly in Sub-Saharan Africa (SSA), are driving a transportation revolution. This occurs at a period when the majority of African countries are facing mobility issues such as traffic congestion, a lack of infrastructure, health problems, air pollution, and the financial liability that high fuel costs and subsidies impose on the economy. Electric and battery-powered vehicles are an excellent solution to the aforementioned difficulties.

Africa has a very high potential for renewable energy resources, making it an excellent location for an electric vehicle (EV) revolution. EV solutions are both technically and economically appropriate in Africa since temperatures seldom fall below zero and daily average daily travel durations are less than 80 km at 60 km/hr. Africa also has one of the youngest populations with a propensity for technology, which might aid the continent's rapid transition to electric transportation while also providing a workforce for the development of its vehicle manufacturing capabilities (Siemens Stiftung, 2020a).

Additionally, EVs have drawn attention as a way to reduce reliance on petroleum and increase energy stability with regards to rising transportation needs, that may be very advantageous for the economy of African countries (Siemens Stiftung, 2020a).

Several Sub-Saharan African nations have already taken big strides in enhancing their total vehicle fuel efficiency, enforcing vehicle standards and laws like Kenya's Climate Change Act or Rwanda's promotion of non-motorized urban transportation. However, to stop the growing weight of fuel dependence and find a sustainable solution to utilise Africa's enormous renewable energy resources, these initiatives must be massively scaled-up (Siemens Stiftung, 2020a).

1.2 Problem statement

Socio-economic development is impossible in the current world without access to modern energy services. The global Sustainable Development Goals (SDG) policy is in accordance with the use of modern and sustainable energy services, to promote socioeconomic development and mitigate climate change (Kaunda *et al.*, 2012).

In Africa, the bulk of goods and services are delivered by road, which increases greenhouse gas (GHG) emissions and creates a strong reliance on fossil fuels. Africa's governments are under pressure to substantially subsidise fuels to protect citizens from the volatility of oil prices. Irrespective of these subsidies, periodic gasoline shortages that result in long fuel line wait times place a tremendous financial strain on vehicle users. (Akindare, 2018; Gilbert, 2018).

Moreover, SLoCaT (2018) reported that between 2000 and 2016, there had been a 31% increase in worldwide transportation emissions, with Asia having had the largest increase of 92% followed by Africa with 84% and Latin America with 49%, while emissions in Europe and North America had been declining. In Sub-Saharan Africa (SSA), transportation-related emissions, which are mostly caused by a rise in passenger and freight transport activities, grew by 75% between 2000 and 2016, reaching a level of 156 million tonnes (Mt) of CO_2. This rise in transport-related CO_2 emissions includes, for instance, an increase of 40% in South Africa, 123% in Kenya, 153% in Ghana, 161% in Algeria, and 73% in Egypt.

According to estimates from the World Bank and the Institute for Health Metrics and Evaluation, motorized road transport pollution caused 184,000 early deaths in 2010 (GRSF, 2014). The death figures are supported by the International Council for Clean Transportation (Chambliss *et al.*, 2013). The principal diseases that are impacted by vehicular emissions include lung cancer, stroke, heart disease and respiratory related infections (Paul and John, 2014).

1.2.1 Urban transport in SSA

As reported by (Ajay and Fanny, 2008), the most prevalent form of public transportation in most cities of SSA is both big and small buses. Except in Addis Abeba and Ouagadougou, minibuses are significantly more common than large buses, which illustrates how challenging it is to run large buses profitably. Overall, minibuses make nearly twice as many trips as large buses.

Initially, the majority of the cities' core urban transportation infrastructure was dominated by large-buses transportation. The conventional bus services were typically nationalized during the post-independence era, resulting in structured public transportation (Ajay and Fanny, 2008).

The government-owned bus enterprises were initially able to run independently, but when operational deficits rose and public subsidies did not grow proportionately, operators struggled to maintain and upgrade their fleet, and governments were reluctant to raise fares as they were regulated. The quality and scope of the services suffered as a result. The majority of government own bus enterprises ultimately failed and went out of business.

Accra, Dar es Salaam, Kampala, Kigali, and Lagos are just a few of the cities that have completely stopped offering large-bus services in favour of private and largely unregulated minibus operators. Nairobi, which has maintained the private operation of its large-bus service since independence, is the only city that has not gone through this cycle (Ajay and Fanny, 2008).

Tro-tro in Accra, danfo in Lagos, gbaka in Abidjan, sotrama in Bamako, and matatu in Nairobi are a few examples of the vernacular names for minibuses, which typically carry 8 to 25 passengers. A larger variation of minibuses known as "midi-buses" may accommodate between 30 and 50 passengers (with standees). These vehicles frequently go by slang names as well, such as autos rapides in Dakar and molue in Lagos. Dollar-dollar is the origin of the phrase dala-dala, which is prevalent in Dar es Salaam (see **Figure 1** left- Kampala central taxi terminal, right- Dala dala operators in Tanzania).

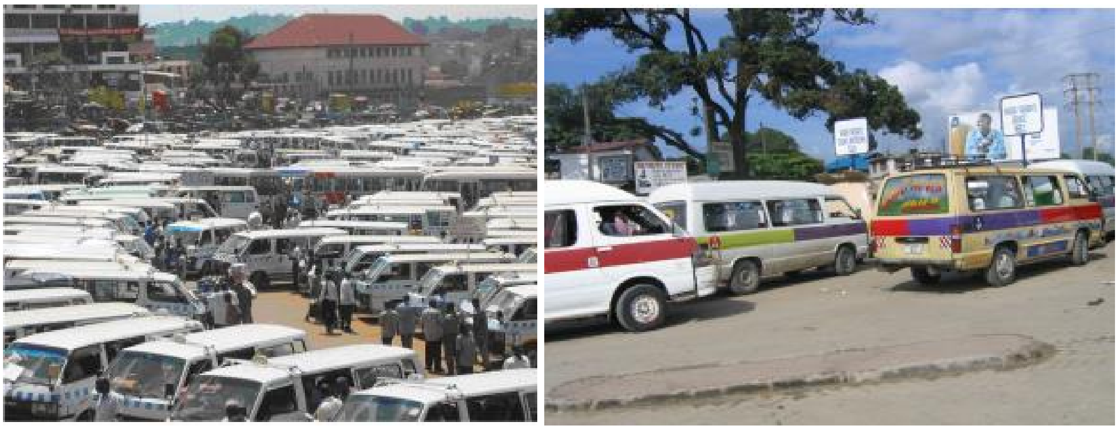


Figure 1: Example of a minibus transport service in SSA cities (Ajay and Fanny, 2008)

Minibus services however exhibit drawbacks from the standpoint of the general welfare, notwithstanding the services they offered in SSA cities due to the vacuum left by large-bus services (Ajay and Fanny, 2008):

Traffic congestion

On some routes, minibuses currently make up close to 50% of all vehicular traffic. Major gridlock has indeed been caused by their increase, especially during peak hours.

Emissions and safety

The majority of minibuses are old, poorly maintained, and driven slowly for long durations. Minibuses were involved in 22% of accidents and the bulk of traffic infractions in Accra in 2004. In all African cities, there is a general practice of lax enforcement of laws regulating car inspection, driver behaviour, and traffic control.

The volatility of prices, connections, and itineraries

When demand increases, minibus drivers can change the routes they travel as well as the rates they charge. In Dar es Salaam, the bus operators' organization and the government coordinate tariffs while the regulator (SUMATRA) decides on routes, otherwise, the dala-dala minibuses will be as erratic.

Unfair incentives

Vehicles remain at the stations until they are fully loaded since drivers must pay to depart the stations and have an incentive to avoid driving with less than a full load. As a result, it is frequently impossible for people to embark at other stops along the route.

To guarantee a place on the bus, many people travel great distances to get to the station (Ajay and Fanny, 2008).

Comfort

Minibuses are small and the seating is congested, which makes getting in and out and moving about challenging.

Due to the deplorable state of the roads and the bus companies' failure to meet the increasing demands, the use of motorbikes for transport has considerably expanded in Douala, Lagos, and Kampala in recent times. In Ouagadougou and Bamako, independent motorbike ownership is now common. Motorbike services originally provided access to major roadways from residential districts, where customers could board cabs or minibuses (see **Figure 2** left- transportation using motorbikes in Burkinabe, right- motorbike taxi ranks await passengers in Lagos).

Figure 2: Example of a motorcycle transport service in SSA cities (Ajay and Fanny, 2008)

1.2.2 Rural transport in SSA

According to (Olinto *et al.*, 2013), the majority of the poorest individuals in sub-Saharan Africa reside in rural areas where they cultivate small plots of land to support themselves through subsistence farming. These individuals rely on the market to sell surplus crops, which is linked to the increased demand for food resulting from urbanization, thus driving rural development. However, inadequate transportation infrastructure such as long travel distances to markets, poor roads, and limited access to transportation, severely hinders this progress. As a result, there is a high demand for cost-effective and efficient transportation services that can provide access to critical services such as healthcare and markets, particularly since many people are unable to afford their own vehicles (Ron and Keith, 2017).

Even though there are several intricate factors influencing the availability and affordability of efficient rural transportation services (RTS), it is argued in this by (Ron and Keith, 2017) that one important reason is that traditional cars that are made to travel at high speeds on tarmac terrains perform inefficiently at low speeds on rural earth terrains, resulting in higher GHG emissions and fuel consumptions. Due to these high running costs, it is extremely difficult to provide both lucrative and cost-effective RTS (Ron and Keith, 2017).

The majority of RTS are operating on major roads, because there is a consistent demand that enables RTS operators to generate a profit. However, even in this case, customers may experience significant delays as operators wait for full loads to reach profitability (Ron and Keith, 2017).

(Starkey *et al.*, 2007) discovered that a generic model may be utilized to characterize the pattern of RTS in SSA using case studies in four countries. This is the hub and spoke concept depicted in **Figure 3**, where the hubs are the primary sites where RTS operate and the spokes are the roadways on which they regularly operate.

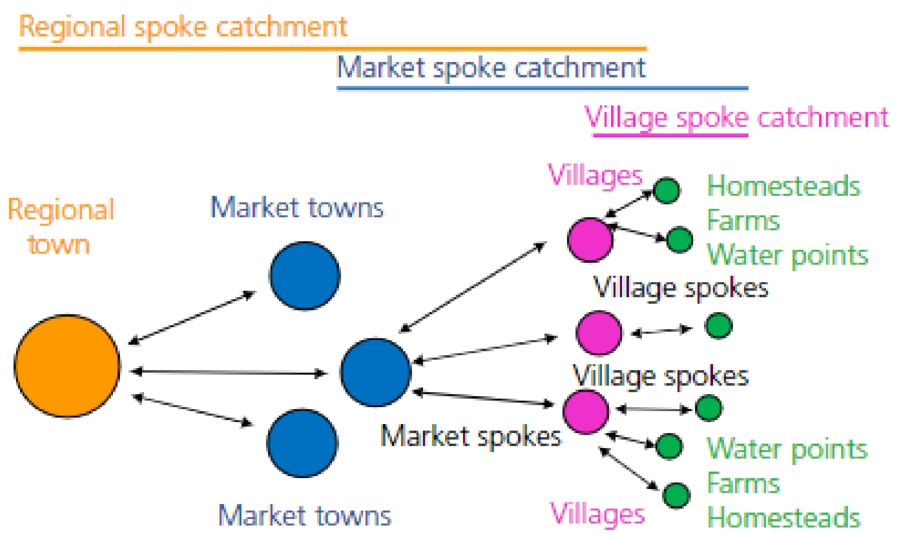


Figure 3: Pattern of transportation services in rural areas of SSA (Starkey *et al.*, 2007)

In RTS, the links between villages and markets, healthcare facilities, and other resource facilities are typically where there is a significant deficit. A significant barrier to enhancing rural livelihoods and rural growth is the absence of an efficient RTS in this region (Starkey *et al.*, 2007; Ron and Keith, 2017).

Several other recent significant assessments of rural transportation in SSA including those by (Starkey and Njenge, 2010; Starkey *et al.*, 2013; Hine, 2014; Banjo *et al.*, 2012) emphasize the function and significance of these "village-to-local resource center" RTS. According to the authors, infrastructure has accounted for up to 98 % of funds spent on rural transportation.

Compared to motorized road transport services (RTS), the funding allocated to promoting appropriate modes of transportation such as bicycles and animal-drawn carts has been significantly low. The common belief was that with improved roads, RTS would naturally follow as transport operators recognized the opportunities presented. However, this has not been the case, and it is widely believed that it is exceedingly challenging to make a profit using traditional RTS on village-to-market routes due to several reasons. These reasons include:

- Fragmented, erratic, and seasonal demand
- High vehicle operating costs due to poor road quality
- Low affordability due to low incomes
- Potentially low payloads, and a lack of support for vehicle operations

Conventional cars designed for medium to high speeds on bitumen roads have significant operating costs when used at lower speeds on typical rural earth and gravel roads. In **Figure 4**, minibuses and modified pickups are commonly used modes of transportation. Many of these vehicles are initially purchased as refurbished cars for use on main hub routes, but they are often over 10 years old by the time they begin operating on rural routes (Starkey *et al.*, 2013).

Figure 4: Example of transport vehicles used in rural areas of SSA (Ron and Keith, 2017)

According to a specific fuel consumption study presented by (Ron and Keith, 2017), the fuel consumption and carbon dioxide emissions of a minibus travelling at an average speed of 50 km/h on earth/gravel roads are roughly twice those of a minibus travelling at an average speed of 80 km/h on asphalt roads. The expenses of operating on earth/gravel roads are expected to be at least double that of asphalt roads due to increased maintenance costs and longer travel times resulting from the rougher road surface.

It's evident that to increase the profitability of RTS operations at fair prices and increase their accessibility, the running costs of RTS vehicles should be reduced, requiring the selection of vehicles best fitted to the operating environment. These point to the usage of vehicles with a top speed that is roughly half that of normal vehicles and less horsepower. The fastest growth in motorcycle use is being seen in South Africa. For example, Tanzania's motorcycle fleet increased by 323 192 from 31 006 in 2005 to 323 192 in 2010, or 60% annually (Hine, 2014).

The advent of taxi services where one or two passengers are transported on the two-wheeler seating while behind motorcyclists has significantly improved the movement of the people in numerous areas of SSA. Therefore, an effective motorcycle transport service would go a long way in improving rural passenger and goods transport (Ron and Keith, 2017).

Similarly, another study reports that while access to good roads remains a goal for the future, however efficient transport services may have a very significant impact on agricultural and rural development by boosting commercial agriculture and participation in the market (Berg *et al.*, 2018).

Subsequently, with the current penetration of stand-alone PV systems in rural areas of SSA where there is no or little access to flowing water, electricity, taxi services, petrol stations, the introduction of off-grid PV-charged battery electric vehicles such as e-boats, e-cars, e-cargo bikes can be a real socio-economic development opportunity in most of SSA's rural communities (Mueller and Mueller, 2014). Similarly, apart from improving the lives of the rural inhabitants, electric vehicles charged using renewable energies can also contribute to a sustainable and cleaner environment with lower greenhouse gas (GHG) emissions.

Remarkably, the majority of Kenyan homes are now connected to the grid, this is due to recent significant government investment in extending the electric grid to rural regions. However, the rate of rural electrification is still quite low (Lee *et al.*, 2016). Solar energy charging stations could be used to remedy this issue. Similarly, when electric vehicles (two and three-wheelers) become more prevalent in rural areas, they can unleash value and increase demand for solar mini-grids (EED Advisory and Siemens Stiftung, 2020; Remeredzai Joseph, 2021).

Hence, with the above-mentioned problems faced by SSA´s regions, especially rural communities, the Ph.D. research work focused on the implementation of an off-grid PV charging station for battery-powered lightweight electric vehicles such as e-motorcycles, e-cargo bikes, etc., and other electrical applications such as charging of electric fishing lanterns, water treatment device etc. around Lake Victoria in Western Kenya. This would assist in improving the socio-economic lives in terms of income and health conditions of the populace of the case study location.

1.3 Transport and mobility demand for short-range electrical vehicles at the case study location

Kenya and the other East African countries have recently begun to see the effects of climate change on human health, agricultural output, and economic losses. There has never been a time when it was more crucial for the world to move toward a low-carbon economy (Siemens Stiftung, 2020a).

Kenya has been making significant efforts since the early 2010s to become a leader in East Africa's energy transformation. To achieve this goal, the country has enacted two ground-breaking laws, namely the Climate Change Act of 2016 and the more recent Energy Act of 2019, which have a direct impact on its transition to a low-carbon economy. These policies were initially put in place to reduce greenhouse gas (GHG) emissions by 30% by 2030, improve climate change resilience, and promote low-carbon and climate-resilient growth (Siemens Stiftung, 2020a; UEMI, 2020a).

The highest priority mitigation measure selected is the nationwide electrification of the vehicle fleet since the transportation sector contributes more than 13% of all national emissions. Nevertheless, as of 2019, only around 350 electric vehicles (EVs) have been registered in Kenya, indicating that the country's EV infrastructure is still in its early stages. Currently, Kenya has approximately 3.2 million vehicles, with the majority of the fleet consisting of two and three-wheelers, as evidenced by the registration of 108,000 new motorbikes in 2018 and the highest motorization rate (DW, 2019; Siemens Stiftung, 2020a).

Many of these 2- and 3-wheel vehicles with internal combustion engines are outdated and inefficient, generating more black carbon and particulate matter than a passenger automobile (Siemens Stiftung, 2020a).

1.3.1 Case study

Water Energy Hub (WE Hub)

WE Hub is a social enterprise focused on improving the living conditions of rural Kenyans by providing clean water, solar lighting, and charging services. Their services support employment growth, promote better health, and protect the local environment. In addition to seven solar-powered hubs, WE Hub also operates five smaller solar-powered "satellite" hubs around Lake Victoria (Siemens Stiftung, 2020b; WeTu, 2019).

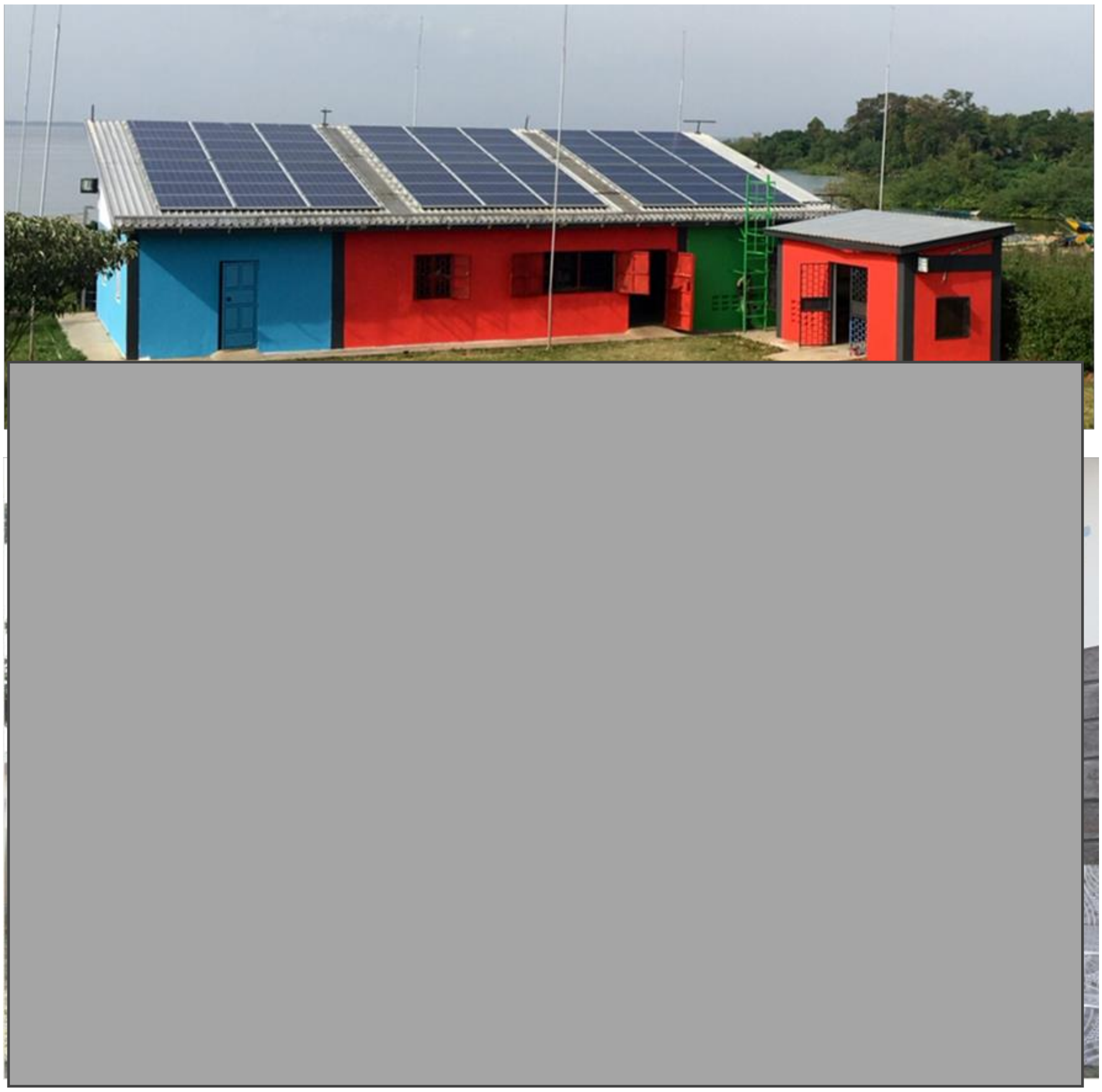


Figure 5: Example of a WE Hub - Kenya (*Lake Victoria*) (Siemens Stiftung, 2020b)

Homa Bay, Migori, and Siaya County mobility pattern

WE Hubs are operating in Homa Bay, Migori, and Siaya counties which are among the most densely populated areas in Kenya, with a total population of 3,241,569 people, although they are primarily rural. The majority of the population, ranging from 43% to 48%, are poor and the counties have significant infrastructural deficiencies. Only 30% of the population has access to electricity and less than half of the roads are paved, according to the Siemens Stiftung. In these three counties, boats, 2 and 3-wheeled motorbikes are the primary modes of transportation. There are approximately 133 3-wheelers used mainly for cargo transportation services, 104 human and cargo boats, and 4,820 motorbikes which operate from unofficial stations located close to human activities such as transportation hubs or markets (Siemens Stiftung; IFRTD, 2021).

Accordingly, based on socioeconomic data collected from the three counties, it has been found that motorbike riders known as "boda-boda" spend around 350 KES per day on their motorcycles, while their daily living expenses amount to 499 KES on average. They spend around 6,000 KES per month on their motorcycles and earn approximately 75% of their income from operating motorbike taxis. About 29% of the riders have outstanding loans and their monthly discretionary income is around 6,173 KES.(IFRTD, 2021; Siemens Stiftung; Siemens Stiftung, 2020b).

Moreover, Siemens Stiftung conducted a study that found formal and informal markets have a long-standing practice of providing financial services to support mobility. High fuel costs and the excessive fuel consumption of motorcycles are the primary concerns for motorbike taxi drivers. Riders generally view e-bikes as a favorable alternative to avoid excessive fuel costs, and nearly 85% of those interviewed expressed a desire to switch to an e-bike if provided with adequate financial assistance. (Siemens Stiftung, 2020b).

Furthermore, the research also examined the preparedness of motorbike taxi drivers to switch to e-bikes. It discovered that only 7% of those surveyed were willing to borrow e-bikes, while 30% preferred to purchase them outright. The study also revealed that 62% of riders would consider renting an e-bike, indicating the potential market for an e-bike leasing business model. However, riders expressed concerns about several e-mobility issues, including a lack of knowledge and trust in the technology, battery dependability, and inadequate charging infrastructure.

Mbita

Mbita was selected as the research location because it fulfilled the selection criteria for a case study location, such as the potential for short-range electric vehicles. The town is situated on the shores of Lake Victoria in Homa Bay County (see **Figure 6**).

It is mostly a rural area with a total size of 163.28 km^2, and it is located around 400 km west of Nairobi, Kenya's capital. The International Centre for Insect Physiology and Ecology (ICIPE) research facility, Tom Mboya Mausoleum, Remba Island, Mfangano Island, Rusinga Island, and other tourist sites are all located in *Mbita* (Ochieng, 2017).

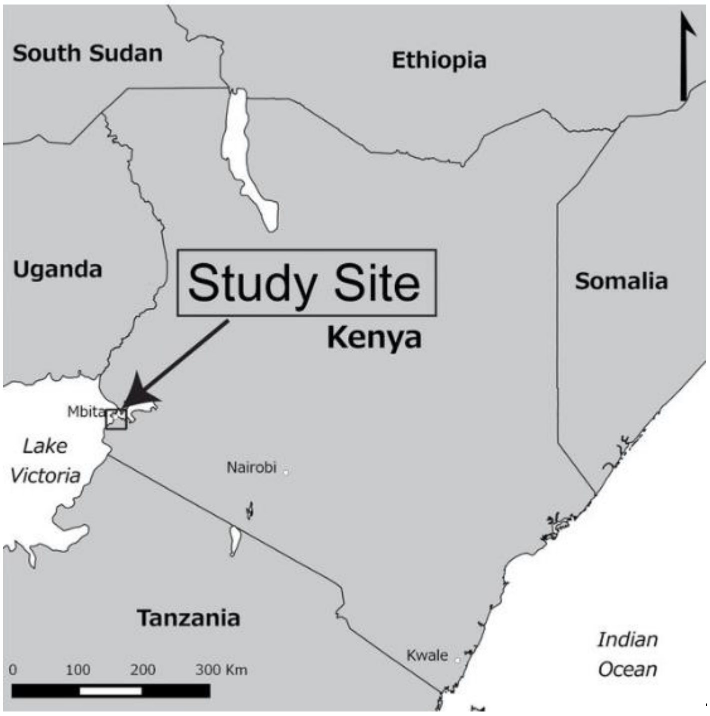


Figure 6: Mbita - Case study location (Tomonori *et al.*, 2016).

Commerce is a significant source of income for the people of Mbita town, and they depend heavily on it. Additionally, fishing is a vital economic activity in the Homa Bay area, which has more than 80% of Kenya's Lake Victoria beachfront. Mbita town is primarily a fishing area, with over 80% of the population being fishermen (Ochieng, 2017).

Despite the importance of fishing to the economy of Homa Bay County, fishermen on Lake Victoria still rely on traditional gasoline boat engines that are known to be unreliable and emit over 400,000 tons of CO_2 annually. The use of gasoline also poses a risk of oil leaks that can have harmful effects on the lake's ecology and drinking water. Furthermore, there are approximately 20,000 fishing boats operating on Lake Victoria, with night-time fuel costs ranging from $15 to $25 per boat, depending on the size of the engine (Hönig and Gregor, 2018).

The transportation sector is a crucial source of income for Mbita town, with motorcycles being the most commonly used mode of transportation. These motorcycles are used to transport people and goods within short distances, as well as to Kisumu, which is the largest city in the region (Ochieng, 2017).

Although motorcycles are the primary mode of transportation in Mbita town, they have negative externalities such as noise pollution and increased greenhouse gas (GHG) emissions that are inefficient for society as a whole (Kumar, 2011). Hence, the transition to electric motorcycles and boat engines can have significant socioeconomic benefits for the poor in Mbita and the broader Lake Victoria region. The adoption of electric vehicles can lower gasoline costs and GHG emissions, preserve aquatic life, and enhance the quality of drinking water in Lake Victoria.

1.4 Research justification, objectives and contribution

1.4.1 Research justification

By 2050, the population of Sub-Saharan Africa is expected to increase fourfold, with more than half of the global population increase occurring in this region. If a shift is not made towards low- or zero-emission vehicles, the rapid expansion of the vehicle fleet will greatly increase air pollution, GHG emissions, and oil import costs. To enable the establishment of the required infrastructure, training, and capacity building for a clean energy future that could support green growth across the African continent, significant investments in the production of renewable energy at a large scale are necessary (Siemens Stiftung, 2020a; United Nations, 2019).

Electrifying minibuses, motorbike taxis, and public transportation in general is expected to have a significant impact because these vehicles cover more distance than other types of vehicles. However, to meet the growing demand and address concerns about range-anxiety, it will be necessary to establish sufficient charging infrastructure (Siemens Stiftung, 2020a).

1.4.2 Research objectives

This PhD research project was proposed to build a sustainable off-grid model based on solar PV technology for charging battery-powered electric mobility and other non-mobile electric loads. The PhD research utilises a WE Hub (i.e. a 30kWp off-grid PV standalone system) owned by *WeTu Limited* in Mbita which is used to supply sustainable power for charging electric fishing lamps and water treatment devices. The integration of the electric mobility concept into the current infrastructure of the WE Hub will help increase the operational region of the WE Hub and to provide new avenues for the power generated. Electric cargo bikes and motorbikes (for delivering treated drinking water, transportation of products, and services) are among the mobility alternatives considered in this study.

Therefore, the PhD aims to achieve the following objectives:

- Analyse the electricity demand and production (with and without e-mobility) at the investigated WE Hub.
- To optimally distribute the charging of the various loads at the investigated WE Hub by maximum utilisation of the solar PV production while using the central batteries as last resort.
- To develop an off-grid solar optimisation design tool that can be used in any given location for non-mobility and e-mobility loads integration.
- To determine the Levelized Cost of Electricity for the off-grid PV system

To achieve the above objective, the following research questions arose:

- Can the existing system sufficiently cover the future consumption loads (e-mobility) at the investigated WE Hub?
- In the case of energy deficit, how best can the different loads charging be possibly distributed throughout the day? This is critical for the sustainable extension of the investigated WE Hub.

To answer these questions, the research followed the methodology shown in **Figure 7**

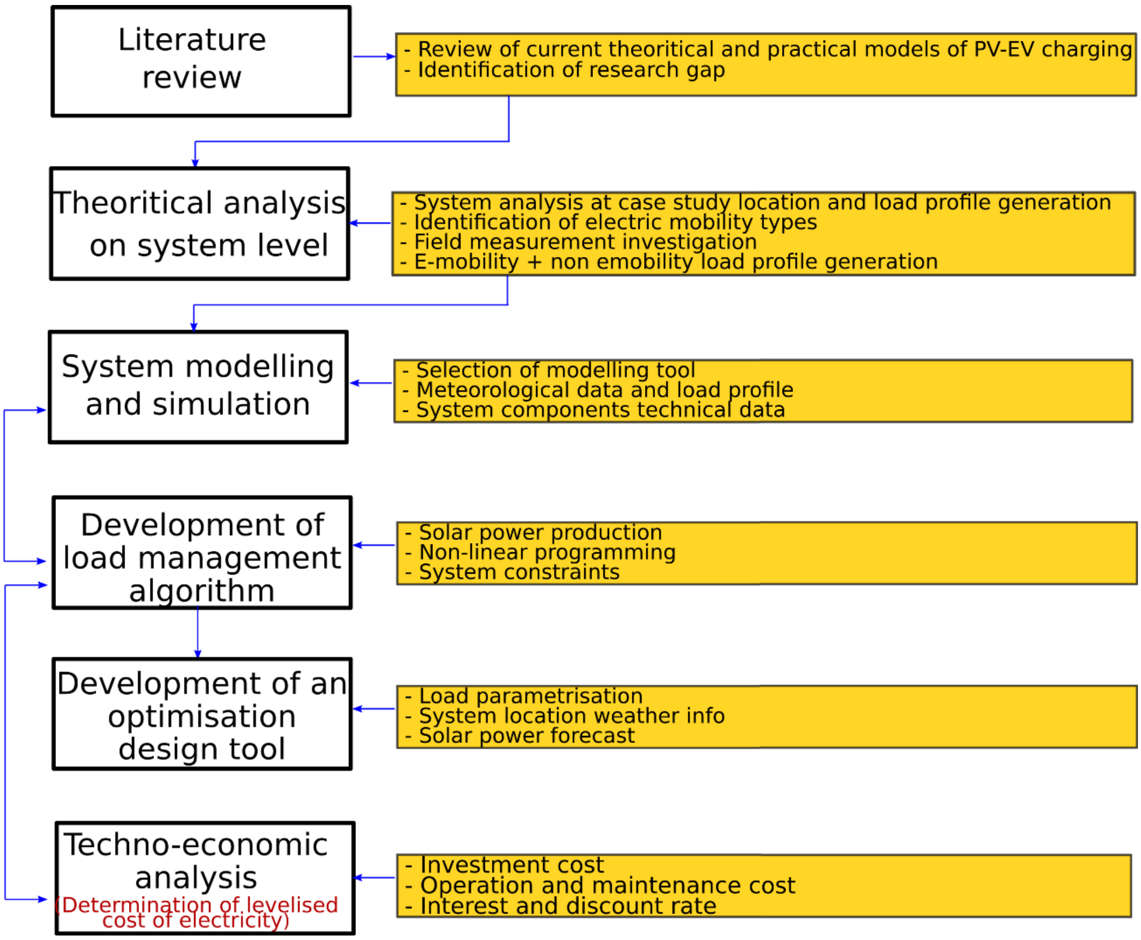


Figure 7: Research methodology.

1.4.3 Research contribution

The study focused on creating a solar PV charging station that can cater to both non-mobility loads and e-mobility battery charging in the Western Kenyan region around Lake Victoria. The goal is to make electric vehicle (EV) market penetration sustainable in Africa by demonstrating that an off-grid PV model that is well-designed, optimized, and economically feasible can work and provide electric mobility charging services in remote areas. This achievement could attract private investors to participate in rural electric mobility electrification projects, allowing communities in developing countries to increase their electrification rates. As a result, governments could meet their goals set under the UN Sustainable Development Goal 7 (SDG 7).

Using Kenya as an example of a developing country with a bold action plan to reduce transport emissions from 11.25 $MtCO_2$ e in 2015 to 3.46 $MtCO_2$ e by 2030 (Martin *et al.*, 2019), it's critical to think about how to scale up programs that try to meet these goals.

The following is a summary of the key contributions made by the research in answering the research questions posed:

Modelling and investigating the performance of rural off-Grid photovoltaic systems with Electric-mobility solutions

The study involved modeling and analyzing the performance of a rural off-grid PV system (charging station) equipped with electric-mobility solutions (mobile batteries for e-bikes) using MATLAB, Simulink, and CARNOT 7.0 Toolbox. The researchers analyzed the PV electricity generation, consumption, and deficit, and used scenarios to demonstrate how the energy supply and load demand of the WE Hub (charging station) might evolve in the future, considering e-mobility.

The scenarios were divided into two groups based on the typical daily distance traveled and energy usage of electric bikes. Design scenario 2 assumed e-bikes traveled 100 km per day, while scenario 1 assumed only 50 km.

The results showed an annual energy deficit of approximately 350 kWh and 1600 kWh for system design scenarios 1 and 2, respectively, due to the variability of a PV system and its reliance on weather conditions and load charging schedules.

This indicated that the system was unable to meet the entire energy demand, necessitating the implementation of a load management algorithm to optimize the integration of electric mobility options into the WE Hub and avoid the use of a diesel generator to address the energy deficit.

The article outlining this contribution was published in

Bugaje, A., Ehrenwirth, M., Trinkl, C., Zoerner, W., Investigating the Performance of Rural Off-Grid Photovoltaic System with Electric-Mobility Solutions: A Case Study Based on Kenya, 2020 J. sustain. dev. energy water environs. syst., 1090391, DOI: https://doi.org/10.13044/j.sdewes.d9.0391.

Development of a Load Management Algorithm for Optimum Integration of Electric-Mobility Solutions into Rural Off-Grid PV Systems

An optimization problem was transformed into a nonlinear programming (NLP) problem to incorporate electric mobility into the investigated WE Hub. The aim was to maximise the use of PV generation and minimise energy deficit and cost by proposing a load optimisation model that optimizes electric loads, such as electric mobility and battery storage. The load management algorithm successfully collected the maximum variable solar power and scheduled a limited number of devices throughout the day.

The PV system was simulated using an hourly metrological dataset for a year, and the NLP optimisation model was analysed to evaluate the effect of electric loads on the objective function. The system with NLP optimiser was able to distribute the charging schedule of various loads, including e-mobility, throughout the day at the investigated WE Hub with less dependence on central batteries.

Results indicate that the system with NLP optimiser was able to increase annual electricity demand consumption by 11% compared to the system without NLP optimiser. The NLP algorithm also reduced energy deficit present in the non-NLP system by maintaining the same PV capacity and reducing central battery capacity.

The articles outlining this contribution were published in

Bugaje, A.; Ehrenwirth, M.; Trinkl, C.; Zörner, W. Electric Two-Wheeler Vehicle Integration into Rural Off-Grid Photovoltaic System in Kenya. Energies 2021, 14, 7956. https://doi.org/10.3390/en14237956.

A. Bugaje, M. Ehrenwirth, C. Trinkl, K. Baer and W. Zoerner, "Development of a Load Management Algorithm Using Nonlinear Programming (NLP) for Optimum Integration of Electric-Mobility Solutions into Rural Off-Grid PV Systems," NEIS 2020; Conference on Sustainable Energy Supply and Energy Storage Systems, Hamburg, Germany, 2020, pp. 1-6.

1.5 Thesis outline

The thesis is organised into seven chapters and the description of the individual chapter is as follows:

Chapter 2 – Literature review: focuses on the review of the rural electrification situation in Kenya, review of Kenya's transport sector emission, review of renewable energy concepts, review of electric vehicle integration with solar energy, and review of existing works to identify the strengths and weaknesses of the respective methodologies used in solar-electric vehicle charging applications.

Chapter 3 – Theoretical analysis on system level: focuses on system analysis at the case study location (i.e. the investigated *WE Hub*) and load profile generation in line with socio-economic activities of the inhabitants, identification of the type of electric mobilities to be used in line with socio-economic activities of the inhabitants. Field measurement on the selected e-mobility to determine the energy consumption in line with the terrain and socio-economic activities of the inhabitants. Derivation of characteristic loads and driving profiles (on a daily and annual basis) of the electric vehicle(s) at the selected location based on consumer behaviour as well as socio-economic activities such as residential, commercial or agricultural.

Chapter 4 – System modelling and simulation: focuses on the modelling of the PV-EV charging concept based on PV system components considering the different electric mobility demand scenarios from the investigated *WE Hub* using the consumer behaviour, driving profiles and meteorological data.

Chapter 5 – Development of a load management algorithm: presents the development of a load management algorithm to coordinate the interaction between the PV energy production and the EV charging consumption for proper charging scheduling and prioritisation. Potential energy deficit reduction and optimum integration of e-mobility loads into the investigated *WE Hub* charging system were covered in this chapter.

Chapter 6 –Techno-economic analysis: presents the calculated electricity cost for the investigated *WE Hub* charging system

Chapter 7 – Conclusions and recommendations

Chapter 2: Literature Review

This chapter presents a summary on the socio-economic impact of efficient rural transport services, brief overview of mobility in East Africa, Kenya's transport sector emissions and Kenya's rural electrification. Additionally, it presents the concept of renewable energy and several modelling techniques for charging EVs using renewable energy. The emphasis is on the gaps and current approaches in this field.

2.1 Sociological effect of efficient transportation services on rural Sub-Saharan Africa's economic growth

In the last hundred years, transportation systems have had a beneficial effect on the lives of people living in rural areas of sub-Saharan Africa. However, the extent of their impact on reducing poverty and promoting economic growth has been inconsistent, varying across different regions, periods, and social groups. (Porter, 2013).

After roads were built in various parts of Africa, particularly in major open and market regions, motorized transportation services developed rapidly in the first half of the 20th century. During the colonial era, trucks were often used to provide feeder services to railways, which were crucial for transporting agricultural commodities and minerals for export. However, large areas still lacked all-season roads, which made motorized transportation services inaccessible. As a result, most food for domestic consumption and a large portion of produce for export were transported by women and children who carried them on their heads. In most cultural contexts, porterage was considered a job for women and their children. (Porter, 2013).

Although the features of this structure of transportation services have evolved since Independence, many of its more general characteristics remain. One of the most significant changes was the collapse of rail transport systems in many areas, particularly in West Africa, while road development and more adaptable motorized road transport services increased. The vehicle stock has evolved, but because rural transportation services frequently need to accommodate many passengers travelling with their freight, there has been a persistent and widespread reliance on cars with large cargo capacities, whether they were traditional wagons in earlier times or imported used minibuses in more recent times (Porter, 2013). **Figure 8** shows rural women and children waiting for a vehicle to transport agricultural products to market.

Figure 8: Rural women with children await transport vehicle (George *et al.*, 2012)

The proliferation of motorbike taxi services, which picked up steam in the 1990s, has likely been the most recent and significant shift in rural transportation services in many countries. These are still spreading into more isolated rural regions today, especially because of the accessibility of inexpensive imported motorbikes. This development is particularly remarkable because it coincided with the growth of mobile phone connectivity and the purchase of phones, especially amongst low-income rural people (Porter, 2013).

The ability to request transportation may be available to a sizable proportion of rural individuals, even those who are extremely impoverished. People who live in rural areas experience a transformation in transport as a result of the increased levels of connectivity, with more people now able to access transportation in an emergency even when they cannot afford it routinely (Porter, 2013).

2.1.1 Impacts of transportation services on job creation and poverty

Although there aren't many reliable socio-economic evaluations that indicates the actual scale of the advantages provided by roads or by transportation services on direct job creation or other aspects of rural life. It is undeniable that transportation services have had a positive impact on poverty alleviation and growth among rural populations.

Numerous, extremely underprivileged rural residents earn a direct living by offering transportation services (Porter, 2013).

For some impoverished young men and boys, cart pushing, commercial pedestrian porterage, and comparable jobs (such as minibus call boys, bicycle mechanics, and tyre vulcanizers) have proven to be a significant source of income. They currently operate motorcycle cabs for companies, typically on a temporary contract. There is evidence that suggests this occupation may be keeping young men in the village in some rural places [like the Kibaha district in Tanzania] where otherwise they might migrate to the metropolis in search of work (Porter, 2013).

2.1.2 Impacts of transportation on economic growth: employment in agriculture

Transportation services are crucial for the transportation of commodities in areas with prolific agriculture. This could involve moving food using Intermediate Means of Transport (IMT) like animal-drawn carts, bicycles, push carts or human load-carriers, particularly when it comes to moving it between production locations and marketing facilities. IMTs continue to serve a significant role in many places, especially for more affluent male farmers, despite the general preference for motorized transport (Porter, 2013).

According to surveys conducted throughout Africa, an all-season road is more likely than a poor road to be associated with regular transportation services. If food production conditions are optimal, farmers will produce significantly more yield and experience related economic success than people living in more remote areas with poor access. This is true even though the majority of research on market access places lay more emphasis on the importance of transportation services than on how roads connect to marketplaces. To provide enough market access while food is still in good condition, motorized transportation frequently plays an important role in lowering journey times for perishable items like tomatoes, cassava, or plantains (Porter, 2013). **Figure 9** shows a gasoline-powered cargo motorcycle transporting farm produce.

Figure 9: Motorcycle transporting farm produce (Ron and Keith, 2017).

2.1.3 Impacts of transportation on economic growth: employment outside of agriculture

Due to the importance of off-farm income and employment to the rural economy in alleviating poverty, researchers can speculate that stable, dependable and inexpensive transport service is expected to be of significant relevance in facilitating travels to marketplaces and work (Porter, 2013).

Unquestionably, providing reliable, frequent, and affordable transportation is essential to developing a prosperous business. Women in particular commonly rely upon small trade for a basic, reliable income despite the low returns. Even though they frequently have to travel great distances to access local marketplaces, they could be able to with better prices, travel to marketplaces that are farther away when sufficient transportation is available. Due to the increased availability of mobile phones, many traders—including small business owners—can now use transportation services more efficiently (Porter, 2013).

2.1.4 Impacts of transportation on healthcare access and education

A population that is educated and in good physical condition would have great potency in reducing poverty and fostering economic progress. There is emerging evidence indicating transportation services specifically influence how people attend healthcare institutions. The importance of transportation is particularly clear when it comes to emergency maternal health situations, but even for basic care, commute time has a considerable impact on clinic attendance rates (Porter, 2013). Access to maternity care, ARV therapy, and vaccination services are all enhanced by affordable, efficient transportation.

Figure 10: Rural ambulance motorcycle (Ron and Keith, 2017).

In rural areas where schools are often few and far between, having access to transportation is crucial for formal education. Improved transportation services have been shown to have a positive effect on the attendance rate of girls in both primary and secondary schools.

Having good transportation connections can facilitate the formation and maintenance of social networks, which are often critical for accessing resources such as money for education, employment opportunities, and general welfare. Along with economic activities, the widespread use of mobile phones in Africa has also promoted social networking at both the individual and community levels. Despite the ability to communicate remotely, strong social ties still appear to require regular face-to-face interactions, which are made possible by transportation.(Porter, 2013).

Reliable and efficient transportation services also serve a crucial de-isolating purpose by influencing how people view rural living and so enhancing the standard of services. In addition to providing services to rural residents who require them, they also encourage and permit essential service workers—such as educators, healthcare professionals, and specialists who are based in urban areas—to commute to work in rural areas every day and consequently deliver regular services (Porter, 2013).

2.2 Mobility in East Africa

The literature analyzed in the publication of (Galuszka *et al.*, 2021) focuses on four case study cities in Eastern Africa, namely Dar es Salaam, Nairobi, Kisumu, and Kigali. These cities are considered to be vibrant economic and cultural centers in the region. According to the (KNBS-Kenya National Bureau of Statistics, 2019), Nairobi has a population of 4.4 million, while Dar es Salaam has a population of 6.4 million according to the (United Nations, 2018), and Kigali has a population of 1.29 million according to the United (United Nations, 2016).

Kisumu is the third-largest city in Kenya, with a county population of approximately 1.1 million and an urban population of around 567,963. While these cities differ in terms of geography, activities, and size, they share similarities in the stages of urban development they are going through. (Galuszka *et al.*, 2021).

Similarly, over the years, the population growth in the cities was rapid (Kisumu by 1.63 % on average from 2000 to 2015 (Zhongming *et al.*, 2020), Nairobi by 3.8%, Dar es Salaam by 5.4%, and Kigali by 4.2 % on average from 2000 to 2018 (United Nations, 2018)).

Similarly , the population of the cities studied in this literature has grown rapidly over the years. Kisumu, for example, experienced an average population growth of 1.63% from 2000 to 2015 according to (Zhongming *et al.*, 2020). Nairobi's population grew by 3.8%, Dar es Salaam's by 5.4%, and Kigali's by 4.2% on average from 2000 to 2018 according to the (United Nations, 2018).

A considerable portion of this growth is concentrated in peri-urban informal settlements. For example, it is estimated that 62% of Kisumu's population resides in informal settlements. In Nairobi, the spatial arrangement that remained from colonial times reinforced socio-economic segregation and significant disparities in residential density, with half of the city's population occupying only 5% of the total residential area (Klopp and Cavoli, 2017).

Kigali's intensive infrastructure renovation programs have resulted in waves of evictions and a concentration of impoverished residents in the remote districts (Baffoe *et al.*, 2020). The urban sprawl in Dar es Salaam is also very extreme (Peter and Yang, 2019).

The modes of transportation in Nairobi and Kisumu show some similarities in terms of the high proportion of walking and group transportation. These modes of transportation have developed over the past few decades. In Nairobi, unofficial private minibuses, semi-formal buses, and walking are the most common modes of transportation, accounting for 28.5%, 12.2%, and 39.7% of the modal share in 2013, respectively (NCC-Nairobi City County, 2015). In Kisumu, formal public transportation schemes are inadequate, and walking (52.7%), moto-bodas (13.5%), and matatus/buses (13%) are the most popular modes of transportation (Institute for Transportation and Development Policy, 2021).

Similar statistics may be found in Dar es Salaam, where in 2014, daladalas (minibuses), walking, and private automobiles accounted for 62% of journeys (City of Kigali, 2019). The bulk of trips in Kigali are performed on foot, by bicycle, or by public transportation, mostly bus services (16 %) but also motorbike taxis (12 %). Another distinguished transport profile of the city is the low motorization levels (about 15 cars per 1000 people) (City of Kigali, 2019).

The aforementioned cities have begun significant investments in public transit to varying degrees, except for Kisumu, which is preparing to conduct a study for a future public transportation project.

With the assistance of the World Bank, Dar es Salaam is now working on the Urban Transport Improvement Project, and its bus rapid transit (BRT) system's first phase was introduced in 2016 (Galuszka *et al.*, 2021). A variety of actions are being considered or have already been taken in Nairobi to enhance the mobility situation. This includes the upcoming BRT services, the renovation of the equipment and vehicles used by the railways, and the enhancement of the non-motorized infrastructure, particularly in the city centre. Road and street infrastructure have developed remarkably in Kigali as a result, investments in public transportation grew to serve the majority of urban travellers (Galuszka *et al.*, 2021).

As semi-formal transport providers have historically served as an important part of transportation service in the aforementioned cities, this engagement now varies across the cities. Kigali has the most progressive process. Around 2005, the city implemented the first restructurings leading to decreases in motorcycle taxis and push taxis (Goodfellow, 2015). The City of Kigali Authority launched additional public transportation reform in 2008, which resulted in the regulation of the contracts of bus operators in 2013. Motorcycle taxis now compete with public transportation buses on the same routes, but they augment public transportation buses by delivering door-to-door on-demand trips to numerous areas around the city (Galuszka *et al.*, 2021).

Dar es Salaam's public transportation is mostly covered by a huge fleet of private minibuses (daladala) that informally operate with frequently unorganized timetables and route offerings (Paul and John, 2020). Motorized three and two-wheeler taxis (bajaji and boda bod respectively) are fairly frequent in addition to these bus services. They are used by the general public for shorter distances and provide feeder connectivity to paratransit vehicles. Motorcycle taxis are the sole publicly available method of transportation in places not served by buses, and thus provide substitute public transit service, filling a vacuum in the transportation sector.

As a response to the city's mobility issues, authorities in charge of the sector have in recent years proposed to eliminate mini-buses on all main routes and substitute them in the mid to long term with bus rapid transit (BRT) (Nkurunziza *et al.*, 2012). In the interim, the existing BRT projects launched in 2016 in the city are intended to coincide with the transformation of present commercial transportation services and their incorporation into Dar es Salaam's comprehensive public transportation system (World Bank, 2017).

With little urban planning for paratransit, Nairobi's predominant means of collective transportation—walking and public transit—are carried out in subpar circumstances, with no sidewalks, bus services, and oppressive or non-existent public regulation (KLOPP and Mitullah, 2015). Additionally, planning has come under pressure as it emphasizes significant road transport schemes and top-bottom methodology that excludes civil society involvement (Klopp; United Nations, 2018). Efforts to govern boda-bodas moto-taxis were made by the public sector but were generally ineffective. Recent initiatives to tighten control over the transportation sector include controversial attempts to remove matatus from city centres and bus route licenses (Nairobi City County, 2019).

Since Kisumu lacks a reliable public transportation system, privately run matatus (minibuses) fill the gap. Through fees paid to the Kisumu County Government, the matatu business creates substantial employment and revenue for the government. Moreover, there is an upsurge in two-wheeler (motorbikes and bicycles) and three-wheeler vehicle operations, which are mostly run by working-class citizens but are a crucial part of Kisumu's transportation ecosystem. They complement the matatus by offering on-demand travel to many major cities as well as the rural areas around the city (Galuszka *et al.*, 2021).

2.3 Transport sector emission in Kenya: The necessity for electric vehicles

Kenya is experiencing substantial growth in the transportation industry, similar to the global trend. The government has invested heavily in infrastructure to solidify the country's position as the primary transportation and development hub in East Africa (Ministry of Transport and GIZ, 2019). The vehicle fleet has increased significantly since 2014, with over 2.5 million vehicles registered, and more than 200,000 new units added each year annually (Kenya National Bureau of Statistics, 2019). While this growth has facilitated economic development and improved social connections, it has also brought several challenges, such as air and noise pollution, traffic congestion, increased petroleum imports, and resulting greenhouse gas emissions (Kenya National Bureau of Statistics, 2019).

Second-hand automobiles imported from the United Kingdom or Japan dominate the country's automotive market. According to the Traffic Index 2019, Nairobi is the fourth-worst city in Africa in the world in terms of total traffic system inefficiency (Numbeo, 2019). These traffic jams and congestion cost the economy 50 million Kenyan shillings per day in lost productivity (Faizal, 2019) and have led to respiratory illnesses being the major cause of morbidity in 2018, accounting for 39 % of all disease incidences (Kenya

National Bureau of Statistics, 2019). The transportation sector accounts for around 13 % of the country's overall transportation emissions and is increasing faster than any other sector thus increasing the amount of GHG emissions which leads to extreme weather (Government of Kenya, 2015).

Kenya's domestic transportation sector generated about 11.25 $MtCO_2$ e of total CO_2 emissions in 2015 (see **Figure 11**). By 2030, Kenya wants to reduce emissions from the transportation sector to 3.46 $MtCO_2$ e. As a result, the yearly emissions should not rise by more than 0.4 MtCO2 e to meet the objective. However, between 2010 and 2015, the average yearly emissions rose by 0.6 MtCO2 e, putting the sector off the path to fulfilling its 2030 objective (Martin *et al.*, 2019).

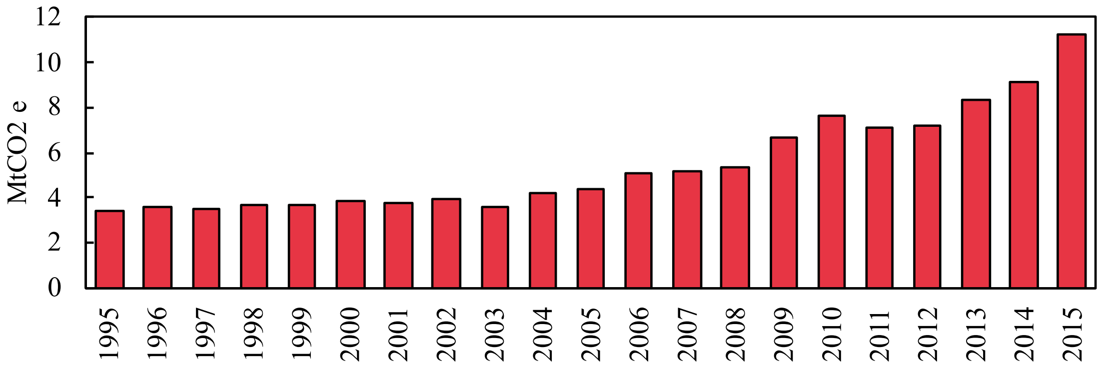


Figure 11: Kenya's road transportation sector CO_2 emissions ($MtCO_2$ e) (Martin *et al.*, 2019).

Additionally, the most common form of transportation for Kenyans in both urban and rural areas are 2 and 3-wheel motorbikes. With a market share of over 95 %, two major Indian motorcycle manufacturers, TVS and Bajaj, dominate the Kenyan 2 and 3-wheeler market (Eshiwani, 2019). Many of these 2 and 3-wheelers are powered by internally combustible engines which are outdated and inefficient, producing more CO_2 emissions than a passenger vehicle (Siemens Stiftung, 2020a).

The Kenyan government has outlined its strategy for establishing a sustainable transportation system and meeting the objectives of the National Climate Change Action Plan (NCCAP). To accomplish these goals, the government is proposing a Light Rail Rapid Transit (LRRT) and Bus Rapid Transit (BRT) system, expanding the Standard Gauge Railway (SGR), and promoting Non-Motorised Transport (NMT) such as cycling and walking. The country is also actively working towards electrifying its vehicle fleet to minimize greenhouse gas (GHG) emissions generated by the transportation sector.

Moreover, the government has offered tax incentives in the form of the Finance Bill 2019, which reduces the excise tax charged for all-electric vehicles from 20% to 10% (Siemens Stiftung, 2020a). The Kenyan Bureau of Standards began revising the regulations for registering new imported cars in 2017. New cars will only be allowed for use in Kenya if they release little carbon monoxide or other fine particulate matter into the environment, according to the re-standardization policy. In addition, Kenya has begun to establish a policy on the usage of two and three-wheelers to transition to electric motorbikes, with numerous pilots being conducted in Western Kenya by Kenya Power, UN Environment, and the Siemens Stiftung (Eshiwani, 2019; Siemens Stiftung, 2020a).

The Finance Bill 2019 introduced tax incentives in Kenya to promote the use of all-electric vehicles, lowering the excise tax rate from 20% to 10% (Siemens Stiftung, 2020a). Additionally, the Kenyan Bureau of Standards has revised its regulations for new imported cars, allowing only vehicles with low emissions of carbon monoxide and fine particulate matter. To transition to electric motorbikes, Kenya is also piloting policies for the use of two and three-wheelers, with multiple pilots underway in Western Kenya by Kenya Power, UN Environment, and Siemens Stiftung (Eshiwani, 2019; Siemens Stiftung, 2020a).

The Kenyan government is also ready to assist private sector efforts such as Drive Electric, an electric vehicle consultancy business, and Nopia Ride, an electric vehicle sharing company, which have pioneered the usage of EVs in Nairobi (UEMI, 2020b)). Kenya's recent advancements highlight the significance of creating suitable frameworks to incorporate new mobility solutions into long-term policies and establishing favorable conditions for the growth and expansion of future technologies and business models, regardless of whether they are led by large international corporations or small local start-ups. (World Economic Forum, 2018). Electric mobs may be made more accessible by increasing public awareness and installing charging infrastructure (Siemens Stiftung, 2020a).

2.4 Kenyan's rural electrification

Kenya's government has set a target of achieving nationwide energy access by 2022, as part of Kenya's Vision 2030 (Thomas *et al.*, 2018). Kenya presently generates over 2700 MW, with over 80% of that coming from renewable sources (Obura, 2019). As of the end of April 2018, the country's electrification rate was about 73.4 % (Kenya Power, 2018). Kenya's electrical supply mix is shown in **Figure 12** (Ministry of Energy, 2019).

However, the geographical distribution of Kenya's population poses a significant difficulty in access to electricity. About two-thirds of the populace lives in the southern region, which has the majority of Kenya's fertile cropland and is connected to the national grid. Though the other one-third of the country is dispersed across the semi-arid north and country's dry regions, which are sparsely populated, and that makes it so expensive to connect to the national grid. Expansion of decentralised electricity generating and distribution networks, such as mini-grids and off-grid solutions, is one possible way forward (Thomas *et al.*, 2018).

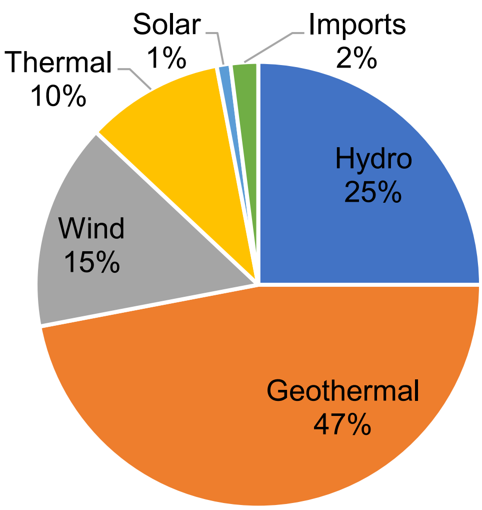


Figure 12: Kenyan electricity supply mix (Ministry of Energy, 2019).

Kenya has a long history of using mini-grids, which are a type of off-grid power system. The first mini-grids were built at the beginning of the 1980s when the government introduced the rural electrification agenda to subsidize energy costs in rural areas and prioritized rural electrification. Kenya's mini-grids have traditionally been diesel-powered and managed by Kenya Power and Lighting Company, the country's largest utility (KPLC) (Thomas *et al.*, 2018).

However, solar and wind energy generation has become more affordable alternatives to diesel for mini-grids due to the fast-falling costs of renewable energy technology and the abundance of renewable energy resources in Kenya (Szabó *et al.*, 2011).

Kenya has a solar photovoltaic power potential of more than 5 kWh/kWp per day, with a maximum annual global irradiation of almost 1,899 kWh/m^2, as shown in **Figure 13**. The research case study is located in Kisumu city in Western Kenya, which has a solar potential of around 4.8 kWh/kWp per day and annual global irradiation of about 1,753 kWh/m^2, as can be seen in **Figure 13**.

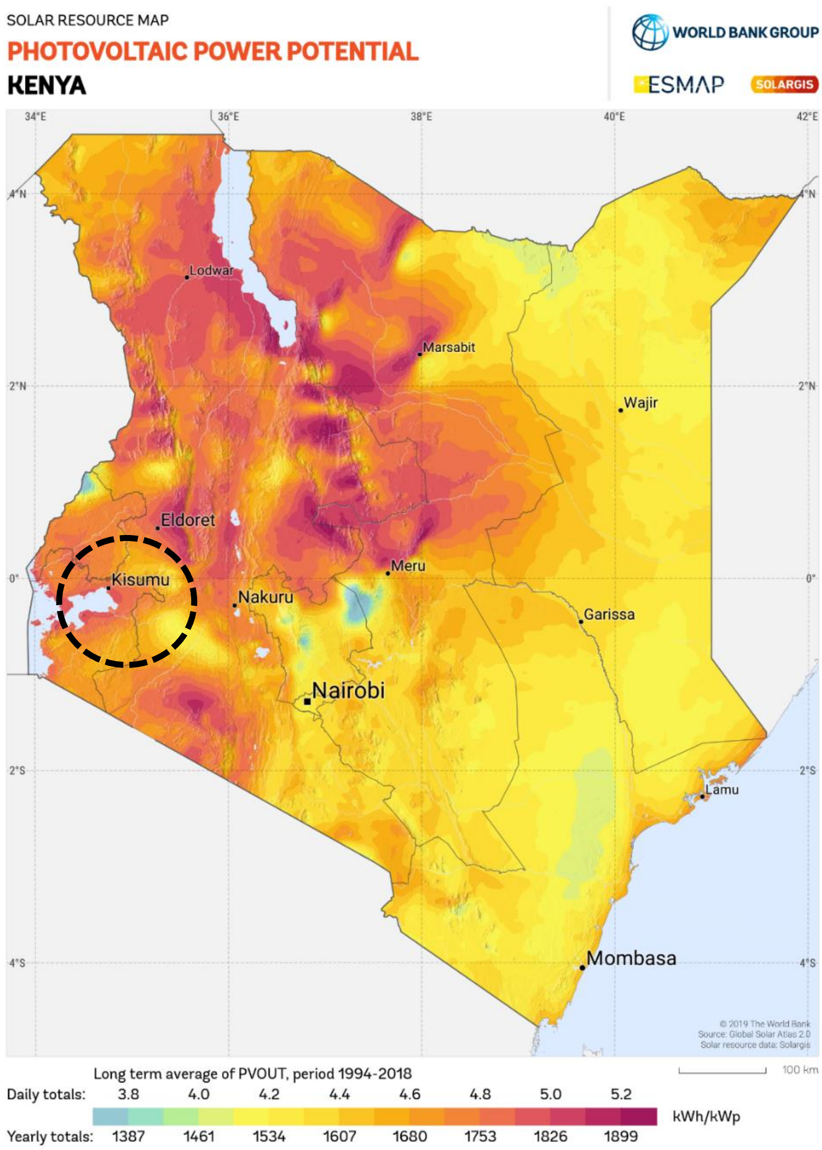


Figure 13: Map of Kenya showing annual average solar photovoltaic potentials (World Bank, 2020).

It's interesting to note that several new renewable energy-based mini-grids have been built since 2011, while some diesel-operated mini-grids have been converted to hybrid systems with a solar or wind power component. (Thomas *et al.*, 2018; AHK Kenya, 2016).

The majority of Kenya's large-scale mini-grids are operated by the national utility company. The national power supply is made up of a grid-connected system and 21 state-owned mini-grids, 19 of which are operated by the Rural Electrification and Renewable Energy Corporation (REREC) and the other two by the Kenya Electricity Generating Company (KenGen). The mini-grid energy prices are the same as those on the national grid, and the higher running expenses of the mini-grids are partially subsided by the "Rural Electrification Programme fee," which is paid by other national grid customers (Ministry of Energy and Petroleum, 2016; Thomas *et al.*, 2018).

Several international partners are vigorously supporting mini-grid initiatives in Kenya, with a particular focus on financing and policy. The Kenya Electricity Modernization Project (2015–2020, KEMP) and Kenya Power Extension Project (2010–2017, KEEP) are two other projects funded by the World Bank in the electricity industry (Thomas *et al.*, 2018).

German Development Bank in collaboration with GIZ, is investing EUR 22.5 million in the ProSolar Programme to promote solar-hybrid mini-grids in rural regions. Following the success of a test project in Talek County, three further mini-grid development project locations have been chosen, with a 690 kW capacity (GIZ, 2016). EUR 2.1 million has been set available under the Energising Development Results-Based Financing for Mini-Grids program to encourage private investment in solar PV mini-grids (Mutonga, 2019).

2.5 Overview of renewable energy

Renewable energy sources are naturally occurring and replenishable sources of energy. Due to their widespread distribution, it is possible to generate energy in remote locations without the need for large transmission networks (Leon and David, 2008). Renewable resources include, for example, (US Energy Information Administration, 2020; Jane, 2020): Hydropower, wind, tidal, geothermal, solar and biomass which comprises biodiesel, wood; biogas; biodiesel and ethanol.

Figure 14 depicts the planet's major energy channels through which renewable energy may be obtained. It suggests that the sun is the primary source of easily accessible renewable energy (Leon and David, 2008). Hence, the decision to choose solar as the energy source for the case study location of this research.

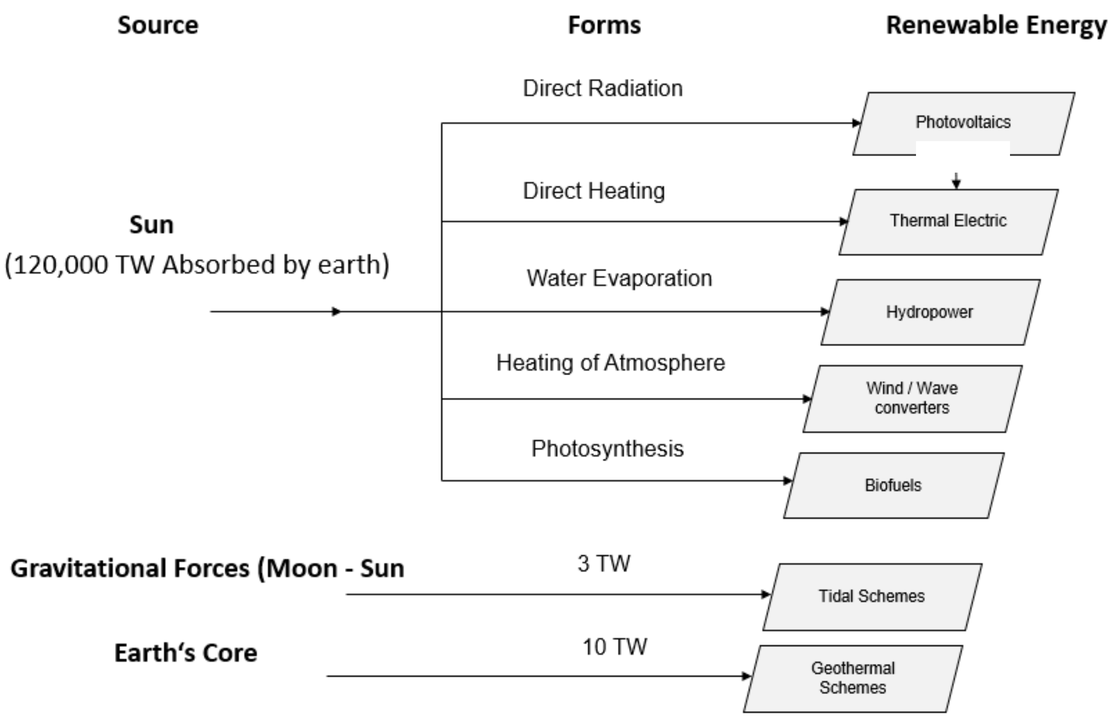


Figure 14: Planet's major energy sources of renewable energy (Jane, 2020).

Renewables have numerous advantages in addition to their capacity to create energy in remote places, including:

i. They are inexhaustible and sustainable and cleaner than fossil fuel-based energies.

ii. In comparison to typical mechanical generators, renewable energy plants may require less maintenance.

iii. Renewable energy may be a reliable source of electricity if adequate planning and infrastructure are in place. Renewable energy sources provide much-needed flexibility in power generation, reducing reliance on fossil fuels (Jane, 2020; Francesco *et al.*, 2013).

2.6 Overview of photovoltaics

2.6.1 The photocell

Sunlight is converted by photocells in a photovoltaic (PV) system to produce energy (M. G. Villalva *et al.*, 200). This is achieved when two semiconductors (i.e) monocrystalline or polycrystalline layers are combined and doped such that one layer (known as an n-type) has more electrons while the other layer (known as a p-type) has fewer electrons (M. Villalva and J. Gazoli and E. Filho, 2009). An ultimate result is the p-n junction and is shown in **Figure 15**.

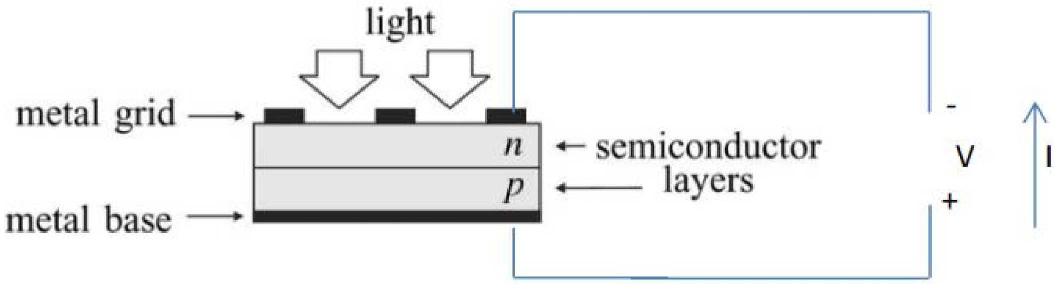


Figure 15: Concept of a PV Cell.

When the sun's radiation is present, additional electrons are produced from the n-type layer. The electric field at the p-n junction, on the other hand, repels these electrons. The electrons will be able to travel from the n layer to the p-layer if an external circuit is available. As a result, a current flow from the positive to negative terminals. **Figure 16**, as illustrated in (L. Eduardo, 1994), can be used to depict the solar cell's equivalent electrical circuit. It comprises a current source connected to a diode in series. The series resistor *Rs* and the shunt resistor *Rsh* are used to compensate for any losses in the solar cell.

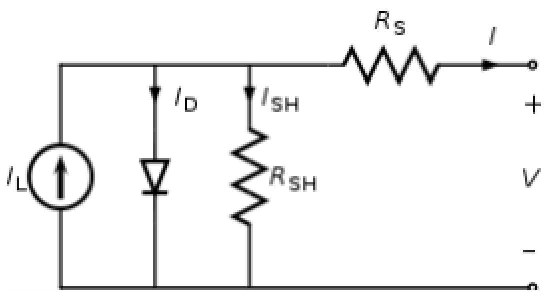


Figure 16: Concept of a PV Cell (L. Eduardo, 1994).

The equation (T. Khatib and W. Elmenreich, 2016) shows the current provided to the load connected to the solar cell.

$$I = I_L - I_D - \frac{V + IR_s}{R_{sh}}$$

(2.1)

Shockley's equation (A. Martí, J. L. Balenzategui, and R. F. Reyna, 1997) may be used to describe the current I_D diverted by the diode, and its temperature (T) dependent on the p-n junction. k is the Boltzmann constant, and the electron charge is q in equation (2.2).

$$I_D = I_0 - \left(e^{\frac{q(V+IR_s)}{nkT}} - 1\right)$$

(2.2)

(*q*=1.60217646 × 10−19 C), (*k*=1.3806503 × 10−23 J/K), The p–n junction temperature is *T* (in Kelvin), and the ideality constant of the diode is *n*. The resulting I–V curve is shown in **Figure 17**. Therefore;

$$I = I_L - I_0 - \left(e^{\frac{q(V+IR_s)}{nkT}} - 1\right) - \frac{V + IR_s}{R_{sh}}$$

(2.3)

Because R_{sh} is infinite and R_s = 0 in an ideal solar cell, the current supplied to the load is given by equation (2.4).

$$I = I_L - I_0 - \left(e^{\frac{q(V+IR_s)}{nkT}} - 1\right)$$

(2.4)

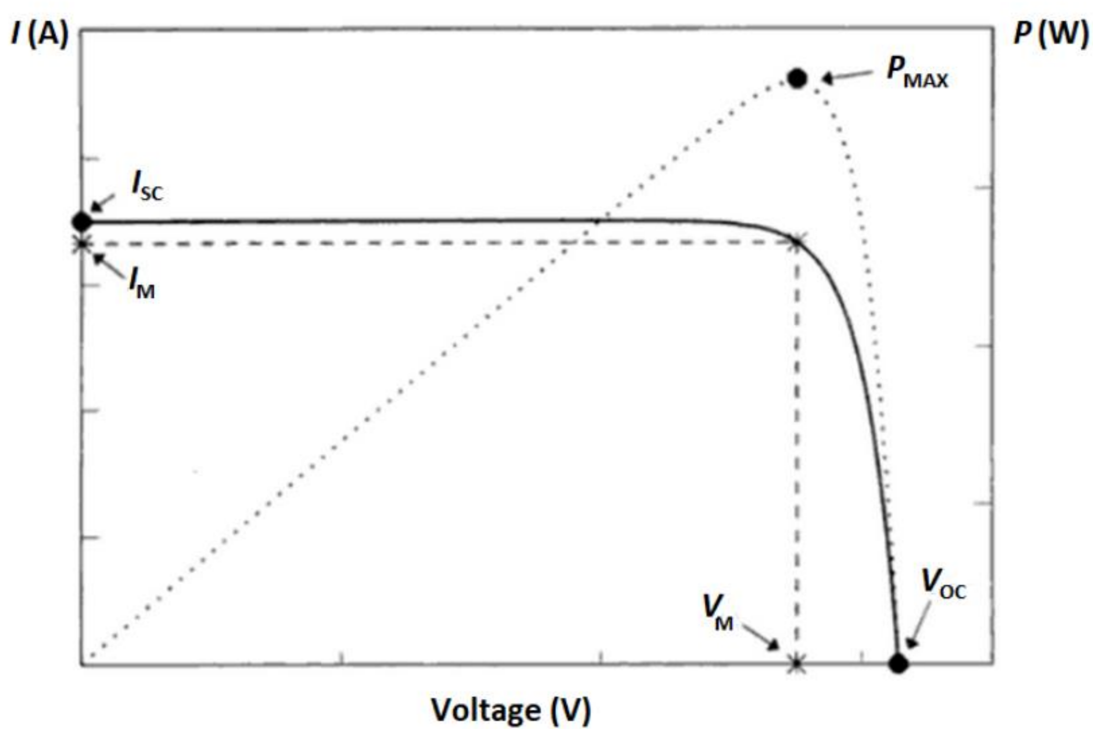


Figure 17: I-V curve of a solar PV Cell (L. Eduardo, 1994).

(V_{oc}) the open-circuit voltage, (I_{sc}) short circuit current and (P_{max}) maximum power point which is a product of I_{sc} and V_{oc}, are all important properties of the solar cell that are explained by this graph. When there is zero voltage, the cell reaches its peak current, as illustrated in the graph. When there is a short current, the cell reaches its peak voltage (Jane, 2020).

2.6.1.1 PV module

The series and parallel connection of PV cells make up a PV module (T. Khatib and W. Elmenreich, 2016). The number of parallel cells determines the module's current output, whereas the number of series cells determines the voltage output. For example, Np is the number of cells in parallel, Ns is the number of cells in series, Vc and Ic are the voltage and current outputs of one cell, and the voltage and the current from the PV module are shown in equations (2.5) and (2.6).

$$I_M = N_P \times I_C \tag{2.5}$$

$$V_M = N_S \times V_C \tag{2.6}$$

(T. Khatib and W. Elmenreich, 2016) elaborates further that the PV module's current output is dependent on the amount of solar irradiance. Nevertheless, when as the temperature increases, the output of the voltage decreases, and hence the output power decreases. Solar irradiance affects the module's cell temperature, and the equation represents the connection between voltage and temperature (2.7).

$$T_c(t) = T_{amb}(t) + G(t) \times \frac{NOCT - 20}{800} \tag{2.7}$$

Where Tc is the module’s cell temperature, *NOCT* is the operating cell temperature for a 20°C ambient temperature, at an irradiance of 800 W/m2, *Tamb(t)* is the ambient temperature, *G(t)* is the irradiance. As a result, the solar panel's power output may be calculated as follows (2.8):

$$P = P_{rated} + ap(T_{sct} - T_{amb}) \times Prated \tag{2.8}$$

Tstc is the temperature (25^oC) at standard test conditions (*STC*), while αp is the power output temperature coefficient. For example, if the cell temperature is 45°C and the coefficient of power is − 0.5%/ ^oC a 300 watts PV module can only produce 270 watts.

2.6.2 Configuration of a solar photovoltaic system

Solar photovoltaic (PV) systems can be configured in a variety of ways. As shown in **Figure 18**, a PV system can be off-grid (standalone), grid-connected (attached to the grid), or hybrid (combining two or more power-producing sources with solar PV systems). Generally, a PV system is made up of solar panels, inverters, battery storage, charge controllers, inverters, and the load. The requirement for inverters and battery storage is determined by the kind of load connected to the PV system.

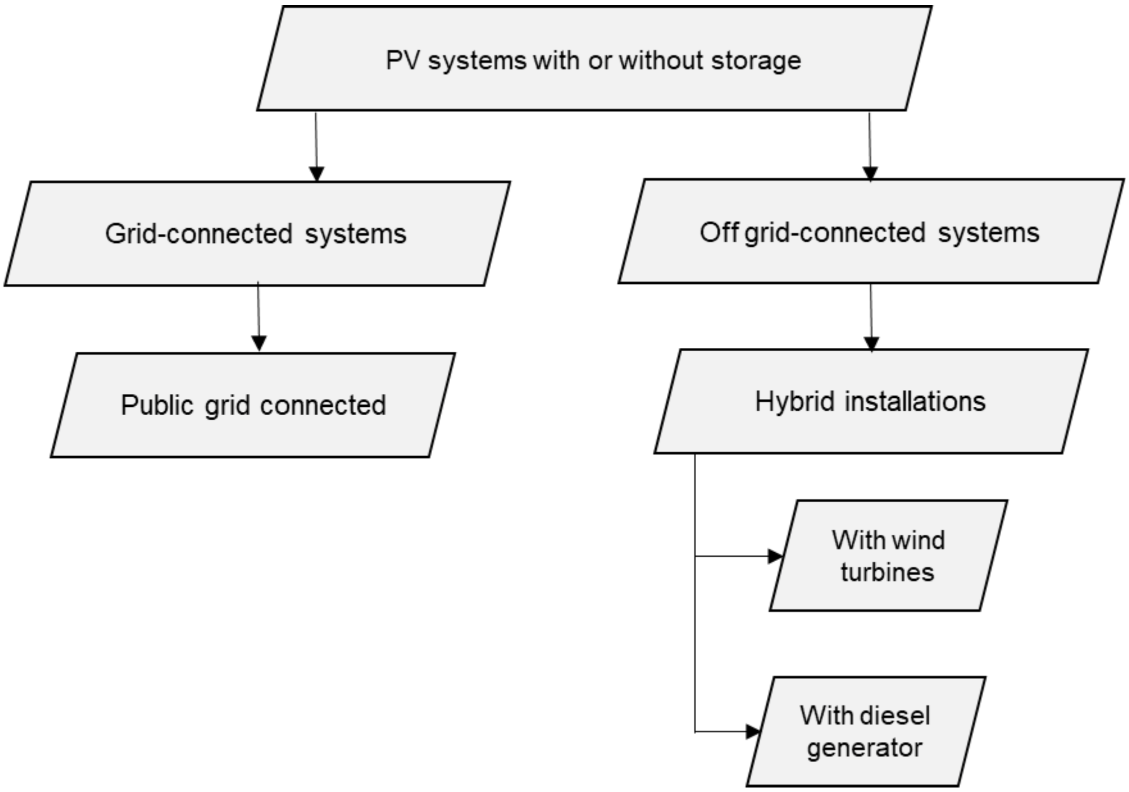


Figure 18: Solar PV Configurations

2.6.2.1 On-Grid System

The majority of homes and businesses use solar systems that are connected into the electrical grid, making them the most widely used solar technology. These systems are powered by solar inverters or micro-inverters and don't need batteries. A feed-in-tariff (FiT) are typically paid to the user for any excess solar electricity exported to the power grid. (Martin, 2016).

On-grid solar systems, unlike hybrid systems, cannot work or generate power during a blackout for safety concerns. Because blackouts often occur when the electrical system is broken, if the solar inverter continued to supply electricity into a damaged grid, it would jeopardize the safety of those working to fix the network's faults. During a blackout, most hybrid solar systems with battery storage may immediately disconnect from the grid (known as islanding) and continue to deliver some electricity (Martin, 2016).

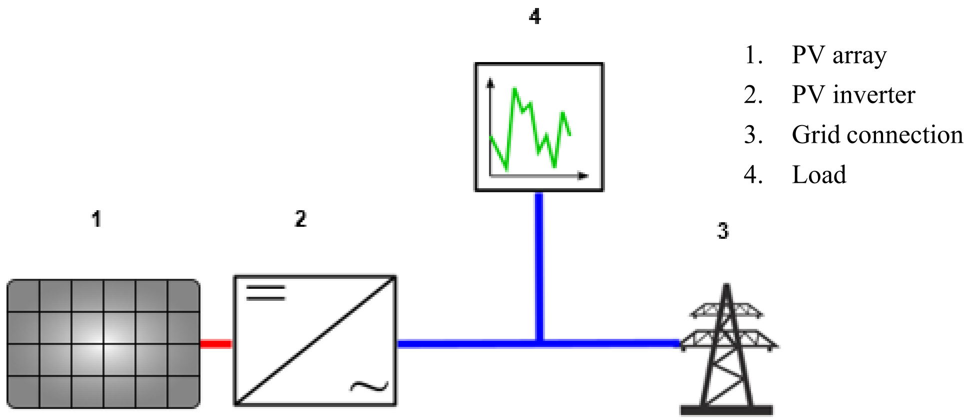


Figure 19: Grid-connected PV systems.

2.6.2.2 Off-grid System

To operate an off-grid PV system, which is a type of solar panel system not connected to the electricity grid, it is important to have battery storage. The design of off-grid solar systems must be able to generate sufficient power throughout the year and possess enough battery capacity to meet the household's energy demands, particularly during winter months when sunlight is limited. During periods of low battery charge and cloudy weather, it is common to use a backup power source such as a generator. The size of the generator (measured in kVA) should be large enough to power the building and charge the batteries simultaneously (Martin, 2016).

Due to the high cost of batteries and off-grid inverters, off-grid systems are much more expensive than on-grid systems. They are therefore usually only required in more remote areas that are far from the national power grid. Though even in cities and towns, the market for off-grid solar battery solutions is growing as battery prices decline (Martin, 2016).

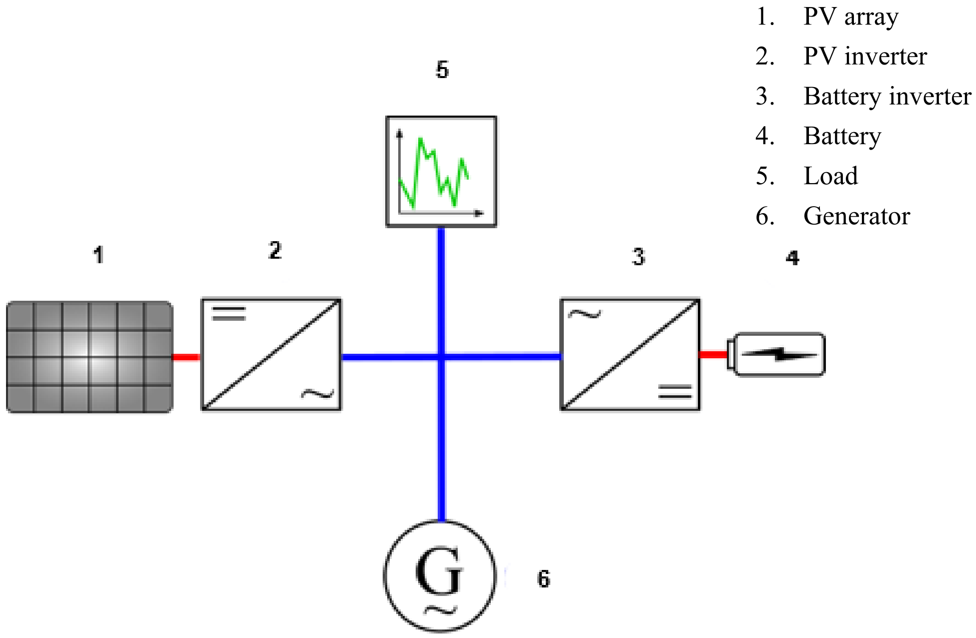


Figure 20: Off-grid connected PV systems.

2.6.3 The typical approach to PV off-grid system sizing

According to research, solar PV microgrids are widely explored and deployed for rural electricity. A crucial element in the design of these PV microgrid systems is sizing system components such as PV modules, batteries, controllers, and other components. (Solar Energy International, 2004) recommends the sizing guidelines for determining the specifications and amount of the technical components needed. The sizing guidelines are divided into six distinct stages, which are outlined below (Jane, 2020; Solar Energy International, 2004).

Step 1: Calculate the electrical load

This entails compiling a list of all the equipment that will be powered by the electricity produced per hour. The electric loads are divided into two categories: Alternating Current (AC) and Direct Current (DC) loads. Then the energy load is calculated in watt-hours.

Step 2: Battery sizing and specifications

The quantity of batteries required is estimated and stated in this stage. According to (Solar Energy International, 2004), equations (2.9) to (2.12) calculate the number of batteries in series (Batteries), parallel batteries (Batparal), and the total number of batteries (BatTotal).

$$Bat_{cap} = \frac{Z \times D_{aut}}{DoD}$$

(2.9)

$$Bat_{parallel} = \frac{Bat_{cap}}{Bat_{AH}}$$

(2.10)

$$Bat_{series} = \frac{V_{dc}}{V_{battery}}$$

(2.11)

$$Bat_{total} = Bat_{parallel} \times Bat_{series}$$

(2.12)

Where Z stands for total daily load, *Vdc* for DC system voltage, *VBat* for nominal battery voltage, *Daut* for days of autonomy, *Batcap* for total storage capacity, *BatAH* for manufacturer's battery rating, and *DOD* for depth of discharge

Step 3: PV array sizing

The total number of PV modules in the PV array, as well as the number of modules in series (PVseries) and parallel (PVparal), are calculated using equations (2.13) and (2.14).

$$PV_{peak} = \frac{Z}{\eta_{bat}\ PSH}$$

(2.13)

$$PV_{parallel} = \frac{PV_{peak}}{I_{mp}}$$

(2.14)

$$PV_{series} = \frac{V_{dc}}{V_{mp}}$$

(2.15)

$$PV_{total} = PV_{parallel} \times PV_{series}$$

(2.16)

PVpeak stands for PV array current, *PSH* for peak solar hours per day, bat for battery efficiency, *Imp* for peak amps per module at STC, and *Vmp* for module nominal voltage. The average solar radiation for the month with the lowest solar irradiance is taken into account when designing the PV module array.

Step4: Selecting a Charger Controller

The charge controller's function is to protect the battery from overcharging from the PV array and undercharging from the load demand below DOD (K. Bataineh and D. Dalalah, 2012; Shukla *et al.*, 2016). It's made to match the voltage of the battery system while also withstanding the current generated by the PV array.

Step5: Choosing and sizing an inverter

The first step in sizing an inverter is determining the amount of continuous current needed by the associated loads. To calculate this, divide the power required to operate the device by the DC system voltage (Solar Energy International, 2004; M. Ishaq and U. H. Ibrahim, 2013).

Step6: Sizing system wiring

The PV arrays, inverter, charge controller, and battery are wired in such a way that the system wiring can resist the maximum rated current generated by the PV arrays, inverter, and charge controller. The safety of the system could be compromised if the system wiring is not properly sized (M. Ishaq and U. H. Ibrahim, 2013). Aside from the current flowing through the wire, the voltage drop along the wire must also be considered. This is determined by the current and wire length. The voltage loss was estimated to be 2% by (Solar Energy International, 2004). (Solar Energy International, 2004) offers wire size tables to assist in determining the appropriate guage for a particular system voltage, current, and wire length. A higher cable current rating should be used to accommodate future expansion.

2.7 Charging electric vehicles from renewable energy sources: an overview review

Wind and solar energy are recognised as credible replacement alternatives for existing energy sources due to their environmental and economic advantages (Xin Li *et al.*, 2009; Birnie, 2009). Nevertheless, one disadvantage of renewable sources of energy is their unpredictability in terms of energy delivery. In comparison to studies on wind power with EVs, research on the utilisation of solar electricity through EVs is far more diversified. PV electricity may be generated at both medium and low voltage levels within a power network. Additionally, this option promotes the idea of merging PV generation with EVs (Richardson, 2013). Bessa and Matos (Ricardo and Manuel, 2011) investigated the use of EVs in the process of integrating distribution networks with PV. Furthermore, the study indicates that throughout the day, when solar radiation is at its greatest, solar electricity may be easily stored in EV batteries for future use.

Birnie (Birnie, 2009), on the other hand, proposed a concept in which EVs might be charged during the day in parking lots located within offices, so that the EVs may be completely re-charged during working times, allowing the solar-to-vehicle (SV2) method to be realised.

Additionally, (A. Ehsan and Q. Yang, 2020; Bao *et al.*, 2018) proposed concepts for solar-powered charging stations. The researchers recommended charging infrastructure for low to medium-range EVs. According to studies on wind turbine control and optimisation, wind energy is a viable alternative for EV charging infrastructure. Researchers in (Haque *et al.*, 2016) developed a model for efficiently adjusting for wind energy fluctuations by exploiting the flexibility of charging EVs, taking into account the constraints of traditional scheduling and dispatching systems. They discovered that rescheduling EV charging to periods of strong wind resulted in cost reductions.

(Ghanbarzadeh *et al.*, 2011) researchers created an ideal charging station employing wind turbines for various charging approaches in terms of optimal charging. The charging station is grid-connected which includes battery storage. For slow, moderate, and quick-speed charging, the rated power was tuned at 52, 84, and 116 kW, respectively. The study also created a power management model to improve wind energy reliability.

Based on the studies described above, it is possible to infer that wind and solar energy are feasible options for EV charging stations. The charging station could be non-hybrid or hybrid (wind and solar) with sufficient storage capacity to facilitate charging during energy fluctuations.

2.8 Existing charging methods

2.8.1 Office Charging

Companies have started to incorporate a green environment concept with the electric infrastructure for their employees. The long parking time allows employees to charge an EV out of their homes as a second location, which accounts for 15 – 25 % of charge events at the workplace (Hardman *et al.*, 2018). The workplace charging (WC) station could rise the daily driving distance, leading to higher acceptance rates and usage of EVs. The vehicles parked at the WC station can, on the other hand, be viewed to be a distributed power supply for the grid. This combination is capable of resulting in the effective operation of renewable energy sources. Meanwhile, it could be connected to the national grid or to a neighbouring micro-grid to resolve swings in renewable energy sources of electricity (Alkawsi *et al.*, 2021).

2.8.2 Public charging

The public charging infrastructure (PC) is a type of charging infrastructure that EV drivers may easily use when needed (Alkawsi *et al.*, 2021). They are better suited than residential areas to implement renewable energy installations. Renewable energy installation in residential areas has many concerns, including parking availability, constraints in building (e.g. insufficient area for solar modules), and governance policies (e.g. wind turbines are generally sited in remote locations) (Lopez-Behar *et al.*, 2019).

2.8.3 Residential charging

Residential charge (RC) covers public and private charging outlets in homes. Few studies indicated that RC is considered to be an encouraging factor for the purchase of EVs by drivers where it is easily accessible (Hardman *et al.*, 2018; Bailey *et al.*, 2015). Implementing a larger infrastructure for home charge (HC) could enhance the rate of EV adoption, particularly in urban areas (Peterson and Michalek, 2013; Erica *et al.*, 2013). The HC infrastructure dominates over the other types of infrastructures.

Around 80 % of the charging stations developed are for HC, and the majority of EV charging times were in household areas (Wood *et al.*, 2017; Franke and Krems, 2013). This shows that electricity from the grid is heavily utilised by EVs, where the most charge is carried out in residential areas. Therefore, the deployment of additional domestic solar charging infrastructure could reduce grid reliance, foster the adoption of EVs and extend the utilization of clean energy sources. As a consequence, greenhouse gasses and air pollution could be reduced.

2.9 Literature on sizing and optimal modelling of charging stations

The investments in battery charging infrastructure have enabled the acceptance of EVs into society. However, this puts additional strain on traditional electrical supply networks. To prevent possible overload concerns, the capacity of power distribution networks must be strengthened by the incorporation of renewable energy systems with charging stations. Furthermore, it is the most difficult challenge to meet the growing demand for EVs by optimizing the size and functioning of the charging infrastructure. Research to solve the aforementioned issues have been reported and are shown in **Table 2** and **Table 3**.

Table 2. Literature reviews on modelling of EV charging stations.

Research	Setup	Vehicle	System size	Location	Research Findings
(Grande *et al.*, 2018)	Off-gid PV	E-car	281 kWp PV with 420 kWh battery storage	Spain	• Hybrid Optimization Model for Electric Renewable (HOMER) was used to model and optimize the system and a load shifting concept then improved the results. • 12 EVs with 35 kWh battery capacity go fully charged using 50 kW DC fast charger and 281 kWp of solar units for 13.5 hours per day. • A tariff for the off-grid PV-BESS was proposed; (0.4 €/kWh during [15–19h] and [8–11h] and 0.25 €/kWh during [11–15h]) is viable when compared to grid-connected charging infrastructures. • The findings demonstrate the reliability and practicality of off-grid PV-BESS from a technical and financial standpoint. Additionally, they considerably reduce air pollution while being profitable.
(Ekren *et al.*, 2021)	PV, Wind	E-car	200 kW wind turbine; 250 kWp PV	Turkey	• The optimal hybrid system uses 55.6 % solar energy and 44.4 % wind energy to generate 843 MWh of power annually at 0.055 Euro per kWh. • Five electric vehicles are charged by the hybrid charging station every hour for 14 hours each day.
(Liang and Tanyi, E. and Zou, X., 2016)	PV, Grid	E-car	294 kWp PV	Sweden	• The findings indicate that 823.2 kWh of energy was produced each day throughout the year, with a daily energy production of about 136 kWh in the winter. • With 6.2 hours of charging time utilizing the PV power and 15.1 hours of charging time utilizing the AC power grid, the system is capable of charging up to 27 electric vehicles simultaneously.
(Mueller, O.M. and Mueller, E.K., 2014)	Off grid PV	E-car	1.02kWp	USA	• Standalone solar energy was used to charge a smart electric car. • Testing carried out over 3 months period, revealed that the car could charge purely from the standalone PV system without electricity from the grid.

					• The system was able to supply 1 to 4 kWh each day, translating to 5 to 20 km of driving, according to the study.
(Gautham *et al.*, 2018)	PV, Grid	E-bikes	2.61 kWp PV	Netherlands	• AC power was supplied by an AC charger when charging from the grid, while DC power was supplied by a DC charger when charging from the PV panels. • Both Off-grid and grid activities were supported by a 10.5 kWh battery. • The findings obtained demonstrate that, while taking into account the grid connection as a backup source, the system was capable of providing AC, DC and contactless charging from 2.6 kW of PV power.
(Wi *et al.*, 2013)	PV, Grid	E-car	50 kWp PV	South Korea	• The analysis of an electric vehicle's charging schedule was done using the prediction of PV production and power usage for smart houses. • 50 kWp PV panels and 3 electric cars were taken into account for the study's numerical analysis. • The suggested strategy shows that charging the cars during off-peak hours can effectively reduce charging expenses. • However, it is impossible to achieve accurate effective electric car charging only based on numerical assumptions and modelling. The report also failed to demonstrate the effects of inaccurate forecasts for PV production and power consumption.
(Chandra Mouli *et al.*, 2016)	PV, Grid	E-cars	10 kWp PV	Netherlands	• Using the grid, PV, and V2G, a 10-kW solar-operated EV charger for offices in the Netherlands is being researched. • 10-kWh energy storage decreased grid energy exchange by 25%. • Results show that, in the Netherlands, seasonal variations in insolation mean that local battery storage does not completely reduce the EV-PV charger's dependency on the grid.

(Bhatti *et al.*, 2016)	Microgrid-PV, Genset	E-car	13 kWp PV, 51 kVA Genset	Maldives	• An energy management system for electric vehicle (EV) charging employing photovoltaic (PV) and energy storage tied to the microgrid was proposed, based on heuristic rule-based methodologies to optimize energy flow inside a microgrid. • When PV is used as the primary source for charging EVs, the microgrid's load is significantly reduced, making charging from a standalone PV more cost-effective. • When PV is not available, EV energy consumption is met by the GenSet.
(Bimenyimana *et al.*, 2021)	Microgrid-PV, Genset	E-car	7,497 kWp PV	Rwanda	• Using HOMER, the integration of solar PV microgrids in Rwanda to support EVs was proposed. • The proposed study might lead to more effective use of Rwanda's domestic energy resources.
(Gammon and Sallah, 2021)	Standalone PV- mini-grid	E-car	4.5 kWp PV	Gambia	• The research was done in the Gambia and employed 4.5 kWp of photovoltaic modules installed on the top of a car parking roof to assess the business potential of deploying electric vehicles (EVs) recharged by solar mini-grids to provide transportation services in off-grid settlements. • The findings show that there are numerous operating situations in which solar-powered electric taxis might be financially feasible in The Gambia. The use of lightweight vehicles such as cargo bikes and tuk-tuks yields the most promising results (autorickshaws).
(Park and Kwon, 2016)	PV, Grid, Wind, Hydro	E-car	3,175 kWp PV, 60 Wind turbines, 50.7 kW hydro	South Korea	• Using HOMER, the article explores potential synergies between local taxi services in Daejeon and potential renewable energy generation systems. • Solar, wind, battery, converter, and electrical grid-based systems are proposed for the third stage of the deployment of electric-powered taxis in Dae-jeon, South Korea (EP taxis). • The proposed grid-connected system's reliability and economic viability are backed by the unpredictable nature of power generation from renewable energy sources. • According to modelling results, building independent renewable electricity production systems is not as advantageous as building renewable power generating systems with grid connections. It could be more economical to sell any extra energy and buy any needed electricity from the local grid.

Table 3. Literature reviews on optimisation of EV charging stations.

Research	Setup	Vehicle	Research Findings
(Haddadian *et al.*, 2016)	Wind, Grid	E-cars	• This research proposes a stochastic programming framework for the day-ahead scheduling of electric vehicles in the power grid. • MILP (mixed-integer linear programming) was employed to solve the problem. • The coordination of wind energy, stationary electric vehicle fleets, and conventional thermal units is modelled as a MILP issue in stochastic SCUC in this paper. The goal (1) is to reduce the cost of power system operation by scheduling demand and wind energy estimates based on the system and producing unit limits. • The objective function (1) is made up of the base case operating cost, which includes the generation and startup/shutdown costs of thermal units, as well as the operation cost of EV fleets, which excludes generator and transmission line interruptions. • The use of renewable energy sources, as well as the intelligent integration of EV fleets, present significant opportunities for lowering peak power system demands, decreasing the cost of electric grid operation and hourly wind energy curtailments, as well as lowering the environmental impact of fuel-based thermal generating units.
(Quddus *et al.*, 2019)	PV, Grid	E-car	• This research provides a unique framework for constructing and operating electric car charging stations that take into account both long-term planning and short-term operational choices across a pre-determined planning horizon and under stochastic power demand. It was decided to use a two-stage stochastic MILP. • To illustrate and evaluate the modelling findings, a case study based on the road network surrounding Washington, D.C. is provided. • When energy costs are low and solar power is unavailable, the results show that electric vehicle power demand is met predominantly through the grid through Vehicle-to-Grid. • This research meets the infrastructure's technological and financial goals, as well as the microgrid's economic and security concerns.
(C. Liu *et al.*, 2012)	Wind, Grid	E-car	• The effects of PHEV charging patterns on power system operations and scheduling are investigated in this paper. It was implemented using a two-stage stochastic MILP.

			• The stochastic unit commitment model outlined in this research takes into account thermal generating units, PHEV charging demands, and the penetration of large-scale wind generation. • Auxiliary services supplied by vehicle-to-grid technologies are also addressed in the suggested paradigm. Based on a PHEV population prediction and a transportation study, daily power consumption by various types of PHEVs is calculated. • The findings suggest that a smart charging pattern can lower power system running costs while also compensating for wind power fluctuations. • The case study demonstrates that the offered algorithms are successful in lowering operating costs.
(M. A. Ortega-Vazquez *et al.*, 2013)	PV, Grid	E-car	• This paper outlines the changes that must be made to include EV aggregation in power markets using MILP. • This enables the system operator to schedule EV charging and services, therefore improving the power system's efficiency and security while lowering its environmental effect. • The paper outlines the changes that must be made to the architecture of a typical day-ahead power market in the United States to include electric car fleet aggregators. The modifications made can effectively and collectively describe the functioning and influence of electric vehicles on the power grid. • The results reveal that when EV penetration levels are coordinated over their charging schedule, the system's ability to absorb more EVs without expanding the supply side is greatly boosted. • The results show that the suggested technique is efficient enough to be applied in embedded systems for real-time EV charging rate allocation.
(Lindiwe Bokopane *et al.*, 2015)	Standalone hybrid renewable systems	E-tuk-tuk	• This study aims to investigate the options for controlling and maximizing the operations of a hybrid renewable energy system to supply energy to an electric Tuk-Tuk charging station without any load rejection. • The objective is to develop an optimization system that ensures renewable energy sources are utilized to the maximum extent possible, while minimizing the use of the battery bank. The proposed control scheme is evaluated and simulated in Matlab software using fmincon. • The simulations aim to establish the minimum of a constrained non-linear multi-variable function. • The study provides findings and analysis of various scenarios for possible charging station locations in South Africa. • An ideal control approach is developed using three case studies: day charging, night charging, and all-day charging.

(Hao Wang *et al.*, 2018)	Standalone hybrid renewable systems , Grid	E-car	• A holistic framework for the development and management of an electric vehicle charging station was established, taking into account grid and local renewable energy supplies. • A two-stage stochastic programming problem was proposed to jointly maximise the capabilities of solar and wind energy, as well as the best daily power scheduling, to capture the linked decisions in two stages (i.e., investment and daily operation). • The ideal planning technique was proven using genuine EV and renewable energy generation traces. • The results revealed the best capacity and lowest prices in terms of budgets. • The optimal energy scheduling of renewable energy and grid electricity in one scenario was also demonstrated. • EV charging power scheduling was improved.
(N. Liu *et al.*, 2015)	PV, Grid	E-car	• A heuristic operating method for commercial building microgrids is proposed to increase PV energy self-consumption and reduce grid effects. • The method is made up of three parts: an EV viable charging zone model, a dynamical event triggering mechanism, and a real-time power distribution algorithm for EVs. • To save money on computing resources, real-time data is used for planning and simulation rather than forecasting solar production or EV charging requirements. A comprehensive result from simulation testing shows that the recommended method delivers good outcomes and great efficiency and that it may be employed in embedded systems for real-time allocation of EV charging rates.
(C. Chen and S. Duan, 2014)	PV, Wind, Fuel Cells, Grid	E-car	• This paper describes a new strategy for integrating plug-in hybrid electric cars (PHEVs) into microgrids (MGs) that takes into account the ideal amount of parking spaces when PHEVs are scheduled optimally. • Radial basis function network (RBFN) approaches are used to anticipate photovoltaic (PV) power production due to the uncertainty of solar energy. To cope with the uncertainties connected with the daily distance travelled by the PHEVs, load values, and electricity market pricing, Monte Carlo simulation is utilized. • The goal is to reduce the total cost (TC), and the genetic algorithm (GA) approach is used to find the best solution to the optimization issue. • Two market policies are utilized as case studies to test the efficiency of the suggested strategy. • The results of the computations may be utilized to assess the influence of PHEV integration on MGs economic performance.

2.10 Research gap identification

The literature used in this research study highlights the limitations of previous work conducted that relates to on- and off-grid PV-based electric vehicle charging systems used in rural applications.

Bloemen (2018) kick-started an electric mobility project in a rural small village in Zimbabwe. The project saw a pilot model of electric tricycle distribution to small-scale farmers. The project would help in reducing the time and cost of moving goods and people in the rural community. However, the charging facility is reported to run using a blended charging system that requires a combination of renewable and diesel generator power.

However, it is known that most generators are fossil fuel-driven which greatly contributes to GHG emissions (Elum and Momodu, 2017). The project only focuses on the distribution of electric tricycles with less emphasis on large-scale integration of an off-grid PV-based charging facility into charging of electric vehicles and non- mobility loads etc.

Liu (2014) conducted a study on how solar and wind energy could be used to charge electric cars and, thereby, change the environment and the economy. The research modelled and analysed the amount of usable solar and wind energy. The results obtained imply that predicting future weather conditions will help to decide on which energy to generate and store for the car to use in the future. However, the weather forecast is always subject to uncertainties. Furthermore, the study only focused on basic climatic estimations without providing a conceptual method on how solar or wind energy could be used through software or hardware model design to charge an electric car.

Similarly, Liang *et al.* (2014) modelled the charging of an electric car by using solar energy. Here, the research focused on how to capture solar energy to charge batteries by modifying a parking lot in Sweden by placing PV modules on rooftops to maximize surface area and solar energy generation. The findings indicate that annual energy of 823.2 kWh of energy was produced, with a daily energy production of about 136 kWh in the winter. With 6.2 hours of solar charging time and 15.1 hours of power grid charging time every day, the system could charge up to 27 electric vehicles simultaneously.

However, this work has involved the use of on-grid charging and electricity from the grid is mostly from conventional energy sources which are not completely clean. Similarly, as more grid charging is used, more overloading on the consumer side is experienced.

Furthermore, a smart electric car was efficiently charged using off-grid solar energy by Mueller and Mueller (2014). The researchers used 4 solar panels generating 1,020 Wp (255 Wp each), a charge controller and batteries to successfully charge the car. After three months of testing, it was clear that the vehicle could be charged using the off-grid PV system and not by using grid electricity. The system was able to supply 1 to 4 kWh each day, which equated to 5 to 20 km of commuting, according to the data. However, this work just considered the demand for a small 2-seat-sized electric vehicle which leads to an unrealistic application in many off-grid rural areas of developing countries like Africa.

Based on predicted PV production and power usage for smart houses, Wi *et al.* (2013) examined the electric car charging schedule. A time series model including forecast and variability for the weather was used to estimate energy usage and PV production. Three electric cars and 50 kWp of PV were taken into account for the analysis of the study. The suggested solution demonstrated that the vehicles may be charged during a time when demand is low, thereby lowering the cost of charging. However, precise electric car charging that is only based on numerical hypotheses and simulation is impossible. Similarly, the research failed to demonstrate how the inaccurate forecasts of PV output and power consumption had an impact on the overall performance.

Six electric scooters used by college students and charged by a grid-based PV system were the subject of research by Dziadek *et al.* (2013). The primary purpose of the scooters was for transportation from homes to schools and because stationary batteries add to the cost of installation, the research did not employ them on the PV system. When the solar panel system produced enough energy to fully charge the electric scooters, charging from the PV system was received; otherwise, grid power was used. The field findings revealed that during the summer, 94.3 % of direct charging from the 3 kWp system and 5.7 % of charging from the grid were attained, with a greater portion of grid charging during the winter. The research isn't entirely environmentally favourable during the winter months because a significant portion of the grid's power was produced from fossil fuels.

Research gaps were identified from the works of literature reviewed (see **Figure 21**) and this PhD research aims at bridging the knowledge gaps in the work of (Gammon and Sallah, 2021) and (Lindiwe Bokopane *et al.*, 2015).

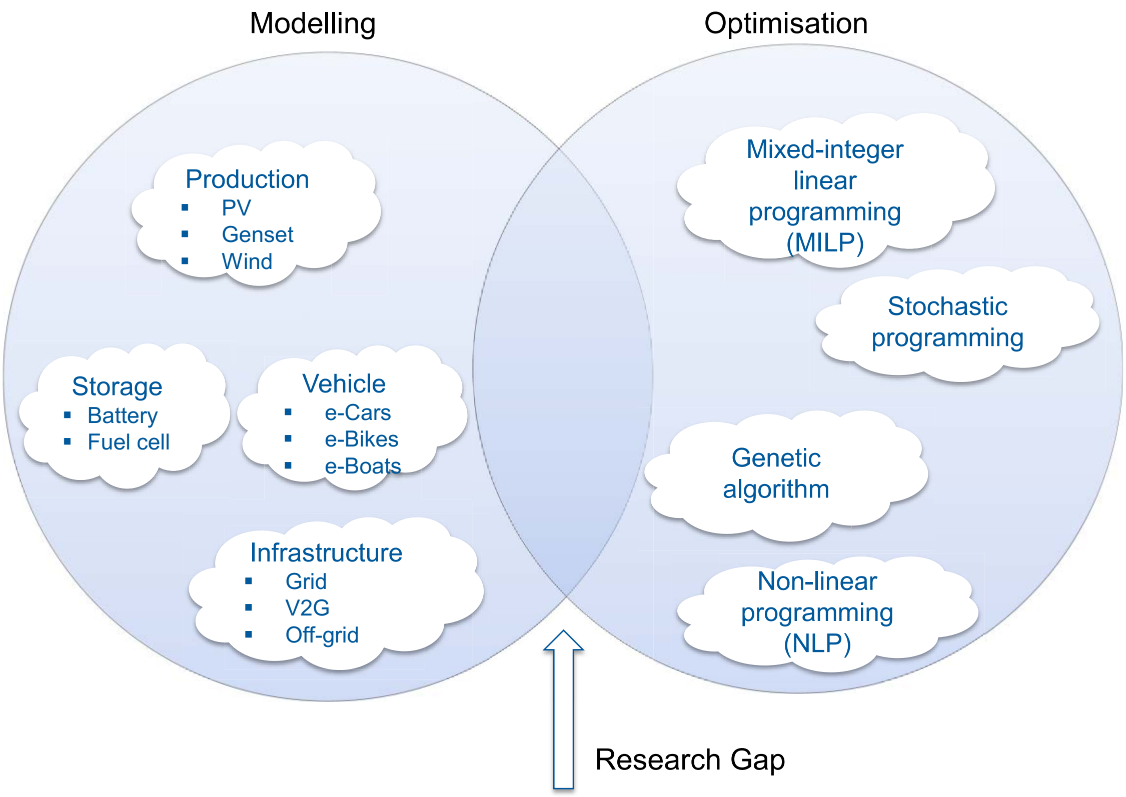


Figure 21: Research Gap

In (Gammon and Sallah, 2021), a field test was undertaken on the charging of an electric minivan (solar taxi) using an off-grid 4.5 kWp solar PV system in The Gambia. The solar PV modules were used to cover the roof of a parking shelter on the electric minivan, which was used to test taxi services. (Gammon and Sallah, 2021) presented a techno-economic study that showed that solar electrified taxis may be economically viable in The Gambia and, by extension, throughout the globe. However, lightweight vehicles such as tuk-tuks (autorickshaws) and motorcycles appear highly suitable for rural transport services in SSA, therefore this Ph.D. research aims to improve the contributions of (Gammon and Sallah, 2021) by incorporating e-bikes (e-motorcycles and e-cargo) into a standalone PV system.

Furthermore, it can be seen from the works of literature reviewed on the optimisation of EV charging infrastructure, that most studies focused on PV-Grid, Wind-Grid, or hybrid renewable source – Grid connections with less emphasis on off-grid PV standalone systems (see **Table 3**). The studies also mostly focus on how to optimally charge EVs by minimising electricity/operation cost based on simulation and economic analysis using various methods such as genetic algorithm, stochastic modelling and mixed-integer linear programming (MILP). Based on simulations and analyses, some concentrate on delivering a day-ahead upper bound profile of the energy usage of the charging infrastructure.

However (Lindiwe Bokopane *et al.*, 2015) presented a study on how to improve the day-to-day performance of a standalone renewable energy system by achieving maximum use of renewable energy resources while lessening the use of battery system to supply the energy needed at an electric tuk-tuk charging infrastructure. An ideal control strategy was modelled with three case studies or scenarios (day charging, night charging and all-day charging). The efficiency of the proposed approach is evaluated and simulated in MATLAB software using fmincon. The goal of the simulation was to determine the minimum of a limited multivariable nonlinear function.

The study focuses on optimising the charging of only one tuk-tuk using instantaneous PV power generation without forecasting. Hence, this PhD research intends to adopt and improve the work of (Lindiwe Bokopane *et al.*, 2015) by developing a load optimisation algorithm that best integrates more e-bikes and non-mobility devices into a standalone PV system using 7 days PV generation forecast. The optimisation algorithm also shifts the charging schedule of the various loads in line with the PV generation forecast. This would aid in minimising the use of the battery banks as mentioned in (Lindiwe Bokopane *et al.*, 2015) and also in energy deficit reduction. The PhD. research also incorporates the optimised algorithm into a standalone optimisation design tool (computer application) so that any operator can use it for EVs and non-EV integration into a standalone PV system at any location.

2.11 Summary

The review of Kenya's rural electrification, transport sector emissions, and the concept of renewable was presented in this chapter. It has also identified existing gaps in the approaches to modelling an EV charging infrastructure using solar energy.

The next chapter will present an overview of the investigated *Mbita WE Hub* by analysing the measurement data obtained from the *Hub* in terms of energy consumption and PV generation. Potential solar energy surplus from the *WE Hub* will be identified through the means of modelling and simulation. This potential solar energy surplus will later be used to integrate electric mobility solutions.

Chapter 3: Theoretical Analysis on System Level

This chapter focuses on the technical overview of the investigated Mbita WE Hub, and the analysis of the measurement data obtained remotely from the hub. The measurement data consists of energy consumption and PV generation at different time steps throughout the day. The measurement data was ultimately used to generate daily and annual load profiles. Similarly, the chapter presents the future electric load (e-mobility) as well as the field measurement results obtained.

3.1 Technical overview of the investigated WE Hub

The technical system layout can be seen in **Figure 22**. Arrays of PV modules with a capacity of 30 kW_P are converted from direct current to alternating current by an 18 kVA inverter (see **Figure 22**, left) to meet the electrical demands of the WE Hub (see **Figure 22**, top) or a charge the backup 104 kWh battery storage (see **Figure 22**, right) (Bugaje *et al.*, 2021a).

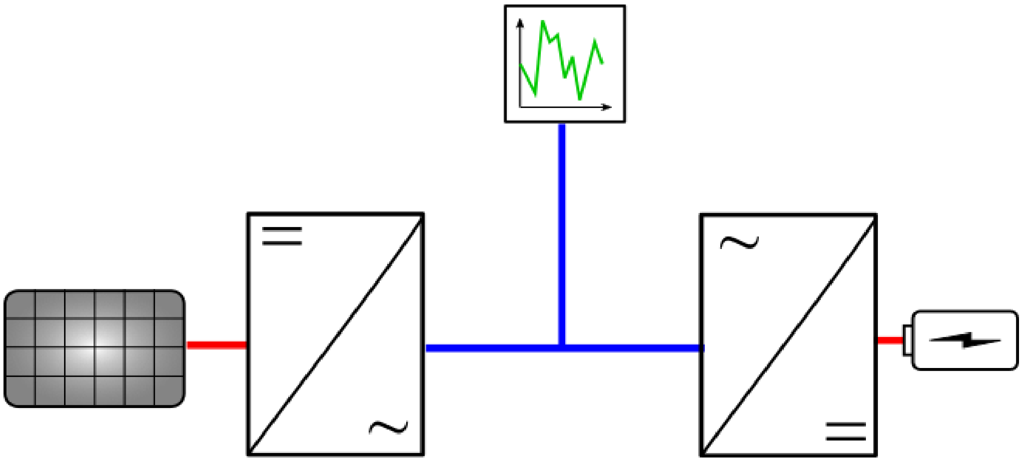


Figure 22: Technical layout of the investigated WE Hub (Simiyu Sitati, 2021).

In addition to the typical usage of the WE Hub (such as charging fishing lanterns), the electricity is also used to purify water that is pumped from Lake Victoria (Bugaje *et al.*, 2021a). **Figure 23** shows the pictures obtained during the onsite assessment of the investigated WE Hub. The details of the electricity generation and major consumers of Mbita WE Hub are shown in **Table 4** and **Table 5** respectively.

Figure 23: On-site assessment of the existing charging station at Mbita WE Hub (Simiyu Sitati, 2021).

Table 4. Mbita WE Hub electricity generation (Simiyu Sitati, 2021; Knights Energy, 2020; HOPPECKE, 2013; SMA Solar Technology AG, 2011, 2015; SolarWorld, 2005; Bosch Solar, 2012).

System Components	Current System
PV Modules	Bosch Solar c-Si-M60-M240-3BB (240W)
PV Module Quantity	126
PV Module Power Rating	30.24 kWp
PV Inverters	STP15000TL-30 (SMA Sunny Tripower 15kVA)
PV Inverter Quantity	2
PV Inverter Rating	30 kVA
Batteries	Hoppecke (2V, 2170Ah)
Battery Rating	104 kWh
Battery Inverters	SI 8.0H-12 (SMA Sunny Island 6.0)
Battery Inverter Rating	18 kVA

Table 5. Mbita WE Hub major electricity consumers (SERC - Strathmore University Energy Research Centre, 2018).

Major Electricity Consumers	Operating Power (W)	Number
Fishing Lanterns	105	200
Water Purifier	120	1
Floodlight	40	1
CFL Light Bulbs	8	7
Fluorescent	18	2
Computer	150	2

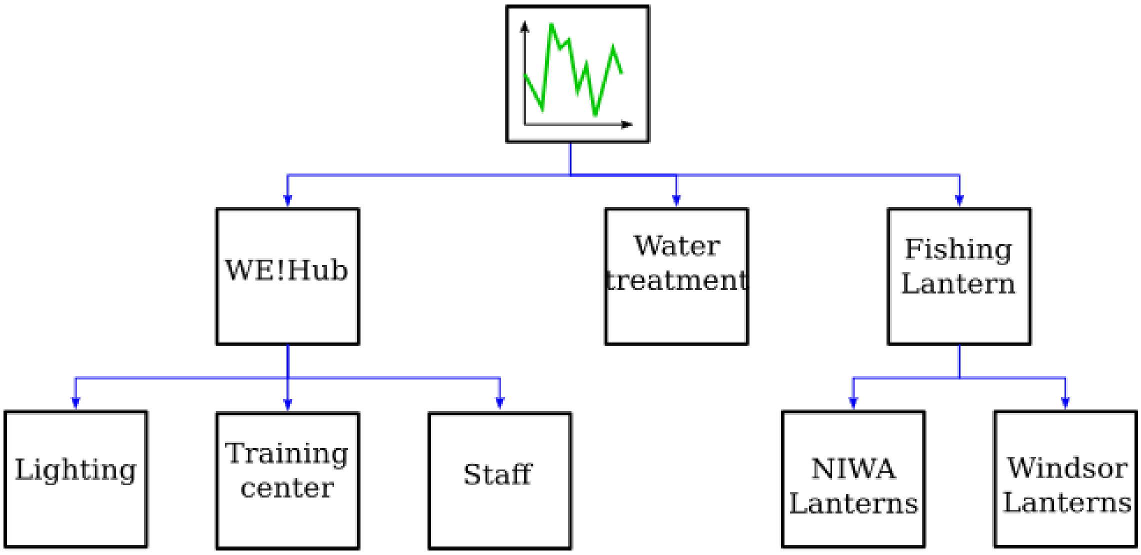


Figure 24: Existing electrical loads at the *investigated WE Hub*

The fishing lanterns are used by fishermen around *Lake Victoria* for night-time fishing. Around 3:00 pm daily, the boat owner or any fishermen collects the lanterns from the *WE Hub*. Until around 6:00 pm the boat is prepared. The fishermen drive their boats on the lake to the fishing grounds and position the lanterns. After a while on the lake, flies are attracted by the lanterns which in turn attract the Omena fish. The fishing nets are placed and the fish are caught. This is repeated until the number of fish is satisfying or the next morning comes. Early in the morning, the fish are brought to the beaches and sold to women who dry the fish and resell it. The lanterns are brought back to the *WE Hub* to charge in the morning (AMPS Power GmbH, 2018). Interestingly, low fishing catches are naturally recorded during days with high moon brightness while high fishing catches are recorded during days with low moon brightness.

For the fishing business, two different types of lanterns, produced by NIWA, (see **Figure 25** left), and Windsor Hunter, (see **Figure 25** right), are used. From the Mbita WE Hub operator's information, there are a total of 300 lanterns in daily active operation (Simiyu Sitati, 2021). The technical detail of the lanterns is shown in **Table 6**.

Figure 25: Fishing Lanterns charged around Lake Victoria (WeTu, 2021).

Table 6. Technical detail of fishing lanterns at Mbita WE Hub (Simiyu Sitati, 2021; Knights Energy, 2020).

Type	Battery Capacity (Ah)	Battery Voltage (V)	Charging Rating (W)	Energy Required (Wh)
Niwa	21	5	30	105
Windsor	21	5	30	105

3.2 Analysis of electricity consumption data from *WE Hub*

An SMA data manager installed at Mbita WE Hub was used to determine how much electricity was used during the day and night. A carpet plot of the electricity consumption was developed (see **Figure 26**) to better understand the electricity consumption pattern at the WE Hub and to build load profiles for the e-bikes.

Figure 26 shows that the WE Hub's typical operational period was from August to October, whereas the time for e-bike field measurements was from October to December. Due to a partial COVID-19 lockdown to curtail Christmas celebrations, December saw the lowest electricity usage.

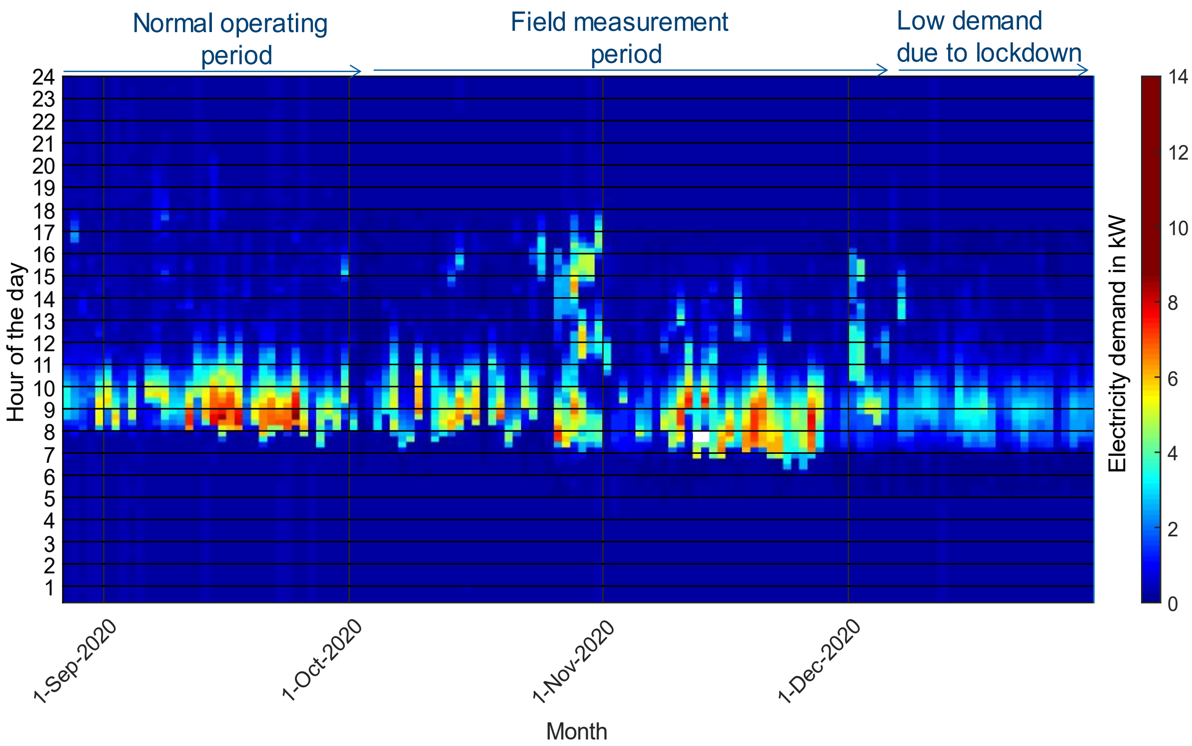


Figure 26: Carpet plot of Mbita WE Hub's measured electricity consumption data

3.2.1 Electricity consumption of WE Hub's normal operation period

It was determined from **Figure 26** that the WE Hub operated normally between August 27, 2020, and October 7, 2020. **Figure 27** carpet plot depicts the identified normal operation period.

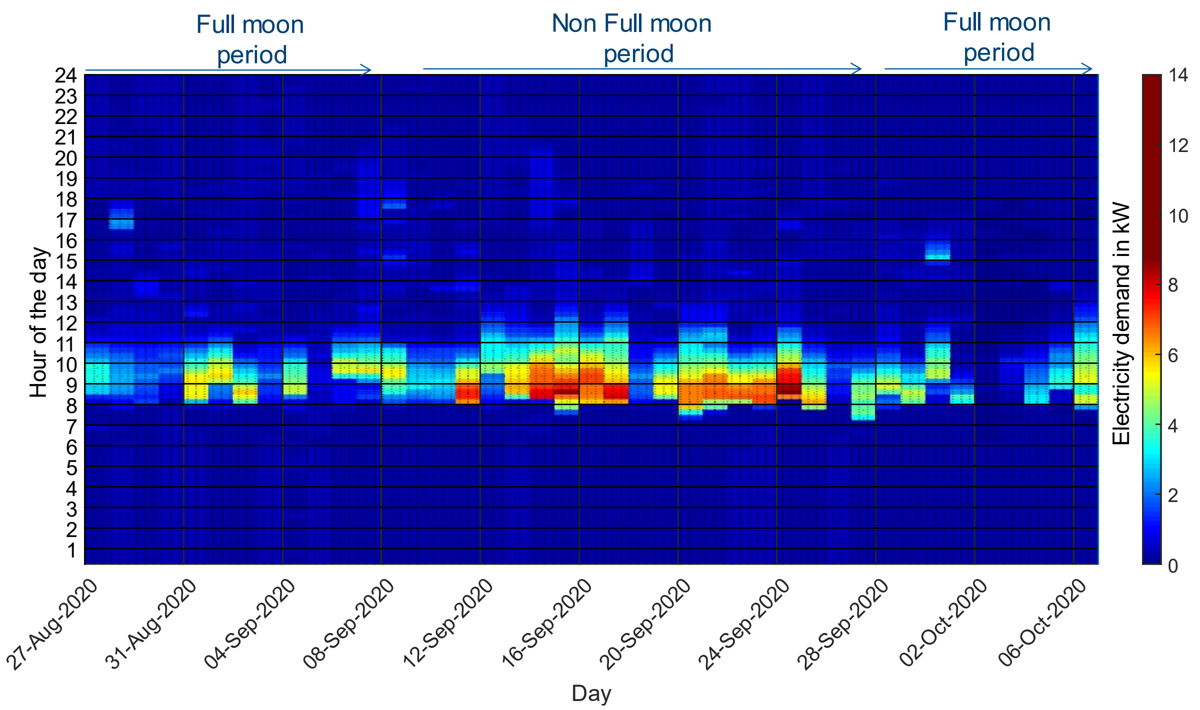


Figure 27: Carpet plot of Mbita WE Hub's measured electricity consumption data during the normal operation period

Weekends and weekdays were determined using the 2020 gregorian calendar, while moon phases were determined using the 2020 lunar calendar (Time and date, 2020). As can be observed from **Figure 27**, there is a low power consumption from the 27th of August to the 7th of September and from the 27th of September to the 6th of October. This was because of full moon phases. Moon phases are the days that make up a month's cycle of the moon. These days are divided between the full moon and non-full moon days. In a year, there are around 10 full moon days every month.

On Lake Victoria, fishing catches are naturally lower during full moon phases because there is too much light for the fish to rise to the surface, as opposed to other times of the month.

The fishermen use floatable electric lanterns on the lake to attract tiny insects during the non-full moon phase, this causes the fish to surface and be captured by the fisherman. However, when there is a full moon, the moonlight is so brilliant that it diverts insects away from the floatable fishing lanterns, which results in a lower fishing catch. Therefore, during full moon phases, fewer fishing lanterns are charged at the

Mbita WE Hub. For the time of normal operation, **Figure 28** displays the daily power demand in relation to the phases of the moon.

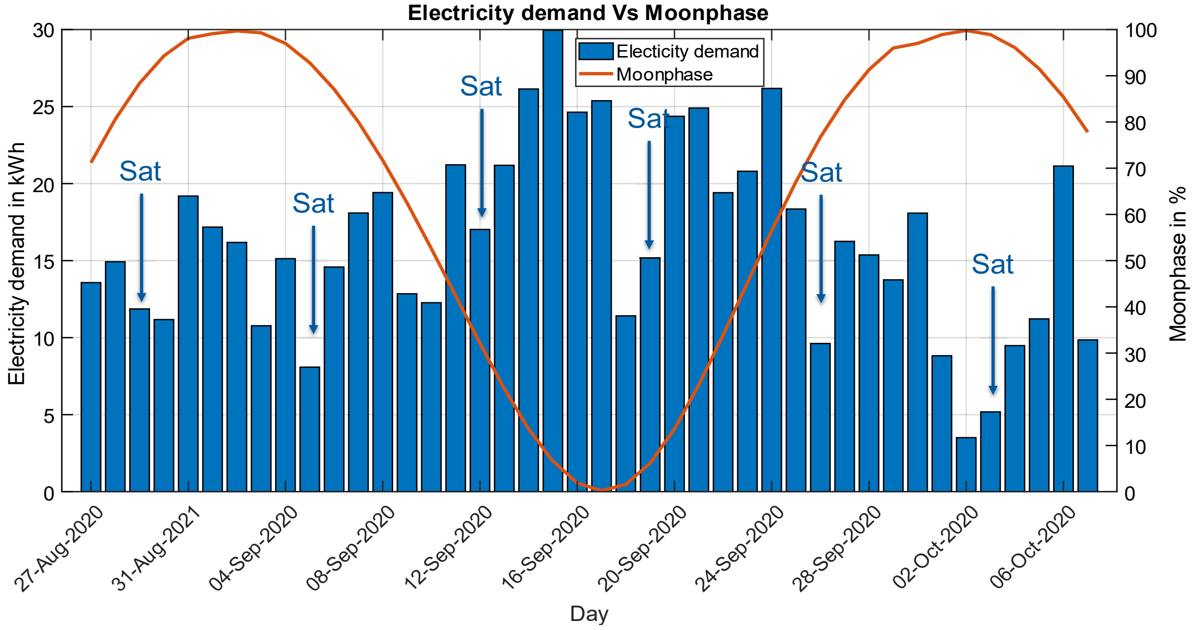


Figure 28: Electricity consumption during the normal operating period

3.2.2 WE Hub electricity demand profile during moon phases

Weekdays and weekends between 27th August 2020 and 6th October 2020 were identified using the data in **Figure 28**. A MATLAB code (see Error! Reference source not found.) was written using the measured data for weekdays and weekends for non-full and full moon phases to derive the average hourly load profile (see **Figure 29**, **Figure 30**, and **Figure 31**).

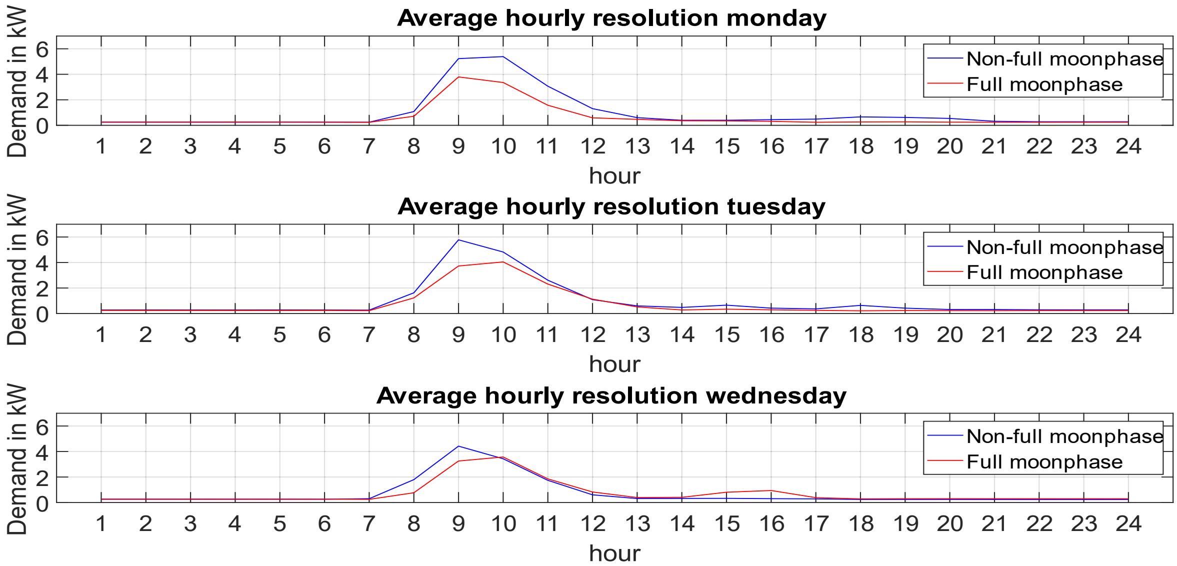


Figure 29: Extracted hourly electric load profile.

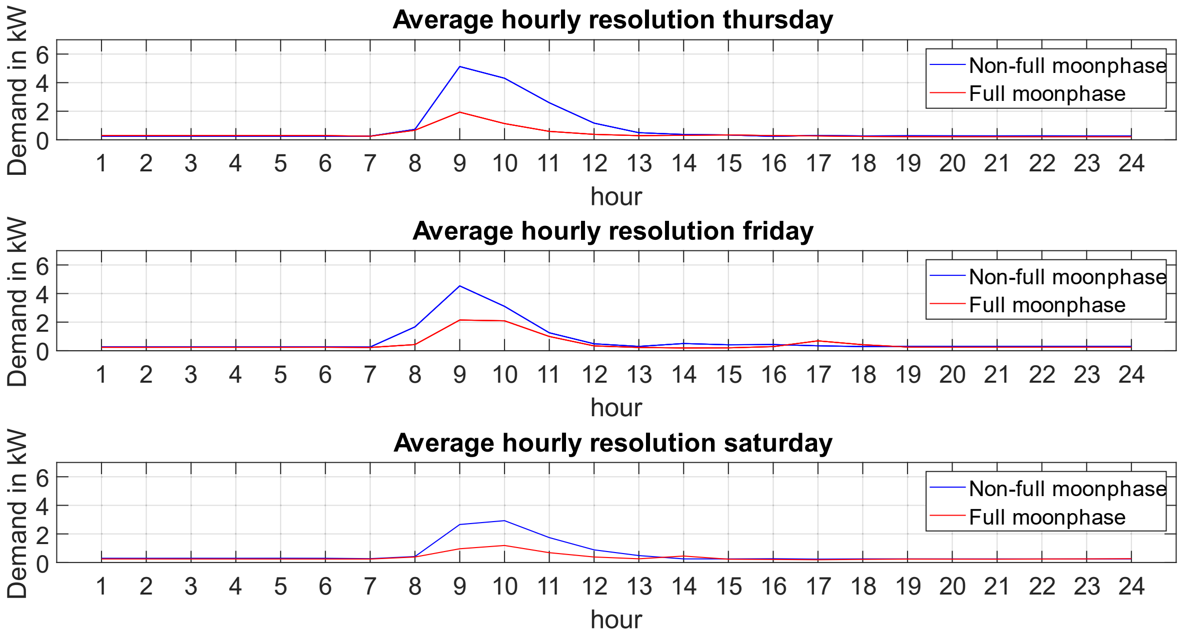


Figure 30: Extracted hourly electric load profile

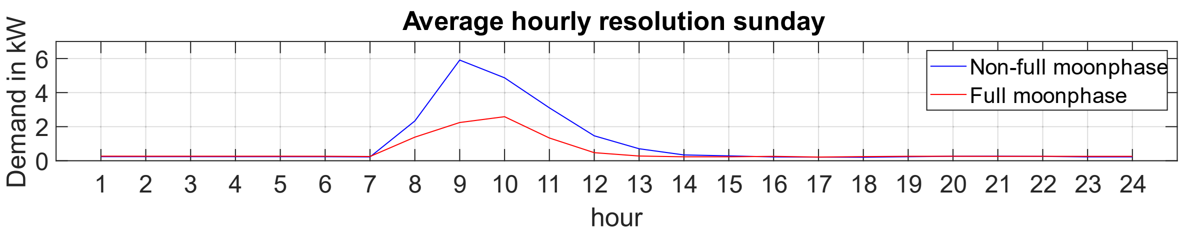


Figure 31: Extracted hourly electric load profile

3.2.3 Annual load profile generation without e-mobility

Using the extracted load profiles in **Figure 29**, **Figure 30**, and **Figure 31**, a MATLAB code was used to generate a 6,278 kWh annual electricity load profile for the Mbita WE Hub using the lunar calendar of the year 2021 (see **Figure 32**).

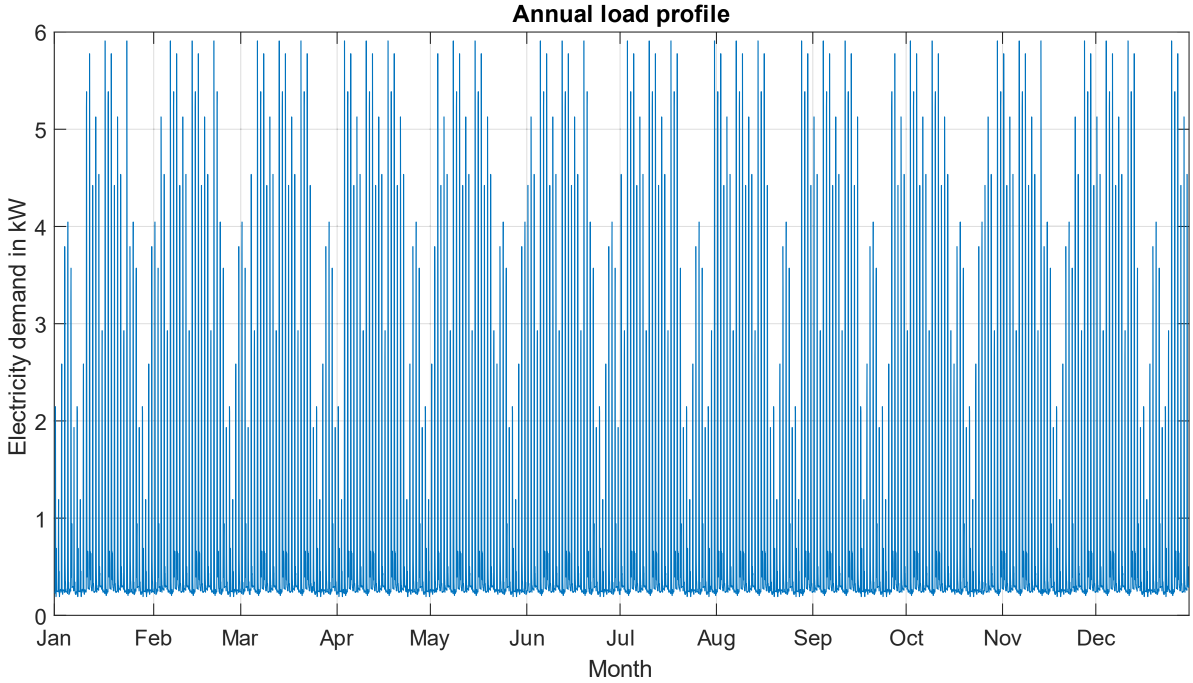


Figure 32: Annual hourly electricity consumption profile of WE Hub.

3.3 Determination of Future Consumers at *Mbita WeTu Hub*

The future electricity consumers/loads that will be incorporated into the WE Hub have been shown in **Figure 33**. e-Cargo, e-OpiBus, and e-BodaWerk were identified as e-mobility consumers. It was projected that the required number of fishing lanterns would rise from 300 to 450 every day.

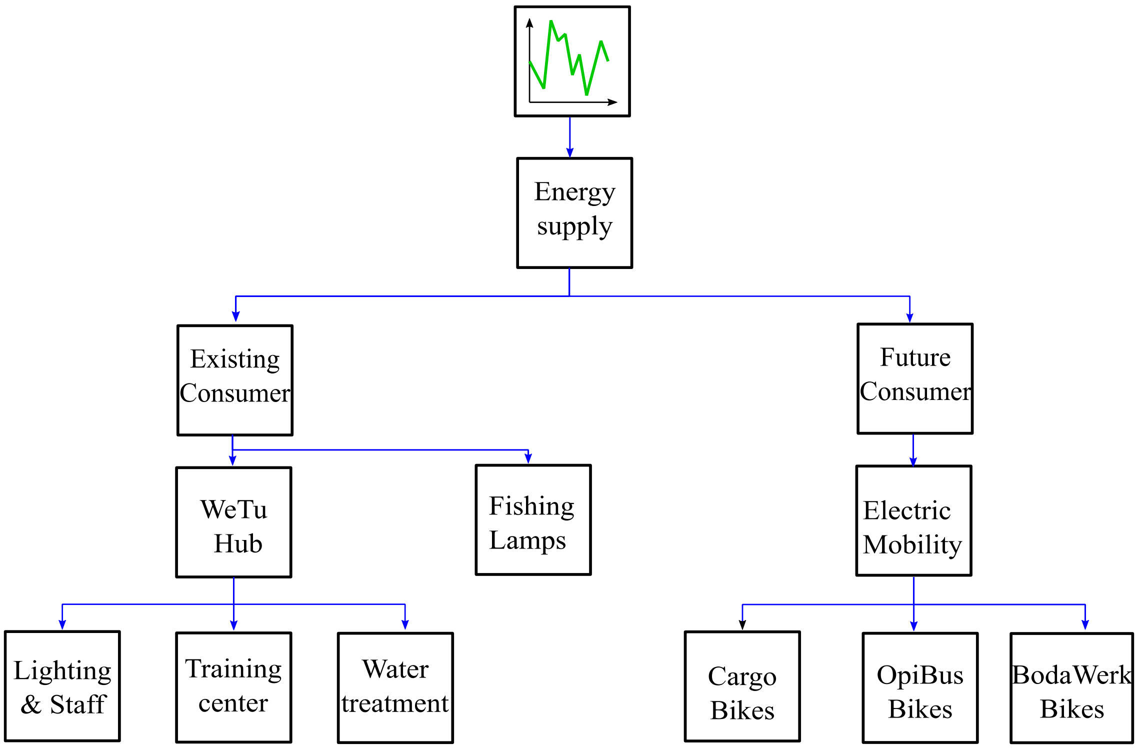


Figure 33: Different electrical loads at the *Mbita WeTu Hub*.

3.3.1 BodaWerk bike

The electric *BodaWerk* bike, (see **Figure 34**), is an internal combustion engine motorcycle converted to an electric motor by *BodaWerk* International Limited (Bodawerk International Ltd, 2021). *Siemens Stiftung* cooperated with *WeTu Limited* to test the bikes and develop a suitable business model around the *Lake Victoria* region. Its batteries were charged at the Mbita WE Hub with the possibility of battery swaps depending on the battery range in relation to the rider’s driving behaviour (i.e. payload, terrain, and speed). The technical details of the *BodaWerk* bike are shown in **Table 7**.

Figure 34: *BodaWerk* bike (WeTu, 2019).

Table 7. Technical detail of *BodaWerk* bike (Siemens Stiftung, 2020a).

Type	Battery Capacity (kWh)	Top Speed (km/h)	Range with 1 Passenger (km)	Range with 2 Passengers (km)
Bodawerk	2.2	65	100	60

3.3.2 Anywhere Berlin cargo bike

The electric cargo bike (see **Figure 35**) is manufactured by *Anywhere Berlin* company (anywhere berlin GmbH, 2020). *Siemens Stiftung* has cooperated with *WeTu Limited* to test the bikes and develop suitable business models around the *Lake Victoria* region. Its batteries are to be charged at the Mbita WE Hub with the possibility of battery swaps depending on the battery range in relation to the rider's driving behaviour (i.e., payload, terrain, and speed). The technical details of the cargo bike are shown in **Table 8**.

Figure 35: *Anywhere Berlin* cargo bike (WeTu, 2019).

Table 8. Technical detail of the electric *Anywhere Berlin* cargo bike (anywhere berlin GmbH, 2020; Siemens Stiftung, 2020a).

Type	Battery Capacity (Ah)	Battery Voltage (V)	Battery Capacity (kWh)	Load Capacity (kg)	Range with 4 kWh battery (km)
Cargo	20	52	1.04	160	80

3.3.3 OpiBus bike

The electric *OpiBus* bike, (see **Figure 36**), is manufactured by *OpiBus Limited* (Opibus, 2021). *Siemens Stiftung* cooperated with *WeTu Limited* to test the bikes and develop suitable business models around the *Lake Victoria* region. Its batteries are to be charged at the Mbita WE Hub with the possibility of battery swaps depending on the battery range in relation to the rider's driving behaviour (i.e., payload, terrain, and speed). The technical details of the *OpiBus* bike are shown in **Table 9**.

Figure 36: *OpiBus* bike (Opibus, 2021).

Table 9. Technical detail of the *OpiBus* bike (Opibus, 2021).

Type	Battery Capacity (kWh)	Top Speed (km/h)	Range with Dual Battery (km)	Payload Weight (kg)
Opibus bike	2.9	90	160	150

3.4 Field measurement investigation on e-bikes

A measuring investigation was conducted to comprehend how much power the electric bikes and fishing lanterns used. Fluke energy loggers and multimeters were used during the measurement investigation. Together with MOI University and the WE Hub engineers, a measurement concept was developed by generating key performance indicators for the measurement campaign on the e-bikes (e-Cargo bike, e-Opi Bus bike, e-BodaWerk bike). Identification of various data to be recorded such as terrain type, battery SoC, distance covered, energy consumption, charging time, charging power, average speed, payload weight etc. was achieved. An excel sheet was developed for data recording in collaboration with MOI University and WE Hub engineers. Factors neglected during the field measurement were the use of GPS trackers on the bikes, and the terrain gradient/slope, weather conditions.

The electric bikes' energy consumption in kWh per 100 km was calculated, taking the aforementioned key performance indicators into account. The test results, which are meant to assess battery energy usage in kWh per 100km, aided in determining how many batteries swap a rider could require for the daily trip route. The measured data is therefore used to optimize the integration of the e-bikes into the WE Hub.

3.4.1 *OpiBus* bike measurement investigation

Results of energy recording and evaluation for the OpiBus bike batteries were determined. Information gathered included the distance covered, the bike's payload (driver + passenger), and the energy needed (kWh/100 km) (see **Figure 37**). Seven distinct experiments were carried out on tarmac-surfaced routes and six different tests on non-tarmac-surfaced routes, depending on the kind of road surface (i.e., gravel or soil roads were evaluated). The battery energy requirements of the OpiBus bike are graphically shown as a function of the road surface in **Figure 37**. Driving in non-tarmac terrain uses more energy than driving on tarmac, as can be seen.

The assessment shows that battery test number 4, which has an average payload of 160 kg and an average speed of 45 km/hr, consumes less energy than battery test number 3, which has an average payload of 80 kg and an average speed of 45 km/hr. This may be explained by the road surface's topography or gradient angle, which were not recorded during the test study.

On tarmac terrain, an average payload of 145 kg, travelling at 50.7 km/hr used 5.7 kWh of battery kWh every 100 km. When travelling on non-tarmac surfaces with an average payload of 136 kg at a speed of 45.8 km/hr, the average battery power usage was 7.3 kWh/100 km.

With an average weight of 141 kg and an average speed of 48.5 km/hr on both terrains, the entire test's distance-related average energy consumption was 6.4 kWh/100 km. The conclusion is that a 2.16 kWh OpiBus bike running at an average speed of 48 km/hr with an average payload weight of 141 kg would need at least two battery swaps to cover a distance of 100 km. This is in line with the findings of (Weiss *et al.*, 2020), which show that the energy consumption of an electric motorbike in the actual world ranges from 0.71 kWh/100 km to 9.3 kWh/100 km.

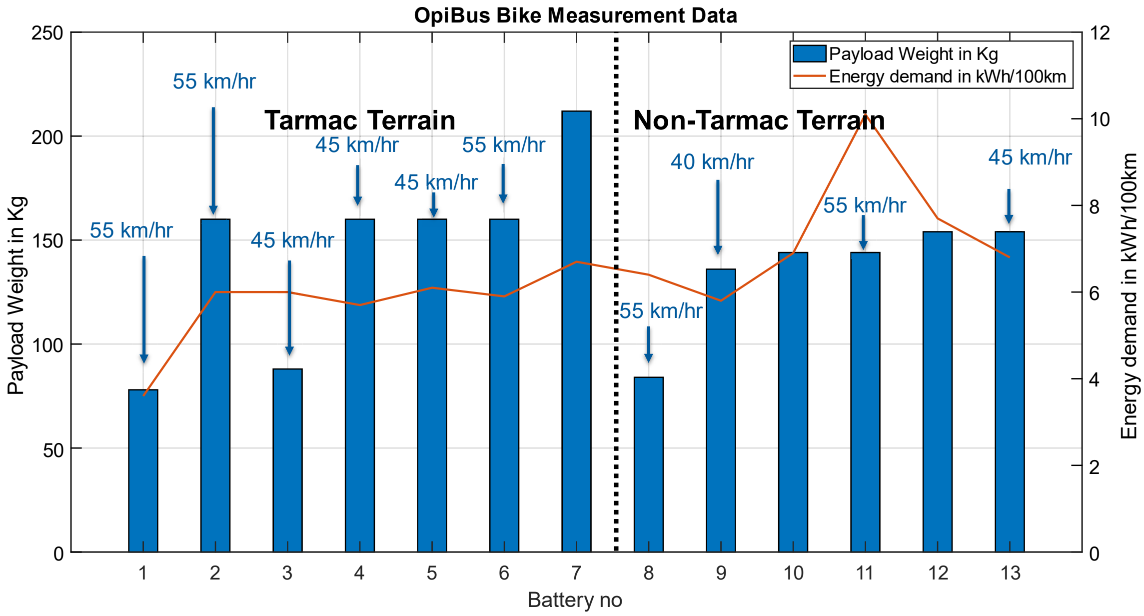


Figure 37: *OpiBus* bike energy consumption.

3.4.2 *BodaWerk* bike measurement investigation

Analyses of the OpiBus batteries and the BodaWerk bicycle were conducted simultaneously. Among the measurements used were the distance covered, the bike's payload, and the energy consumption (kWh / 100 km). Five distinct tests were performed on tarmac-surfaced roadways. **Figure 38** depicts the average energy consumption throughout the assessment phase on tarmac terrain with an average payload weight of 74 kg and a speed of 39 km/hr.

As a result, a 100 km journey would necessitate at least one battery swap for a BodaWerk bike with a 2.2 kWh battery capacity running with an average weight of 74 kg, and an average speed of 39 km/hr. This is in line with the findings of (Weiss *et al.*, 2020), which reports that the real-world energy consumption of an electric motorbike ranges from 0.71 kWh / 100 km to 9.3 kWh / 100 km. This also validates the assertion of (Siemens Stiftung, 2020a) that a BodaWerk bike with a 2.2 kWh battery capacity and operating with an average weight of more than 70 kg would require at least one battery changeover to achieve a 100 km range.

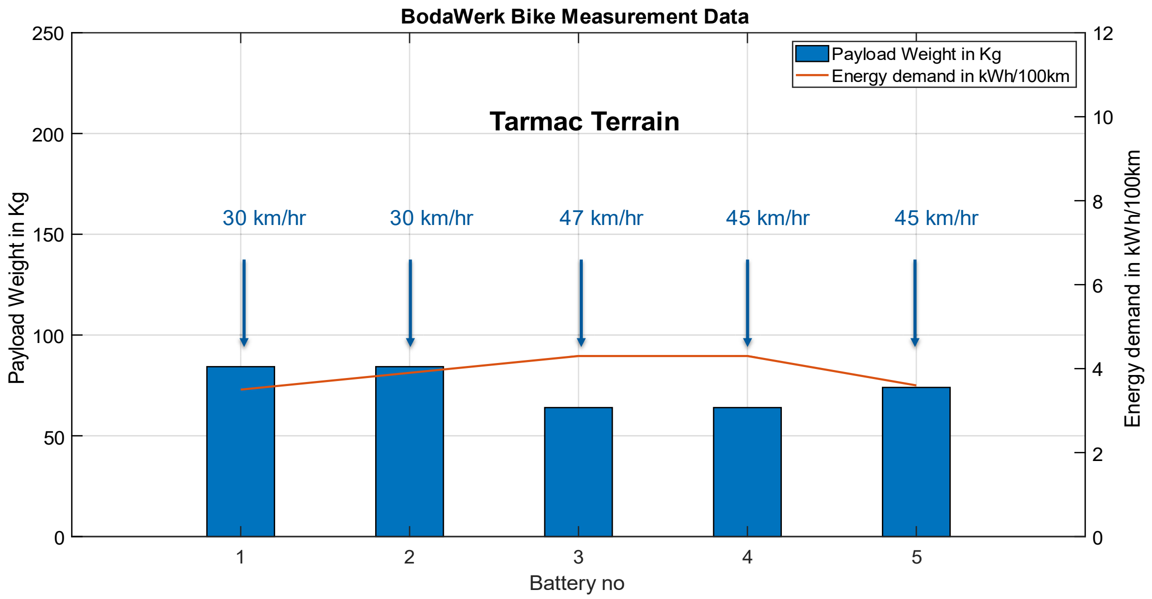


Figure 38: *BodaWerk* bike energy consumption.

3.4.3 Cargo bike measurement investigation

Figure 39 depicts a measurement investigation performed on the cargo bikes in relation to energy consumption in kWh/100 km. One test was conducted on mixed terrain (tarmac and non-tarmac) and four tests on non-tarmac terrain. As shown in **Figure 39**, the average energy consumption on non-tarmac terrain during the assessment was 3.3 kWh/100 km with an average payload of 86 kg and an average speed of 22.7 km/hr.

When travelling over mixed terrain at an average speed of 24 km/h and a payload weight of 210 kg, the energy usage was 10.2 kWh/100 km. The whole test average energy usage with a payload weight of 102 kg travelling at 22.9 km/h on both terrains was 4.2 kWh/100 km. A cargo bike with a 1.1 kWh battery, a 102 kg payload, and an average speed of 22.9 km/hr would thus need to make at least three battery swaps to cover a 100-kilometer range. This is consistent with the report of (Siemens Stiftung, 2020a) that a 4-kWh battery capacity is required for the Anywhere Berlin cargo bike to cover an 80 km range.

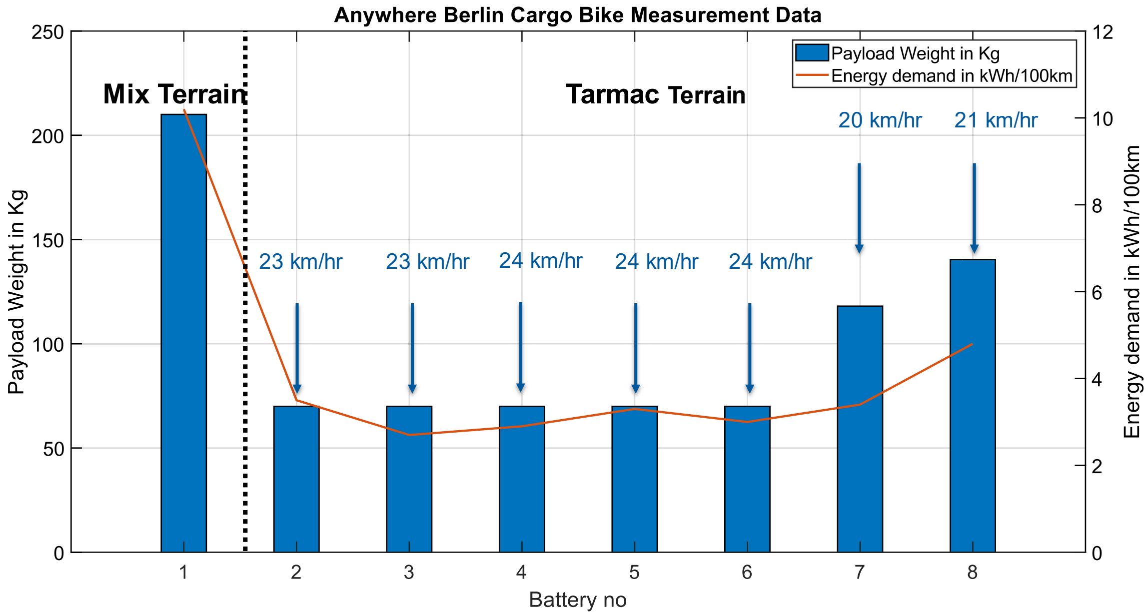


Figure 39: Anywhere Berlin cargo bike energy consumption.

3.4.4 Summary of field measurement

Table 10 summarizes the Mbita WE Hub future consumer (i.e., e-bikes) measurement findings. The OpiBus bike has an average energy consumption per recharge of 2.16 kWh, with an average energy need of 6.3 kWh / 100 km at a 129 kg average payload (rider + passenger). The BodaWerk bike has an average energy consumption per recharge of 2.2 kWh, with an average energy need of 3.9 kWh / 100 km and a 74.12 kg average payload. At 102.31 kg, the cargo bike has an average energy consumption per recharge of 1.05 kWh and an average energy need of 4.23 kWh / 100 km.

The energy requirement in kWh for the various bikes is varied, as shown in **Table 10**. The OpiBus has the highest energy consumption of 6.3 kWh/100 km, while the BodaWerk bike has the lowest energy demand of 3.93 kWh/100 km. This is due to the differing payload weights and speeds of the bikes. However, additional impacts that were not addressed during the measuring investigation, such as the gradient of the road surface, must be examined further.

Table 10. Measurement investigation summary.

Type of Bike	Battery Size In kWh	Energy per recharge in kWh	Total weight in kg	Average Speed in km/h	Charge time in h	Charge capacity in W	Energy demand in kWh/100 km
Opibus	2.16	2.25	129.84	47.80	3.00	800.00	6.30
BodaWerk	2.20	1.88	74.12	39.40	1.93	941.62	3.93
Cargo	2.20	1.05	102.31	22.88	5.36	195.65	4.23

The measuring study presents the amount of energy needed to charge the e-bike batteries. The measurement analysis also assisted in the formulation of hourly, daily, and annual load profiles for each bike, taking into account energy consumption, battery capacity, charging power, and charging time.

3.5 Load profile generation with e-mobility

Using the electricity surplus obtained in **Figure 45**, a scenario was used for the potential integration of the e-bikes into the WE Hub. Depending on the type of day, the scenario took into account or assumed a various number of e-bike batteries and supplementary additional fishing lanterns (see **Table 11**).

Table 11. Scenario for load profile generation.

Type of day	BodaWerk battery target	Cargo battery target	OpiBus battery target	Fishing lantern target	Total electricity demand in kWh / day
Full moon	9	6	9	100	51.9
Non-full moon	9	6	9	200	60.6

Realistic daily runtimes for the future loads were generated for workdays and weekends in line with the year 2021 lunar calendar and then added to the already-existing load profile in **Figure 32**. Using MATLAB, the daily profiles were used to create the annual electrical load profiles. A total of 27,267 kWh of annual energy demand was generated, with a peak demand of 14.8 kWh as shown in **Figure 40**.

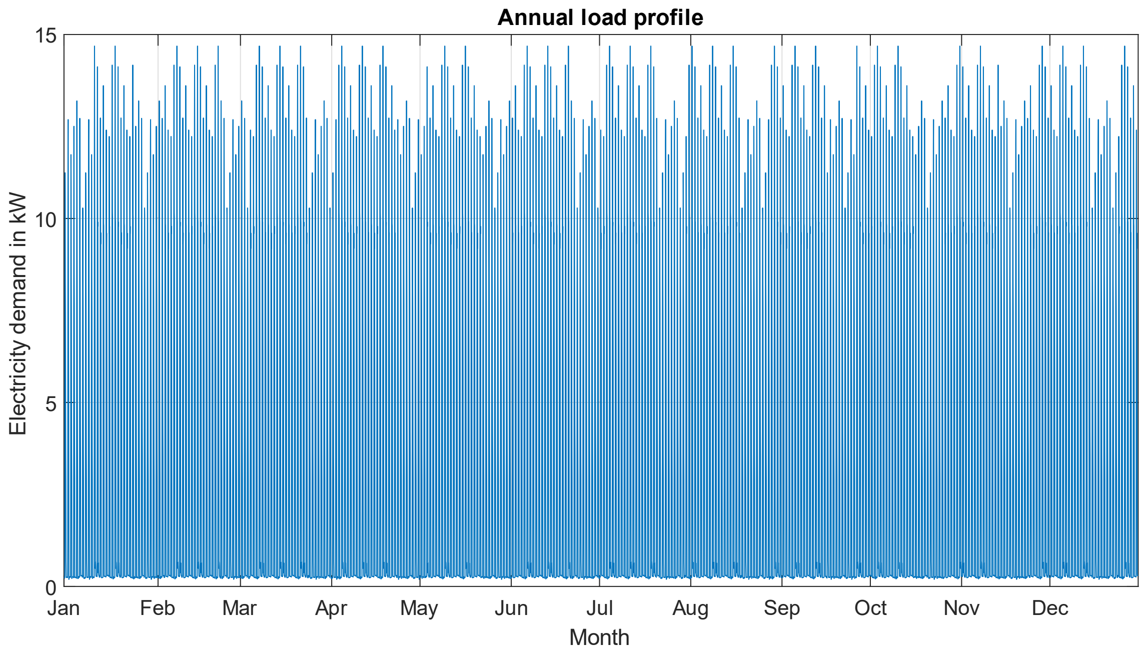


Figure 40: Hourly resolution of WE Hub's annual electricity load profile including e-bikes.

Chapter 4: Development of a simulation model

This chapter presents the simulation model of the WE Hub. Electricity production, demand, battery discharge, and hours with energy deficit were analysed. The simulation assisted in determining the performance of the WE Hub PV system.

4.1 Simulation Model of the *Mbita WeTu Hub*

One of the inputs to the simulation model was the yearly load profile created in the chapter before. Similarly, the simulation model was provided with the matching historical yearly weather data (Meteotest AG, 2020) from Mbita town in a mathematical model. The mathematical model accurately predicts yearly PV power output or annual electricity consumption for a year at hourly precision. As a result, hours with a significant electricity deficit were identified.

4.1.1 Method

The CARNOT toolbox in the MATLAB / Simulink simulation environment was used to create an appropriate simulation model of the Mbita WE Hub (Arnold Wohlfeil, 2019; Bugaje *et al.*, 2021b). CARNOT toolbox was used because it gives designers the liberty set the variables to attain the intended design criteria. The vast quantity of data needed for this research, including weather data, load profile, and other data, makes it essential to adopt a fast computing platform like MATLAB.

Additionally, employing MATLAB also provides the flexibility for fine-tuning and manipulating parameters for control of different off-grid components, which may not be possible when using other available software.

According to the available datasheets, the key components, such as PV modules, inverters, battery storage, and battery inverters (see **Figure 41**), have been parameterized as they are necessary for the simulation (Shukla *et al.*, 2016). An hourly-based weather data of Mbita location and WE Hub’s load profile served as input to the model. The CARNOT program enables an analysis of the system's energy generation, consumption, battery SoC, inverter efficiency, and electricity deficit using time-series data in MATLAB and Simulink.

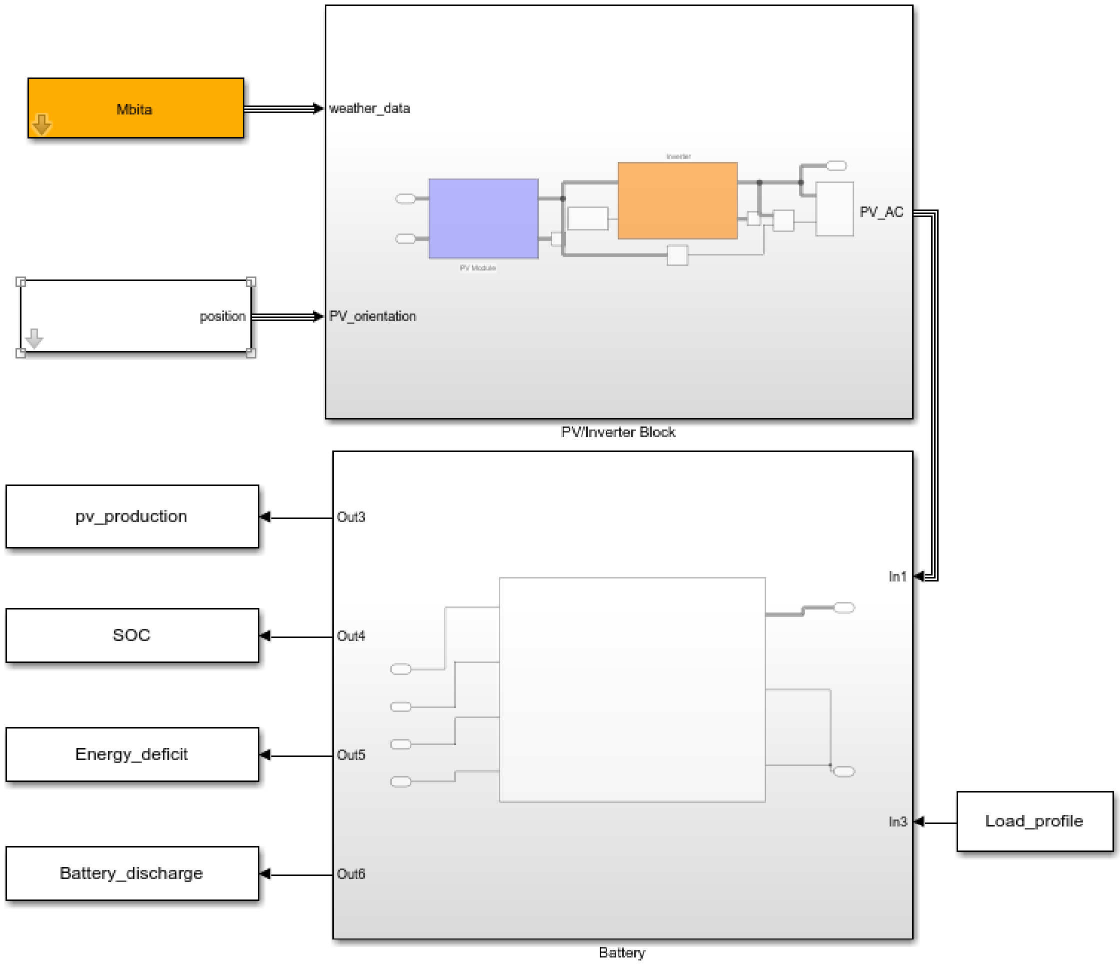


Figure 41: High-level layout of the WE Hub PV system model.

For the modelling, a 30 kWp PV system with a 30 kVA inverter was taken into account. Also taken into consideration was a battery of 104-kWh capacity with a 60-kWh useable capacity (60 % depth of discharge (DOD)). The proportion of the battery's usable energy is represented by the state of charge (SoC). To prevent overcharging and undercharging of the battery, the maximum and lowest SoC of the battery bank is assumed to be 100 % and 40 %, respectively.

4.1.2 CARNOT PV model

The meteorological data, PV module orientation, and PV modules are all part of the CARNOT PV module block set (see **Figure 43**). Equation 4.1 is used by the CARNOT tool to simulate and determine the output power (P) of the PV module in watts (W) based on the module characteristic parameter:

$$P = \frac{S_R}{I_R} \times IAM \times P_{max} \times (1 - (T_a + T_d \times \frac{S_p}{I_R}) - M_T) \quad (4.1)$$

where:

P	=	output power of the PV module in W
S_R	=	solar radiation
I_R	=	incident radiation at STC: 1000 W/m²
IAM	=	incidence angle modifier: 1 for vertical direct solar radiation. It follows the reflection law of Fresnel.
P_{max}	=	peak power (Wp) at STC in W
T_a	=	ambient temperature
T_d	=	temperature difference to ambient at full solar radiation (1000 W/m²): 40 K
S_p	=	solar power
M_T	=	module temperature at STC: 25°C

4.1.2.1 CARNOT PV module input data

The CARNOT PV module block has two inputs which are the weather data and PV orientation. In this project, the weather data of *Mbita* town at *Lake Victoria* in Kenya was used.

4.1.2.1.1 Weather data

The Meteonorm weather database was used to gather the weather information (Meteotest AG, 2020). Information on temperature, solar radiation, humidity, precipitation, wind speed, and other factors are included in the weather data in 1-minute, 15 minutes or 1-hour resolution (Bugaje *et al.*, 2021a, 2021b). The temperature and global solar irradiation of the chosen site are displayed in **Figure 42**. The chosen area receives 1,838 kW/m² of yearly global radiation and an average annual temperature of 22.9 °C. **Figure 42** shows that the maximum sun irradiation occurs in January and May, whereas the lowest solar irradiation occurs in February, April, and June.

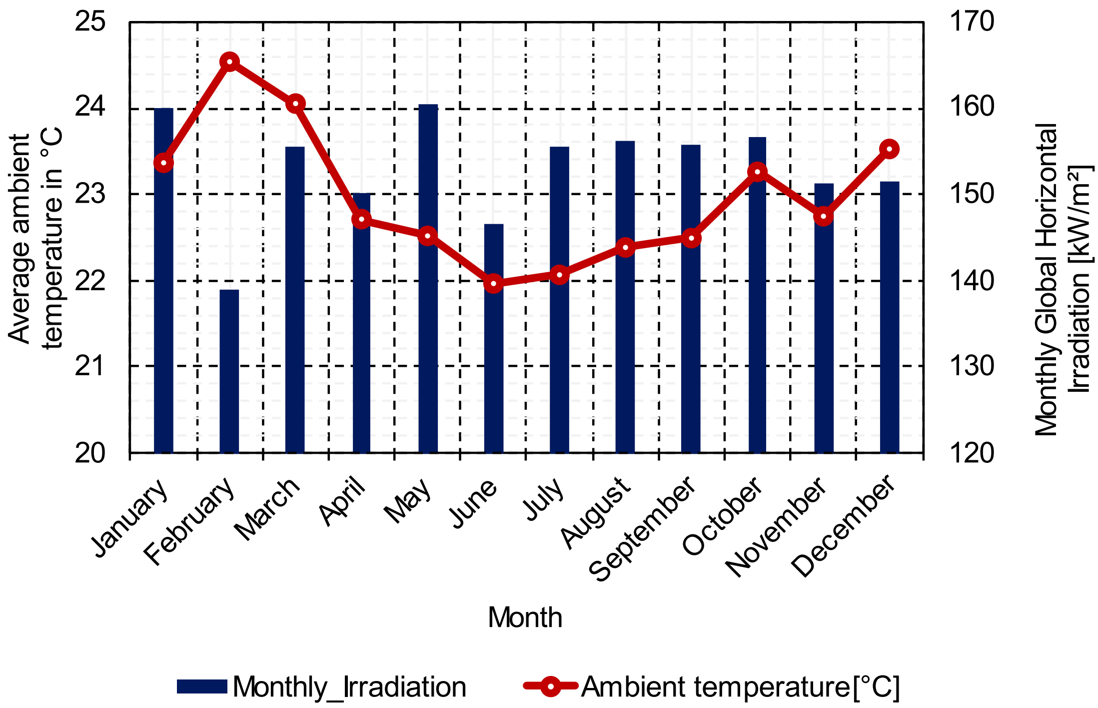


Figure 42: Ambient temperature and solar irradiation of the Mbita location.

4.1.2.1.2 PV orientation

The PV orientation input stores the tilt and azimuth angles of the PV module orientation. According to Kacira et al. (Kacira *et al.*, 2004), the optimal array tilt angles are those between the local latitude plus 8° and 15°, therefore in this investigation, a tilt angle of 5° and an azimuth angle of 180° were selected for improved PV system performance (Bugaje *et al.*, 2021b).

4.1.3 CARNOT PV inverter model

A lookup table is used by the block set "Inverter" in **Figure 43** to simulate the PV AC power while taking the inverter's efficiency into account. The 30 kVA nominal power of the inverter is stored in the block set "Inv capacity." (Bugaje *et al.*, 2021a, 2021b).

4.1.4 CARNOT battery and battery inverter model

The block set in **Figure 44** with the name "battery" determines the maximum quantity of electricity that the storage bank can take in. The block set named "Load demand," which is utilized as the system's input stores the developed electric energy requirements for water purification, fishing lamps, and mobile batteries for e-bikes.

The battery module takes as an input the difference between PV AC and energy demand and stores it as PV AC and energy demand. The battery utilises all extra PV AC power that is available for charge when energy demand is below the PV AC output. The battery discharges to provide the necessary energy when PV AC generation falls short of the energy demand. The maximum charge power varies from one one-time step to the next depending on the battery's state of charges and discharges (Bugaje *et al.*, 2021b).

Solar irradiance, PV production from the solar (Pcharge_DC), PV production from the inverter (Pcharge_AC), battery state of charge (SoC), energy deficit (Punder), and battery discharge (Discharge_DC) were then taken into account for system performance analysis as outputs of the system, as illustrated in **Figure 44**.

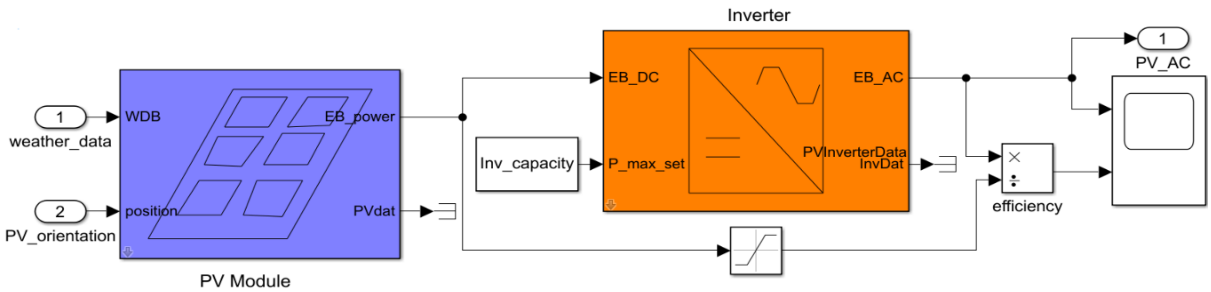


Figure 43: Mid-level CARNOT model of the PV system

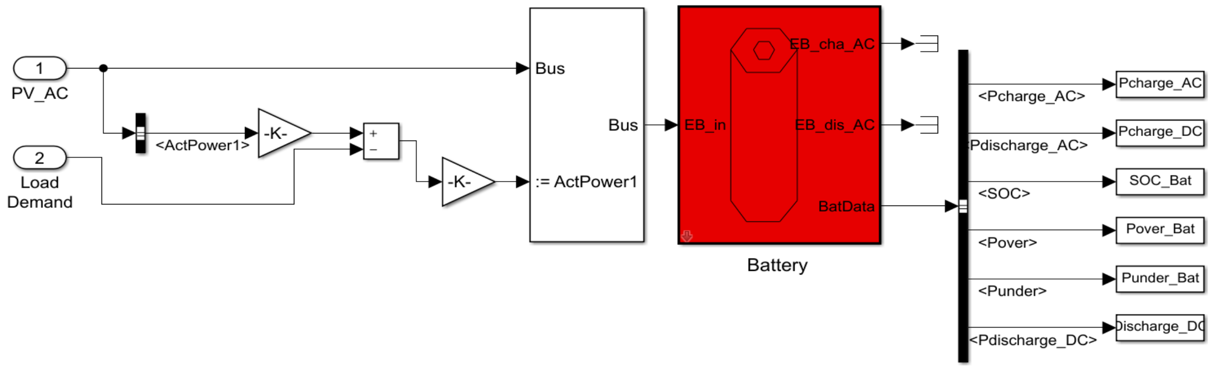


Figure 44: Mid-level CARNOT model of the PV system

4.2 Simulation results without e-mobility

In **Figure 45**, the entire annual hourly PV electricity production is shown as being 37,785 kWh, together with the demand for electricity at 6,278 kWh and the excess electricity at 30,493 kWh. Due to the PV system's ability to meet the whole annual electricity demand, there was a 0-kWh electricity deficit. **Figure 45** also shows that due to the low electricity demand, the battery SoC wasn't below 80%. As a result, the number of e-bike batteries that must be charged each day at the WE Hub will be based on the surplus power generated.

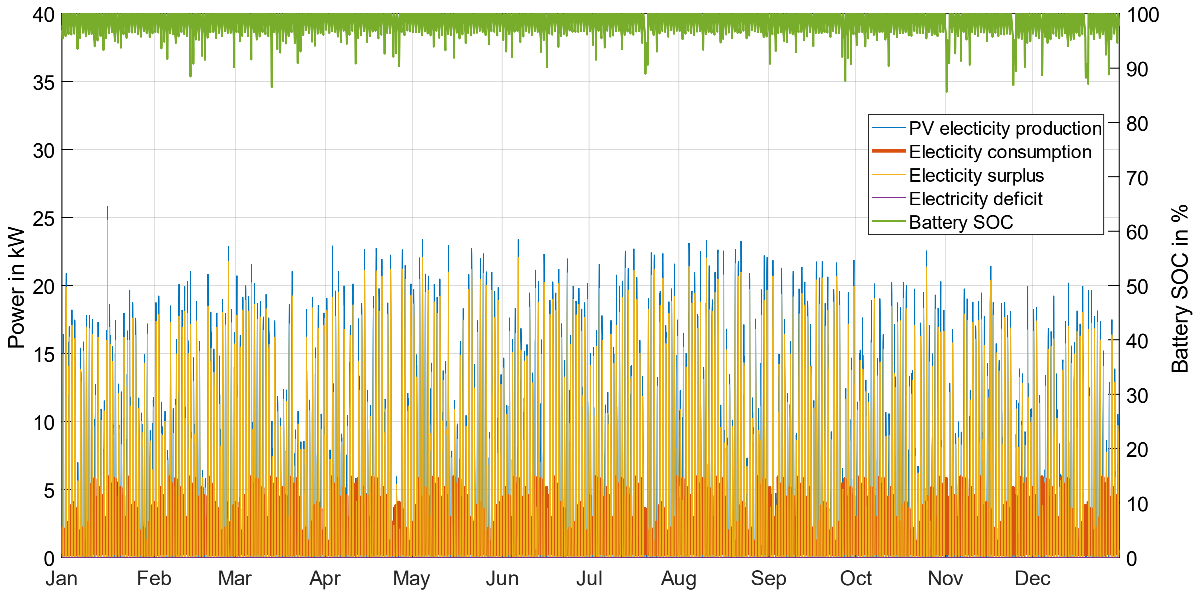


Figure 45: Hourly resolution of annual PV electricity production, consumption, and the surplus in kW.

4.3 Simulation results with e-mobility

The annual PV electricity production, demand, and deficit in hourly resolution are displayed in **Figure 46**. The result presents an electricity deficit of 375 kWh which means that the Mbita system could not cover the future loads. The electricity deficit is lowest from June to September. Due to the weather, November has the biggest electricity deficit, followed by May and April. The obtained annual PV electricity production and demand are 37,700 kWh and 27,200 kWh respectively. The lowest electricity production week in the entire annual result was in April and is depicted in **Figure 47**. This results in the largest energy deficit of 70.6 kWh for the whole month.

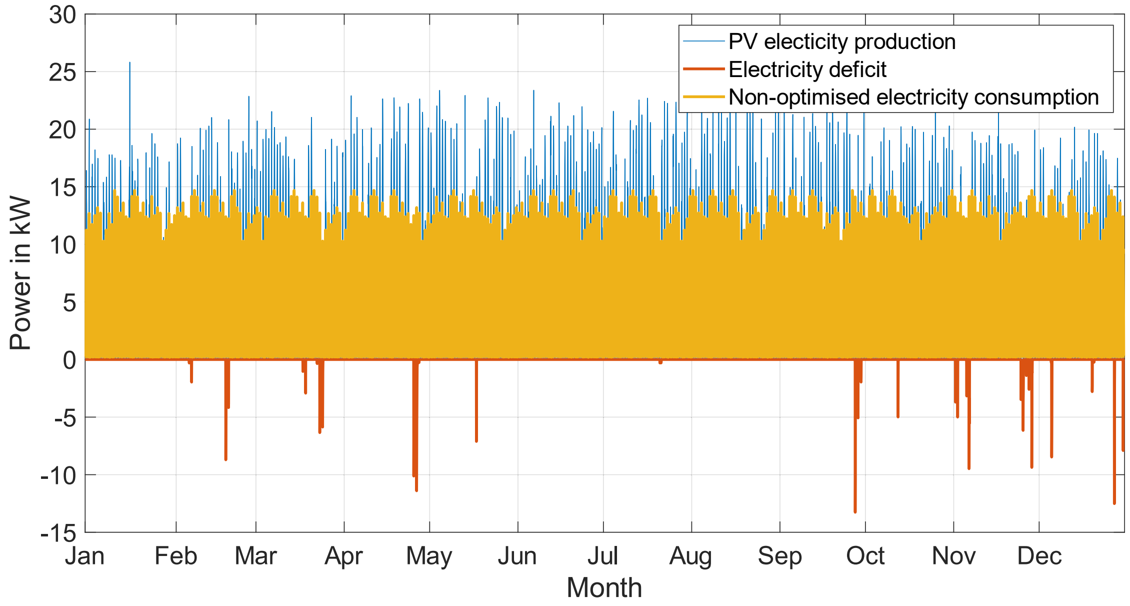


Figure 46: Hourly resolution of annual PV electricity production, consumption and deficit in kW

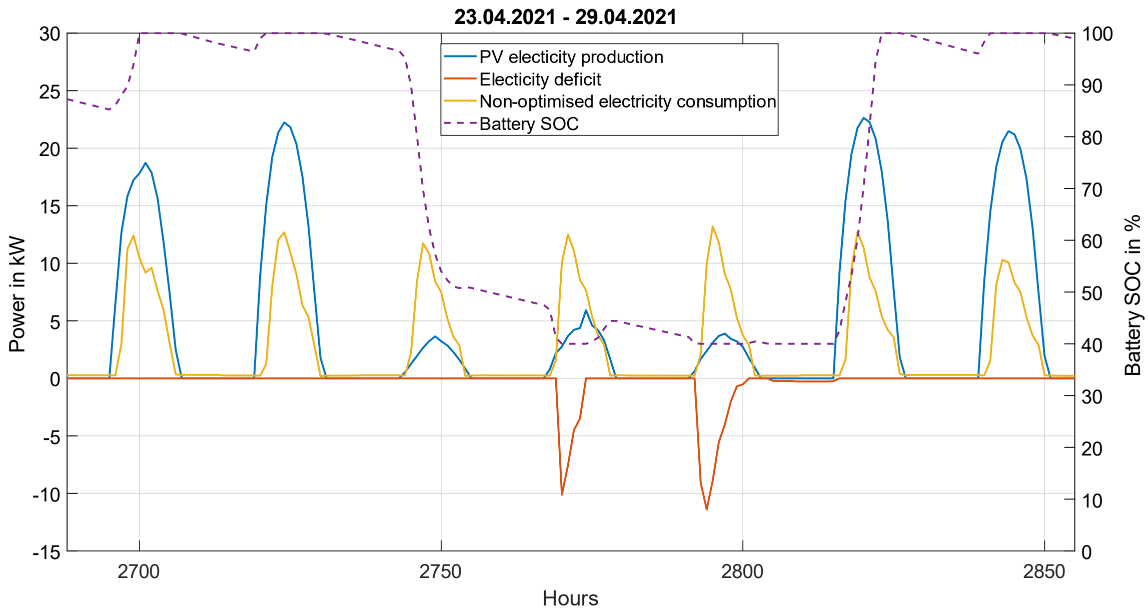


Figure 47: Hourly PV electricity production, demand, and deficit in kW for a week in April (23.04 – 29.04).

Additionally, **Figure 47** shows that the backup battery was depleted to its predetermined minimum SoC of 40% between hours 2768 and 2800 as a result of poor PV electricity output.

Hence the first question “ ***can the existing system cover the future loads?*** ” was successfully answered in this chapter. The next chapter provides an answer to the second research question.

Chapter 5: Development of a load optimisation algorithm

To better integrate electric mobility into the investigated Mbita WE Hub, this chapter presents the development of a load management algorithm using nonlinear programming (NLP). By maximizing the use of PV production, the NLP reduced the burden on the central backup batteries, the energy deficit, and the cost of energy.

5.1 Overview

To reduce overloading on the demand side, the goal in this situation is to regulate the loads rather than the power generation. The limitations on the charging capacity and the order in which the various electric loads are prioritized will have an impact on this.

The size and performance of PV systems are highly influenced by metrological factors such as solar radiation, wind speed, and ambient temperature. Oversizing can solve the reliability problem, but it could be costly. Due to their low energy density and non-negligible self-discharge rate, battery storage systems (BSS) are typically employed for short-term storage (George Kyriakarakos *et al.*, 2015), but they appear to be insufficient for long-term storage (Cau *et al.*, 2014). Therefore, proper load optimisation is necessary for an off-grid PV system to be profitable (Maleki and Askarzadeh, 2014a).

Consequently, several researchers have offered numerous optimisation techniques. For instance, (Maleki and Askarzadeh, 2014b; Maleki and Pourfayaz, 2015) examine several evolutionary algorithms (EA) for an optimum hybrid system size, using the total annual cost as the goal function. In contrast to other publications, [13] employs ant colony optimization (ACO) to determine the sizes of PV/wind hybrid systems.

In (Maleki and Askarzadeh, 2014a), artificial bee swarm optimization (ABSO) is utilized to address the PV/WT/FC hybrid system's size issue while taking the possibility of power supply failure into account (LPSP). (Maleki *et al.*, 2015) investigates how various particle swarm optimization (PSO) algorithm variations perform in predicting the size outcomes of hybrid (PV/Wind/Batt) systems.

5.2 Non-Linear Programming (*NLP*) for load optimisation

By Utilizing the MATLAB fmincon solver for NLP, the load optimization algorithm is created with the fundamental goal to capture the most available PV-generated power possible, after which a limited number of electric loads are sized and scheduled.

NLP is an optimisation problem that involves minimizing a variable-expressed objective function while adhering to inequality and nonlinear equality constraints. To guarantee that the load sizing is appropriate and prevent system overloads at the same time, constraints are required. The concept of the NLP-based load optimisation algorithm is depicted in **Figure 48.**

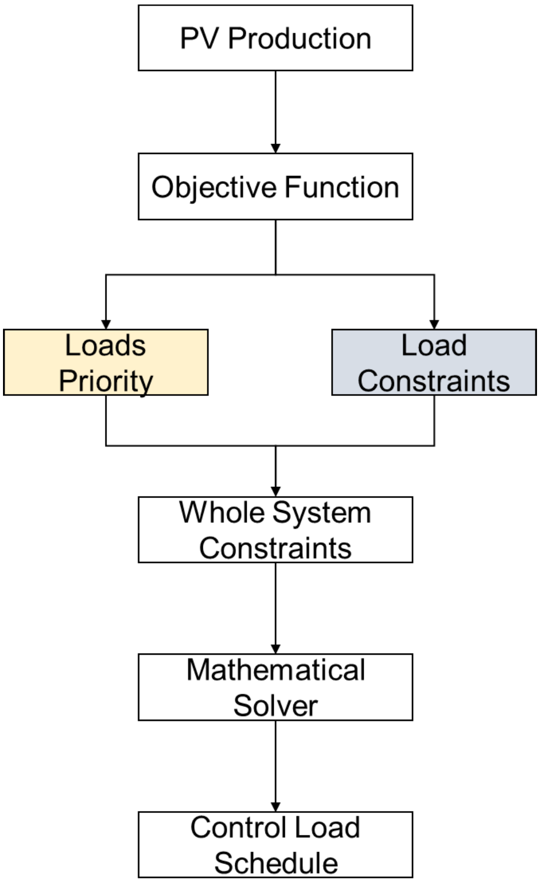


Figure 48: Overview of the *NLP*-based load optimisation algorithm.

The NLP approach uses a branch and cut algorithm to arrive at the global optimal solution (IBM, 2010), in contrast to the Lagrangian relaxation technique, which solves large-scale issues while sacrificing global optimality (Bertsekas *et al.*).

An objective function, constraints, and variable boundaries have to be solved, similar to linear programming. However, a nonlinear program differs in such that at least one nonlinear function must be included, which might be the objective function or some or all of the constraints. The minimum of a problem defined by equation 5.1 is found using the MATLAB nonlinear programming solver.

$$\text{Minimise } f^T x \text{ subject to } \begin{cases} c(x) \leq 0 \\ ceq\ (x) = 0 \\ A.x \leq b \\ Aeq.x = beq \\ lb \leq x \leq ub \end{cases} \tag{5.1}$$

Where A and Aeq are matrices, whereas $c(x)$ and $ceq\ (x)$ are non-linear functions that return vectors, $f(x)$ is a non-linear function that returns a scalar and b and beq, are vectors. x, lb, and ub can be used as either vectors or matrices. For the objective function to be accurately solved, equality constraint $Aeq.x = beq$, $A.x \leq b$ and $lb \leq x \leq ub$ non-equality constraints must be taken into account (Bugaje *et al.*, 2021a).

5.3 Load optimisation problem formulation

The objective function that takes into account each load's charging capacity, operational priority, and maximum number of loads recharged per hour formulates the load optimization issue. The objective function is then minimized at a certain PV generation using the NLP fmincon solver by carefully planning the scheduling of the various loads.

5.3.1 The objective function of the problem

The derived objective function for the research problem is shown in equation 5.2

$$\text{fun} = \sum_{k=1}^{n}\left(LP_k(t) \times Aeq_k(t)\ .x_k(t)\right) \tag{5.2}$$

Where Aeq_k is the charging rate of each load per hour in kW, n is the number of the load types shown in **Table 12**, and LP_k is the priority of each load at any given time (t). x_k is the hourly target of the various loads that can be optimized at any given time (t). Equation 5.3 depicts the ultimate objective function for the given situation, where lanterns are given priority, followed by Cargo, BodaWerk and OpiBus bikes in second, third, and fourth place, respectively.

$$\text{fun} = (\ 1 \times 37\ .x_1) + (2 \times 200\ .x_2) + (3 \times\ 800\ .x_3) + (4 \times 900\ .x_4) \tag{5.3}$$

5.3.2 Constraints of the problem

Any optimisation problem must take into account various equality and inequality constraints to attain an effective solution to the objective function. Below is the constraint that is taken into account while solving the optimisation problem.

5.4 Inequality constraints

The entire load demand $\sum_{k=1}^{n}(Aeq_k(t) \,.\, x_k(t))$ should not exceed the PV-generated power (beq) to keep the system in balance and satisfy the load demand at any given time (t). This is given by equation 5.4:

$$\sum_{k=1}^{n}(Aeq_k(t) \,.\, x_k(t)) \leq beq\,(t) \tag{5.4}$$

Each load's hourly target (i.e., x_k, x_{k+1}) that may be charged at any given time (t) shall not be more than the maximum hourly target of each load (i.e. ub_k, ub_{k+1}) and so should not be less than the minimum hourly target number which is 0 for each load (i.e., lb_k, lb_{k+1}). This is given in equation 5.5

$$\sum_{k=1}^{n}(lb_k(t) \leq x_k(t) \leq ub_k\,(t)) \tag{5.5}$$

Table 12. Mbita WE Hub load overview

Type of loads (n)	Daily battery target	Peak sun hours (hr)	Charing time (hr) per device	Hourly battery target (x_k)	Charging rate (W) per device	Energy required (Wh) per device
Cargo bike	6	6.5	7	5	200	1,050
Lanterns	200	6.5	2.8	193	37	105
OpiBus bike	9	6.5	2.7	4	800	2,160
BodaWerk bike	9	6.5	2.4	4	900	2,200

Hourly target = Daily battery target ÷ (peak sun hours ÷ charging time)

5.5 *NLP* load optimisation algorithm simulation results

Based on the NLP load optimisation algorithm developed in MATLAB, load demand for the e-bike batteries and fishing lanterns was generated as they are the major consumers at the WE Hub. To track intra-day solar PV power, the developed algorithm first captures the most variable solar PV generation possible. It then sizes and schedules a limited number of loads (such as e-bikes and fishing lanterns) and then generated load profiles for weekdays and weekends based on moon phases.

The PV power production for today and tomorrow are also checked by the NLP optimisation algorithm. A portion of tomorrow's loads is moved to today if tomorrow's PV power generation won't be able to meet the daily demand by reducing today's surplus and allocations tomorrow's load to today. The overview of the NLP load optimization algorithm with the load shifting is shown in **Figure 51**.

After optimization, a load profile of 31,300 kWh per year was produced, an increase of almost 11% above the non-optimized load profile of 27,200 kWh. This increment is enough to charge 4 more OpiBus bike batteries every day or 80 more fishing lamps. **Figure 49** shows the hourly results of the electricity PV production, demand, and deficit using NLP based algorithm. The simulated PV system produced 37,700 kWh annually and had a reduced energy deficit of 50 kWh from 375 kWh for the non-optimised system.

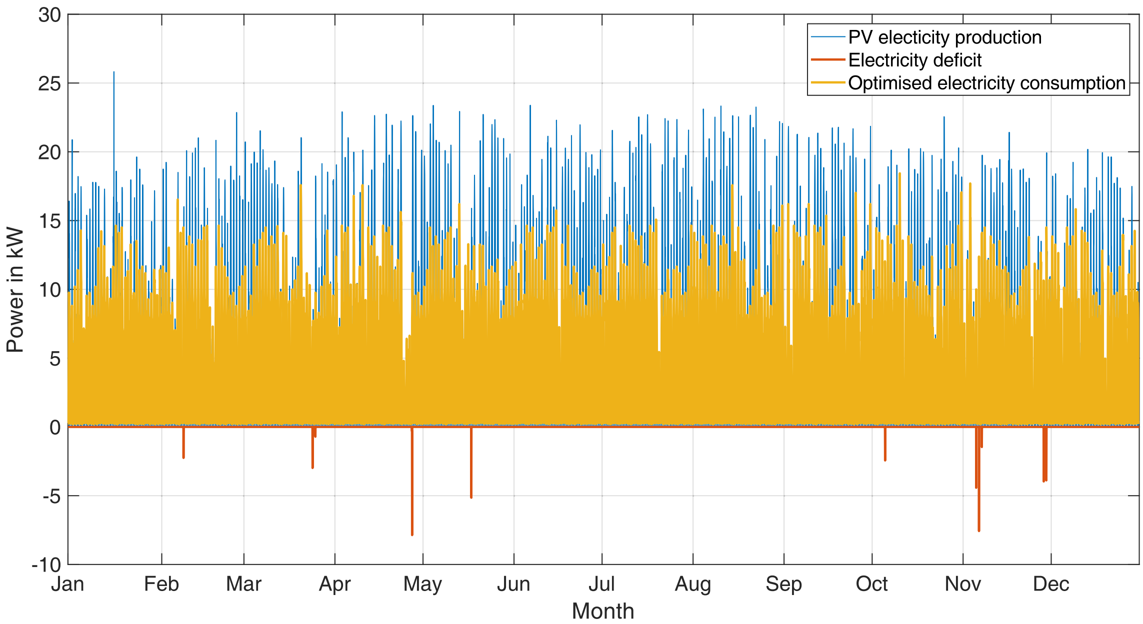


Figure 49: Load shifting and optimisation result.

The outcome of **Figure 47** after load shifting is seen in **Figure 50**. The major loads, which are depicted in **Figure 50**, were shifted to hours with excess energy and optimized to decrease the electricity deficit. Similarly, because of the possible deficit of energy in hours, 2744 to 2756 part of the loads was shifted to hours between 2718 and 2730. The load shifting is solely restricted to the number of devices that are available in stock to be charged during hours 2744 to 2756 and the energy surplus during hours 2718 to 2730.

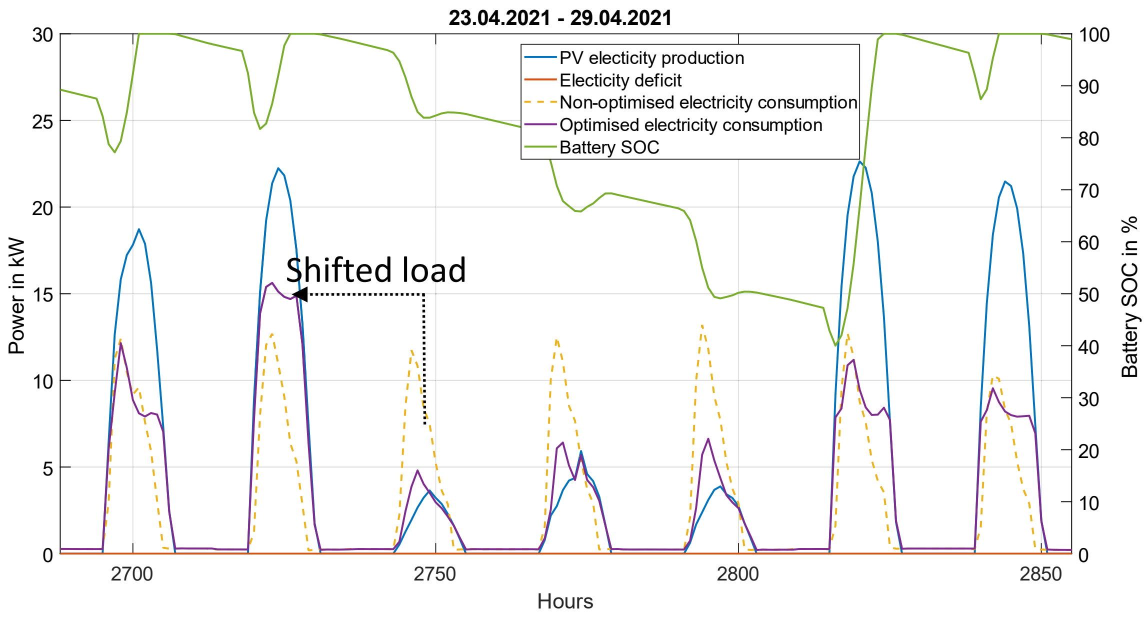


Figure 50: Load shifting and optimisation for a week in April

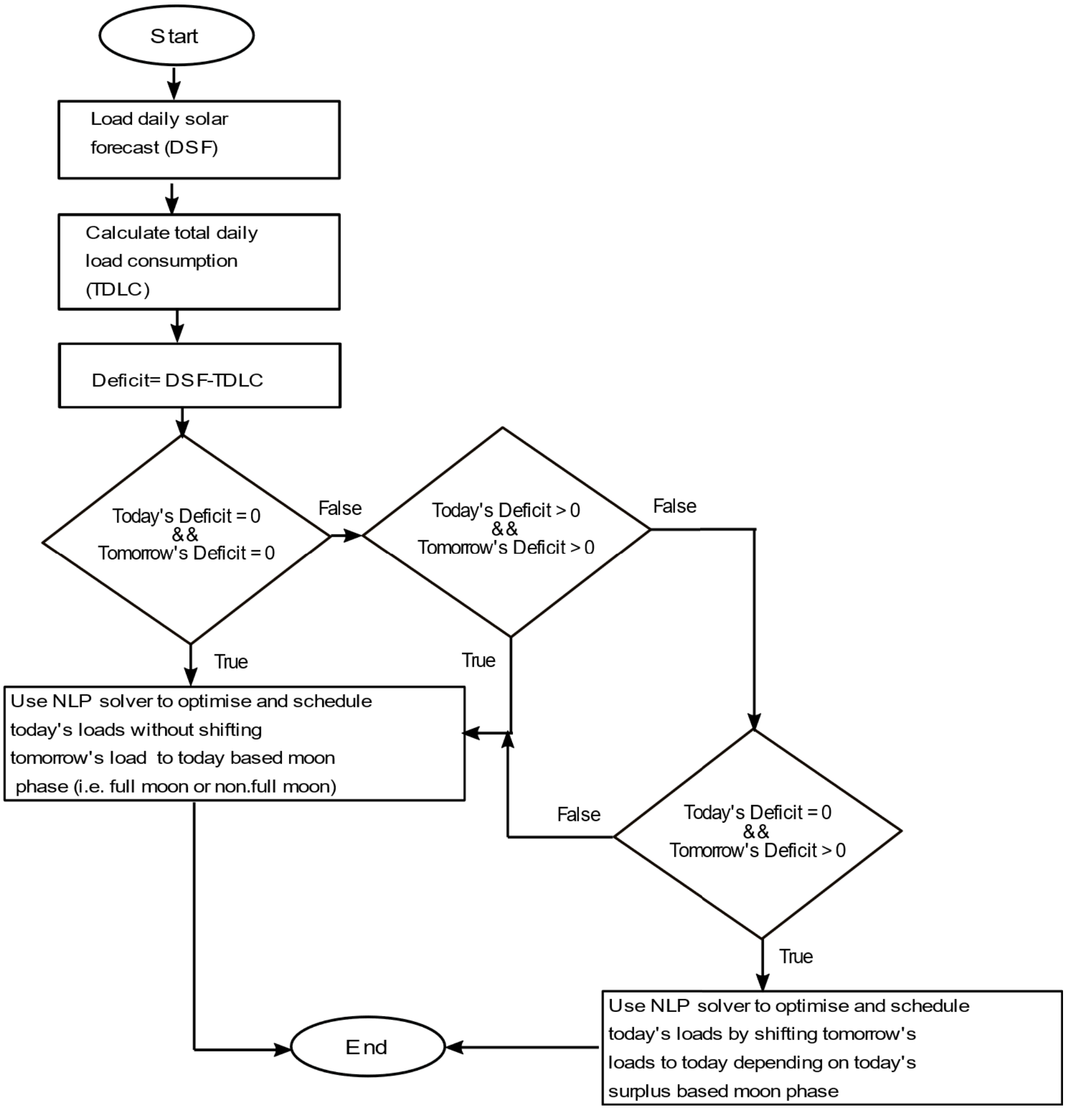


Figure 51: Overview of the *NLP* load optimisation algorithm with load shifting concept.

Without necessarily requiring a larger PV system, the use of a grid connection, or the use of a diesel generator, the development of a load optimization algorithm using the MATLAB NLP solver assisted in the optimum integration of the e-bikes into the Mbita WE Hub. This is achieved by maximizing the utilisation of solar PV production, hence distributing the various loads throughout the day in line with PV production. The algorithm has also helped in reducing the energy deficit and lessening the burden on the backup batteries.

As a result, the load optimisation algorithm based on MATLAB NLP has aided in the most cost-effective incorporation of e-bike solutions Mbita WE Hub. Therefore, this chapter has adequately addressed the second research question ***"In the case of energy deficit, how best can the different loads be possibly distributed throughout the day?"***.

5.6 Summary

It can be seen in **Table 13** that the PV capacity of 30 kWp was maintained for both systems while battery capacity was reduced from 104 kWh to 50 kWh for NLP based system. As a result, the annual electricity consumption was increased from 27,200 kWh to 31,300 kWh for NLP based system.

Table 13. Results of the simulation-based scenarios for non-optimised and optimised load profiles.

Parameters	**Non-optimised load profile**	**Optimised load profile**
e-*OpiBus* bike battery daily target	9	13
e-*BodaWerk* bike battery daily target	9	9
e-Cargo bike battery daily target	6	6
e-Lanterns daily target	450	450
Auxiliary load in kWh	5	5
PV size in kWp	30	30
Battery size in kWh	104	90
Average daily energy demand in kWh	74	84
Annual energy PV production in kWh	37,700	37,700
Annual energy demand in kWh	27,200	31,300
Annual energy deficit in kWh	375	50

Chapter 6: Development of a solar optimisation design tool

Part of the objectives of this research is to develop a technical blueprint that could facilitate the implementation of a similar project anywhere around the world. A MATLAB computer application (MATLAB App) was designed to assist the operator in planning any PV system size as well as schedule and optimise the load charging throughout the day for any location using 7-days PV forecast.

6.1 MATLAB GUI App Designer

The App Designer allows developers to design apps without little knowledge of software development. Developers can use graphic components to design the graphical user interface (GUI), and then use the integrated editor to swiftly write the code. MATLAB Compiler™ is used to distribute the app as web apps or a standalone computer desktop application (MATLAB, 2020).

6.2 Operation of the App

6.2.1 Tab 1 – Parametrisation of e-mobility and non-mobility loads

The operator is given the chance by the *MATLAB App* to size a PV and central battery system (see **Figure 52**) based on the different load specifications such as electricity consumption of electric bike in kWh / 100 km, the energy capacity of electric bike batteries, charging rate, distance covered per day, etc. The *MATLAB App* also gives the operator the ability to set non-electric mobility loads such as fishing lanterns and other electric appliances.

The *MATLAB App* also gives the operator the chance to set central battery days of autonomy, nominal battery voltage, battery depth of discharge, and peak sun hours of the location. This results in the calculation of the estimated total PV capacity and battery capacity required for the set loads.

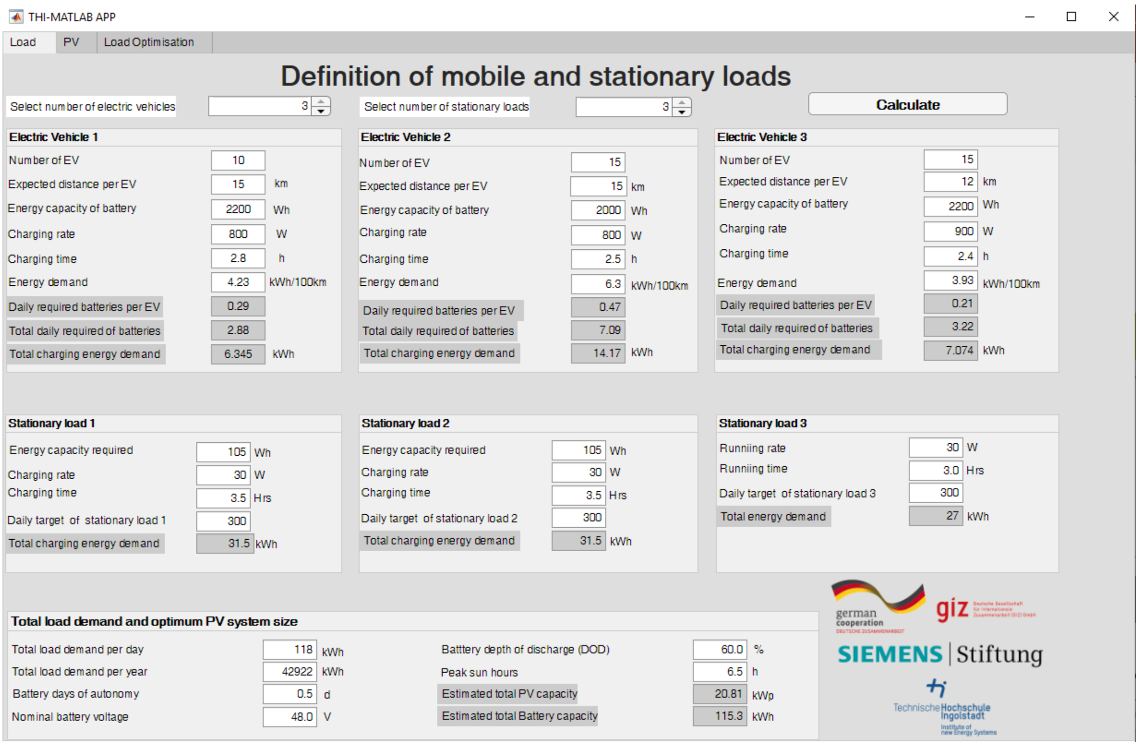


Figure 52: Tab 1 Parametrisation of e-mobility and non-mobility loads.

6.2.2 Tab 2 – PV system characterization

The operator is given the chance by the *MATLAB App* to calculate the annual energy yield of the PV system based on the performance ratio of the system, number of PV modules, global horizontal irradiation of the system location, etc.

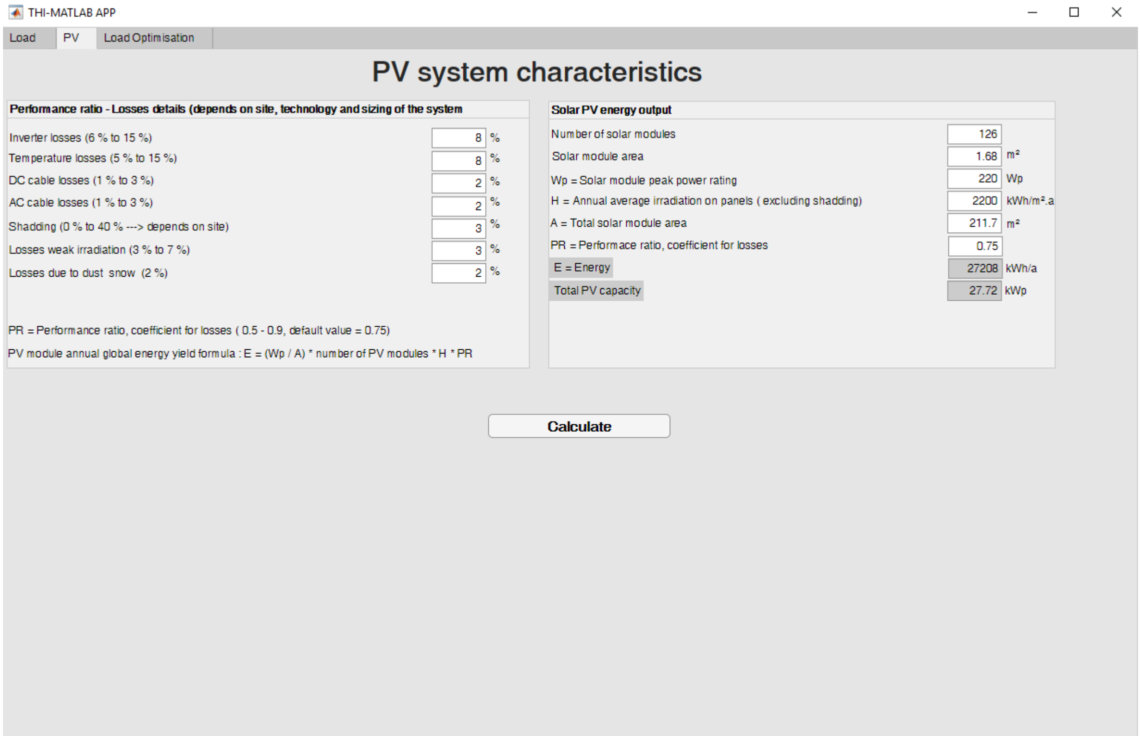


Figure 53: Tab 2 PV system characterization.

6.2.3 Tab 3 – Load optimisation

The operator is given the chance by the *MATLAB App* to use the developed *NLP* load optimisation algorithm in a user-friendly manner. The *NLP* load optimisation algorithm optimises, shifts and schedules the various loads of the operator throughout the day by prioritising the various loads and using the downloaded PV forecast of any location from the internet via the Solcast website (Solcast, 2020).

Finally, the operator is given the chance by the *MATLAB App* to download the results of the load optimisation in Microsoft Excel for further action (see **Figure 54**).

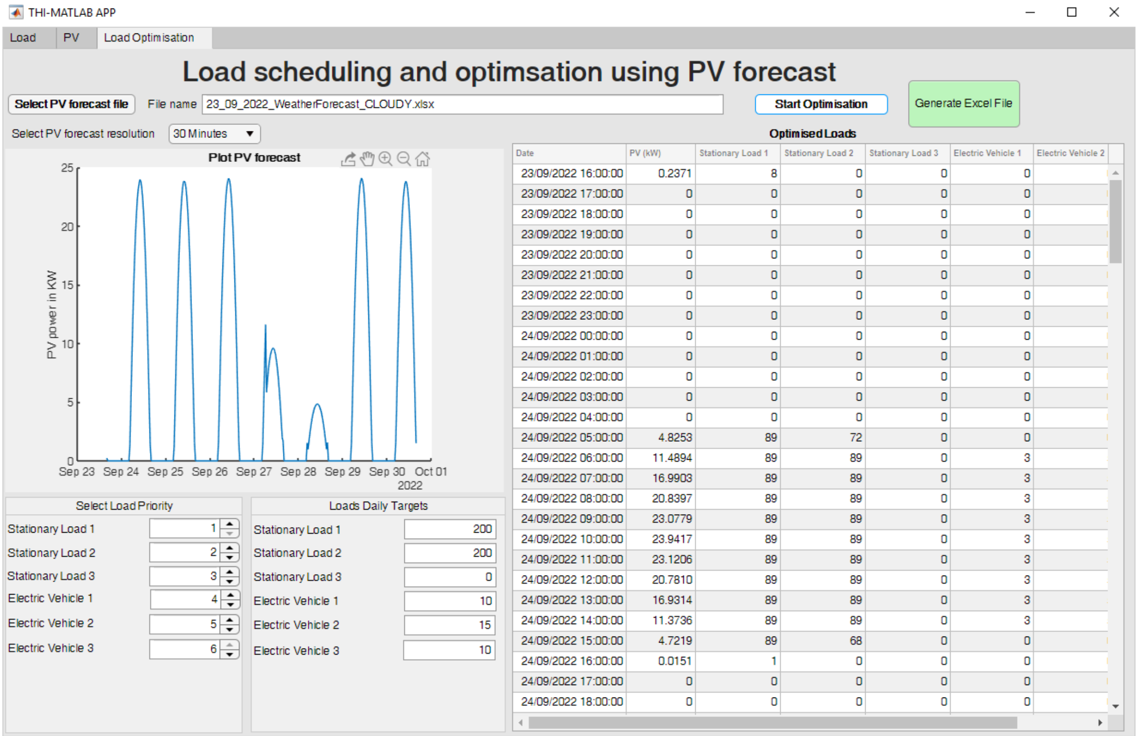


Figure 54: Tab 3 - Load optimisation.

Chapter 7: Techno-economic analysis

This chapter presents the calculated levelized cost of electricity for the 30 kWp kWp PV system considering the system with and without load optimisation algorithm

Numerous methods, including net present value (NPV), discounted payback time (DPBT), internal rate of return (IRR), and Levelized Cost of Electricity (LCoE), may be used to evaluate the economics of PV systems (Spertino *et al.*, 2013; Talavera *et al.*, 2011; Danchev *et al.*, 2010). The latter, known as LCoE, is the average revenue per unit of electricity produced that will be required throughout a production plant's anticipated financial life and duty cycle to pay its construction and operation expenses. LCoE is widely used as a broad estimate of the competitiveness of different electricity-generating technologies (Energy Information Adminstration, 2020).

Capital expenses, fuel costs, fixed and variable activities, maintenance (O&M) prices, finance costs, and the expected consumption rate for any kind of plant are the primary inputs for calculating LCoE. The importance of each of these inputs varies depending on the technology. LCoE changes proportionally to the expected cost of technology for fuel-free technologies with relatively minor variable O&M charges, such as solar and wind power production. Capital expenditures, operational expenses, and maintenance projections all have a significant impact on LCoE for systems with high fuel prices (Energy Information Adminstration, 2020). **Figure 55** shows a simple concept of LCoE (Søren *et al.*, 2009).

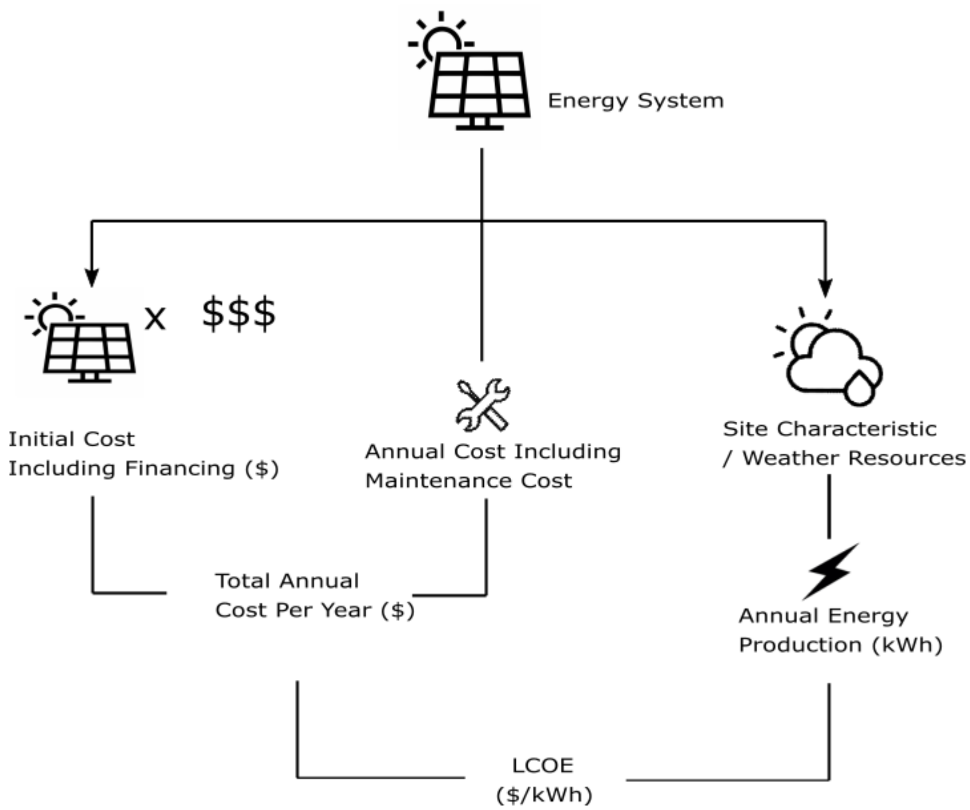


Figure 55: Simple Concept of LCoE (Søren *et al.*, 2009).

The standard formula used for calculating the LCoE of renewable energy technologies is (IRENA, 2012):

$$LCoE = \frac{I_0 - S_0 + \sum_{t=1}^{T} \frac{M_t(1-TR)+F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \quad (6.1)$$

where:

LCoE	=	Levelized Cost of Electricity in € / kWh
I_0	=	Investment costs in €
S_0	=	Subsidies in €
Mt:	=	Annual operating and maintenance
TR	=	Corporate income tax in%
E_t	=	Annual energy generated in kWh
F_t	=	Fuel Expenditure per Annual
r	=	Discount rate in %
T	=	Observation Period / Economic Life of the System (20 years)

7.1 LCoE without load optimisation algorithm

For this research, S_0 and TR were neglected. **Table 14** shows the system configuration used for the calculation of the LCoE of the designed 30 kWp PV system. **Table 15** shows the investment cost used for the calculation of the designed 30 kWp PV system.

Table 14. System Configuration for LCoE Calculation

System Configuration	**Value**
Number of modules	138
Module area in m²	231.84
Battery storage capacity in kWh	104
Battery usable capacity in kWh	62
Annual energy demand in kWh/a	27,200
Annual energy produced in kWh/a	37,700
Annual energy deficit in kWh/a	375

Table 15. Investment Cost for LCOE Calculation (based on contractor’s quotation)

Description	**Value**
Solar array in €	27,600
Battery storage in €	23,650
Solar inverter in €	5,158
Battery inverter in €	6,000
Other components in €	2,000
Mounting in €	1,000
Total investment cost in €	**66,408**

Table 16 shows Kenya's economic variables used for the calculation of the LCoE of the designed 30 kWp PV system. The variables such as inflation rate and interest rate were converted from Kenyan Shillings to Euro for easy computation. Discount rate (r) is calculated using the formula in equation (6.2)

$$r = \frac{r_{interest} - r_{Inflation}}{1 + r_{Inflation}} \tag{6.2}$$

Table 16. Kenya's Economic Variables for LCoE Calculation (Macrotrends.net, 2020; Tradingeconomics.com, 29- Sep- 2019)

Description	**Value**
Inflation in %	4.69
Interest rate in %	7.00
Discount rate in %	2.21

7.2 LCoE using load optimisation algorithm

Table 17 shows the system configuration used for the calculation of the LCoE of the designed 30 kWp PV system with an NLP optimiser. The battery capacity was reduced from 104 kWh for the non-NLP optimiser system to 90 kWh for the NLP optimiser system which lessened the battery cost by 13 %. **Table 18** shows the investment cost used for the calculation of the designed 30 kWp PV system.

Table 17. System Configuration for LCoE Calculation

System Configuration	**Value**
Number of modules	138
Module area in m²	231.84
Battery storage capacity in kWh	90
Battery usable capacity in kWh	54
Annual energy demand in kWh/a	31,000
Annual energy produced in kWh/a	37,700
Annual energy deficit in kWh/a	50

Table 18. Investment Cost for LCOE Calculation (based on contractor's quotation)

Description	**Value**
Solar array in €	27,600
Battery storage in €	20,339
Solar inverter in €	5,158
Battery inverter in €	6,000
Other components in €	2,000

Mounting in €	1,000
Total investment cost in €	**63,097**

The load optimisation algorithm was able to reduce the annual energy deficit from 375 kWh to 50 kWh, and the operation and maintenance cost remains the same as for the system without load optimisation. **Table 19**, shows the calculated LCoE considering equation 6.1 for the 30 kW_p PV system.

7.3 Summary

Table 19. LCoE of system with and without load optimisation

LCoE without load optimisation	**LCoE with load optimisation**
18.24 €-Ct/ kWh	17.07 €-Ct/ kWh

It can be seen in **Table 19** that the LCoE for the system with and without NLP load optimisation is 17.07 €-Ct/ kWh and 18.24 €-Ct/ kWh respectively (**see appendix 1.1** and **1.9**). It can be seen that the system with NLP yields a cheaper cost of electricity because of the use of a lesser central battery bank capacity of 90 kWh as against 104 kWh for a non-NLP system.

Therefore, the load management algorithm has proven to be a good option to reduce the energy deficit, maximise the utilisation of PV power production as well as cut down investment costs.

Conclusion

Using MATLAB, Simulink, and CARNOT 7.0 Toolbox, this study investigated the integration of e-bikes into an off-grid 30 kWp WE Hub PV system in rural Kenya. Analysis of the PV system's electricity production, demand, and the deficit was carried out, this resulted in annual electricity demand of 27,200 kWh and a PV electricity production of 37,700 kWh, respectively for a non-optimised load profile system. Since the size and performance of PV systems are highly dependent on metrological factors like solar radiation, wind speed, and ambient temperature, the system with the non-optimised load profile shows an annual power deficit of about 375 kWh. That indicates that owing to the aforementioned PV system variabilities, the system was unable to completely meet the WE Hub's electricity demand.

In order to avoid increasing the technical scale of the PV system or the requirement for diesel generators for energy deficit reduction, a load management algorithm (NLP algorithm) was created to effectively integrate the e-bike solutions into the WE Hub. The most variable solar energy was captured by the load management algorithm, which sizes and schedules a certain number of devices to follow available solar PV power. After load optimization, 31,300 kWh of annual electricity consumption—11% more than the non-optimized load profile of 27,200 kWh—was attained. For instance, this 11% increase (3,500 kWh) is enough to charge 80 more lanterns per day or 4 more OpiBus batteries per day.

The additional results obtained show that the system with the NLP algorithm was able to maintain the same PV capacity of 30 kWp and reduce the central battery capacity from 104 kWh to 90 kWh, thereby reducing the annual energy deficit for the system without NLP optimization from 375 kWh to 50 kWh. Similarly, by implementing an NLP load optimiser-based system, expenses for buying additional PV modules, and inverters were avoided and central battery capacity cost was reduced. As a result, the NLP-based system assisted in the low-cost and efficient integration of electric mobility solutions into the Mbita WE Hub off-grid PV system.

To aid with the knowledge transfer of the research objectives to additional locations and energy hubs, a *MATLAB App* was created. Based on the available loads, the operator may hypothetically size a PV and battery system using the *MATLAB App* (i.e., fishing lanterns or electric vehicles). For the best integration of electric mobility solutions into any rural off-grid PV system at cheap capital costs, it also included the created MATLAB NLP algorithm for load scheduling, shifting, and optimization.

The Mbita WE Hub has proven to provide a cheaper cost of electricity compared to the cost of electricity for grid connection which stands at 21.10 €-Ct/kWh in Kenya. The system with the NLP algorithm has an LCoE of 17.04 €-Ct/kWh compared to 18.24 €-Ct/kWh for the system with the non-NLP algorithm. This is because the NLP system had a reduction in the central battery capacity from 104 kWh for the non-NLP system to 90 kWh. Hence, for example, to fully charge a 2.2 kWh e-bike battery, the user is required to pay 37.55 €-Ct and 40.13 €-Ct for NLP based system and a non-NLP system respectively.

Based on a study conducted by Siemens Stiftung (research partner) on leasing the e-bike and battery to riders. The leasing options consisted of pay-as-you-swap and flat rates. In the flat rate lease option, the rider pays a bike lease fee of 450 KES with and battery lease fee / swap of 0 KES (battery swaps paid for battery use). In the pay-as-you-swap option, the rider pays a bike lease fee of 200 KES with and battery lease fee / swap of 70 KES (unlimited battery swaps).

According to the study, riders who used the battery pay-as-you-swap leasing option covered less kilometers than rider who used flat rate leasing option. However, the study further shows that the riders with the pay-as-you-swap leasing option drain the battery more. This could be a result of the cost-per-swap pricing model, where they aim to use every battery to the fullest extent possible. Throughout the study, the discharge pattern of the battery was improved by the groups as more awareness was rendered to them on the issue of battery discharge beyond the manufacturer's recommendation.

The volume and number of customers progressively rose over time, reaching seven consistent customers in October 2021 from two clients in April 2021. Consistent marketing and the offering of multiple lease models tailored to varied client demands are the two factors that might explain the rising demand. External factors such as rising gasoline prices might also contribute to the growing acceptability of e-motorbikes in the Lake Victoria region.

Recommendations

The following recommendations have been identified for a possible extension of the research:

Business model

Implementing new technologies might be difficult, particularly in rural areas. A suitable business strategy is therefore essential for addressing socioeconomic and infrastructure problems.

By offering various leasing options that are suitable for various purposes, as well as marketing and awareness campaigns, electric motorbikes may become a practical substitute solution, particularly as gasoline prices are rising.

However, motorcycle batteries are highly dependent on the road's gradient, the quantity of luggage or load carried, and the user's riding style (such as rapid acceleration). The inclusion of the swapping station stops on routine routes necessitates several processes, and customers must be made aware of these modifications.

Instable EV value chains and e-bike technological challenges are additional impediments, particularly in EV business modelling. But if the ecosystem grows and becomes more established, such challenges may be overcome.

However, as this research is solely focused on the charging infrastructure, more studies and data collection are needed to address the following:

- Technical information deficiencies (batteries, maintenance, value chains).
- Future research might include the potential for increased income, lowering costs from the deployment of e-mobility.

Such project could be extended to other WE Hubs that are located around Lake Victoria as well as African cities as a whole. Since an efficient and environmentally friendly transport system is needed in most African cities as presented in this research.

Infrastructure

Install a weather monitoring device that can read especially the solar irradiation, temperature, and humidity of the Mbita location. This would help in further verification of the simulation result.

Connect other satellite hubs with the SMA data manager for remote monitoring of the hub electricity production and consumption.

Implement the proposed load management algorithm for scheduling and optimising the charging schedule of the various load thereby leading to optimum utilisation of the PV electricity production.

Equip all vehicles with GPS trackers for a better understanding of rider’s behaviour such as distance covered, travel routes, speed, etc.

Integrate old vehicle batteries into the central batteries of the hub to strengthen the connection between the mobility and the hub. This could also help to cover the increasing load demands thereby saving battery investment costs.

References

A. Ehsan and Q. Yang (2020), “Active Distribution System Reinforcement Planning With EV Charging Stations—Part I: Uncertainty Modeling and Problem Formulation”, *IEEE Transactions on Sustainable Energy*, Vol. 11 No. 2, pp. 970–978.

A. Martí, J. L. Balenzategui, and R. F. Reyna (1997), “Photon recycling and Shockley’s diode equation.”, Vol. 82 No. 8, pp. 4067–4075.

A. Von Jouanne, I. Husain, A. Wallace and A. Yokochi (2005), “Gone with the wind: innovative hydrogen/fuel cell electric vehicle infrastructure based on wind energy sources”, *IEEE Industry Applications Magazine*, Vol. 11 No. 4, pp. 12–19.

AHK Kenya (2016), “EE-INSELNETZE IN KENIA”, available at: http://www.kenia.ahk.de/uploads/media/Zielmarkt_EE_Inselnetze_Kenia_2016.pdf (accessed 04-Apr-2021).

Åhman, M. (2001), “Primary energy efficiency of alternative powertrains in vehicles”, *Energy*, Vol. 26 No. 11, pp. 973–989.

Ajay, K. and Fanny, B. (2008), “AFRICA INFRASTRUCTURE COUNTRY DIAGNOSTIC Stuck in traffic: Urban transport in Africa”, available at: https://documents1.worldbank.org/curated/en/671081468008449140/pdf/0Urban1Trans1FINAL1with0cover.pdf (accessed 02-Aug-2020).

Akindare, O. (2018), “The World Is Leaving Africa Behind in Electric Vehicle Adoption”, available at: https://techcabal.com/2018/08/20/the-world-is-leaving-africa-behind-in-electric-vehicle-adoption/ (accessed 25 April 2019).

Alkawsi, G., Baashar, Y., Abbas U, D., Alkahtani, A.A. and Tiong, S.K. (2021), *Review of Renewable Energy-Based Charging Infrastructure for Electric Vehicles, Applied Sciences*, Vol. 11.

AMPS Power GmbH (2018), *REPORT TESTS AT LAKE VICTORIA, KENYA*.

anywhere berlin GmbH (2020), “Steel Bird”, available at: http://www.anywhere.berlin/africa.html (accessed 04-April-2021).

Arnold Wohlfeil (2019), “CARNOT Toolbox”, available at: https://nl.mathworks.com/matlabcentral/fileexchange/68890-carnot-toolbox (accessed 8 February 2020).

Baffoe, G., Malonza, J., Manirakiza, V. and Mugabe, L. (2020), "Understanding the concept of neighbourhood in Kigali City, Rwanda", *Sustainability*, Vol. 12 No. 4, p. 1555.

Bailey, J., Miele, A. and Axsen, J. (2015), "Is awareness of public charging associated with consumer interest in plug-in electric vehicles?", *Transportation Research Part D: Transport and Environment*, Vol. 36, pp. 1–9.

Banjo, G., Gordon, H. and Riverson, J. (2012), "Rural Transport, Improving itsContribution to Growth and Poverty Reduction in Sub-SaharanAfrica. Sub-Saharan Africa Transport Policy Program (SSATP),Africa Region, The World Bank, Washington, DC, USA".

Bao, Y., Luo, Y., Zhang, W., Huang, M., Le Wang, Y. and Jiang, J. (2018), *A Bi-Level Optimization Approach to Charging Load Regulation of Electric Vehicle Fast Charging Stations Based on a Battery Energy Storage System, Energies*, Vol. 11.

Berg, C.N., Blankespoor, B. and Selod, H. (2018), "Roads and Rural Development in Sub-Saharan Africa", *The Journal of Development Studies*, Vol. 54 No. 5, pp. 856–874.

Bertsekas, D., G S., L., N.R, S., JR. and T.A, P., "Optimal Short-Term Scheduling of Large-Scale Power Systems 1983", in *IEEE Transactions on Automatic Control*, Vol. 28, pp. 1–11.

Bhatti, A.R., Salam, Z. and Ashique, R.H. (2016), "Electric Vehicle Charging Using Photovoltaic based Microgrid for Remote Islands", *Energy Procedia*, Vol. 103, pp. 213–218.

Bimenyimana, S., Wang, C., Nduwamungu, A., Asemota, G.N.O., Utetiwabo, W., Ho, C.-L., Niyonteze, J.D.D., Hagumimana, N., Habineza, T., Bashir, W., Mesa, C.K., Mo, Y. and Sudhakar, K. (2021), "Integration of Microgrids and Electric Vehicle Technologies in the National Grid as the Key Enabler to the Sustainable Development for Rwanda", *International Journal of Photoenergy*, Vol. 2021, p. 9928551.

Birnie, D.P. (2009), "Solar-to-vehicle (S2V) systems for powering commuters of the future", *Journal of Power Sources*, Vol. 186 No. 2, pp. 539–542.

Bloemen, S. (2018), "Mobility for Africa", available at: https://www.mobilityforafrica.com/new-blog/ (accessed 08-Feb-2019).

Bodawerk International Ltd (2021), "Battery & Energy as-a-Service", available at: https://bodawerk.com/ (accessed 04-April-2021).

Bosch Solar (2012), “Powerful performance – high stability. Bosch Solar Module c-Si M 60 EU30117”, available at: https://www.solarchoice.net.au/wp-content/uploads/Bosch-Solar-Module-c-Si-M-60-Australia.pdf (accessed 05-April-2020).

Bugaje, A., Ehrenwirth, M., Trinkl, C. and Zörner, W. (2021a), “Electric Two-Wheeler Vehicle Integration into Rural Off-Grid Photovoltaic System in Kenya”, *Energies*, Vol. 14 No. 23.

Bugaje, A., Ehrenwirth, M., Trinkl, C. and Zörner, W. (2021b), “Investigating the Performance of Rural Off-Grid Photovoltaic System with Electric-Mobility Solutions: A Case Study Based on Kenya”, *Journal of Sustainable Development of Energy, Water and Environment Systems*, N/A No. N/A, p. 0.

C. Chen and S. Duan (2014), “Optimal Integration of Plug-In Hybrid Electric Vehicles in Microgrids”, *IEEE Transactions on Industrial Informatics*, Vol. 10 No. 3, pp. 1917–1926.

C. Liu, J. Wang, A. Botterud, Y. Zhou and A. Vyas (2012), “Assessment of Impacts of PHEV Charging Patterns on Wind-Thermal Scheduling by Stochastic Unit Commitment”, *IEEE Transactions on Smart Grid*, Vol. 3 No. 2, pp. 675–683.

Cau, G., Cocco, D., Petrollese, M., Knudsen Kær, S. and Milan, C. (2014), “Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system”, *Energy Conversion and Management*, pp. 820–831.

Chambliss, J., Miller, J., Façanha, C. and Minjares, R and Blumberg, K (2013), “The impact of stringent fuel and vehicle standards on premature mortality and emissions. International Council for Clean Transportation, Washington DC, USA. 96p.”, available at: http://www.theicct.org/global-health-roadmap (accessed 01-Jan-2019).

Chandra Mouli, G.R., Bauer, P. and Zeman, M. (2016), “System design for a solar powered electric vehicle charging station for workplaces”, *Applied Energy*, Vol. 168, pp. 434–443.

City of Kigali (2019), “Feasibility Study and Preliminary Design for a Bus Rapid Transit (BRT) System for City of Kigali: Final Report”.

Danchev, S., Maniatis, G. and Tsakanikas, A. (2010), “Returns on investment in electricity producing photovoltaic systems under de-escalating feed-in tariffs: The case of Greece", *Renewable and Sustainable Energy Reviews*, Vol. 14 No. 1, pp. 500–505.

DW (2019), "Solar Motorcycles take on Nairobi smog", available at: https://www.dw.com/en/kenya-solar-motorcycles-take-on-nairobi-smog/a-46308817.

Dziadek, P.-E., Feucht, W., Mittnacht, A., Kula, H.-G. and Frank, H. (2013), "Eco-friendly application of EVs for home-to-work and home-to-education transports", *IEEE International Conference on Industrial Technology (ICIT)*, pp. 705–709.

EED Advisory and Siemens Stiftung (2020), "Environmental Impact of E-Mobility in the Lake Victoria Region, Western Kenya", available at: https://www.siemens-stiftung.org/wp-content/uploads/medien/publikationen/studie-environmentalimpactofemobilityfinalreport-siemensstiftung.pdf (accessed 01-Jan-2021).

Ekren, O., Hakan Canbaz, C. and Güvel, Ç.B. (2021), "Sizing of a solar-wind hybrid electric vehicle charging station by using HOMER software", *Journal of Cleaner Production*, Vol. 279, p. 123615.

Elum, Z.A. and Momodu, A.S. (2017), "Climate change mitigation and renewable energy for sustainable development in Nigeria: A discourse approach", *Renewable and Sustainable Energy Reviews*, Vol. 76, pp. 72–80.

Energy Information Adminstration (EIA) (2020), "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020",. [Online].", available at: Available: https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf. (accessed 26-Sep- 2020).

Erica, G., Larry, E., Bala, N., Gary, B. and Anil, P. (2013), "Solar powered charge stations for electric vehicles".

Eshiwani (2019), "Roundtable Presentation, State of Electric Mobility in Kenya, Ministry of Transport, Infrastructure Housing and Urban Development".

Faizal, A. (2019), "Kenya loses 50m daily on traffic jams", available at: https://citizentv.co.ke/business/kenya-loses-ksh-50m-daily-on-traffic-jams-247945/ (accessed 21-May-2021).

Francesco, F., Matteo, M. and Narghes, D. (2013), "Investigation of different simulation tools for solar photovoltaic modules".

Franke, T. and Krems, J.F. (2013), “Understanding charging behaviour of electric vehicle users”, *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 21, pp. 75–89.

Galuszka, J., Martin, E., Nkurunziza, A., Achieng’ Oginga, J., Senyagwa, J., Teko, E. and Lah, O. (2021), “East Africa’s Policy and Stakeholder Integration of Informal Operators in Electric Mobility Transitions—Kigali, Nairobi, Kisumu and Dar es Salaam”, *Sustainability*, Vol. 13 No. 4.

Gammon, R. and Sallah, M. (2021), “Preliminary Findings From a Pilot Study of Electric Vehicle Recharging From a Stand-Alone Solar Minigrid”, *Frontiers in Energy Research*, Vol. 8, p. 374.

Gautham, R., Chandra, M., Peter, V. and Tim, V. (2018), “Solar Powered E-Bike Charging Station with AC, DC and Contactless Charging”, *20th European Conference on Power Electronics and Applications EPE'18 ECCE Europe*, pp. 1–10.

George, B., Henry, G. and John, R. (2012), “Rural Transport Improving its Contribution to Growth and Poverty Reduction in Sub-Saharan Africa George Banjo Henry Gordon John Riverson”, available at: https://openknowledge.worldbank.org/bitstream/handle/10986/17807/786760SSATP0NW0t0Sub0Saharan0Africa.pdf?sequence=1&isAllowed=y (accessed 12-Aug-2020).

George Kyriakarakos, Dimitrios D. Piromalis, Konstantinos G. Arvanitis, Anastasios I. Dounis and George Papadakis (2015), “On battery-less autonomous polygeneration microgrids: Investigation of the combined hybrid capacitors/hydrogen alternative”, *Energy Conversion and Management*, Vol. 91, pp. 405–415.

Ghanbarzadeh, T., Baboli, P.T., Rostami, M. Moghaddam, M.P. and Sheikh-El-Eslami, M.K. (2011), “Wind farm power management by high penetration of PHEV”.

Gilbert, N. (2018), “Africa urged to use electric cars to cut air pollution”, available at: https://techcabal.com/2018/08/20/the-world-is-leaving-africa-behind-in-electric-vehicle-adoption/ (accessed 26 April 2019).

GIZ (2016), “Mini-Grid Regulation and Practical Experiences from Kenya”, available at: https://www.giz.de/fachexpertise/downloads/2016-en-kenya-regulation-experiences-jasmin-fraatz.pdf (accessed 21-Apr-2020).

Goodfellow, T. (2015), “Taming the “rogue” sector: Studying state effectiveness in Africa through informal transport politics”, *Comparative Politics*, Vol. 47 No. 2, pp. 127–147.

Government of Kenya (2015), “Kenya Second National Communication to the United Nations Framework Convention on Climate Change”, available at: https://unfccc.int/resource/docs/natc/kennc2.pdf (accessed 21-June-2020).

Grande, L.S.A., Yahyaoui, I. and Gómez, S.A. (2018), “Energetic, economic and environmental viability of off-grid PV-BESS for charging electric vehicles: Case study of Spain”, *Sustainable Cities and Society*, Vol. 37, pp. 519–529.

GRSF (2014), “Transport for health: the global burden of disease from motorised transport. Global Road Safety Facility (FRSF) and Institute for Health Metrics and Evaluation (IHME). World Bank, Washington DC, USA. 39p.”, available at: http://wwwwds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2014/03/28/000333037_20140328141207/Rendered/PDF/863040IHME0T4H0ORLD0BANK0compressed.pdf (accessed 21-June-2020).

Haddadian, G., Khalili, N., Khodayar, M. and Shahidehpour, M. (2016), “Optimal coordination of variable renewable resources and electric vehicles as distributed storage for energy sustainability”, *Sustainable Energy, Grids and Networks*, Vol. 6, pp. 14–24.

Hao Wang, A. Balasubramani and Zilong Ye (2018), “Optimal Planning of Renewable Generations for Electric Vehicle Charging Station”, *2018 International Conference on Computing, Networking and Communications (ICNC)*, pp. 63–67.

Haque, A., Ibn Saif, A., Nguyen, P.H. and Torbaghan, S.S. (2016), “Exploration of dispatch model integrating wind generators and electric vehicles”, *Applied Energy*, Vol. 183, pp. 1441–1451.

Hardman, S., Jenn, A., Tal, G., Axsen, J., Beard, G., Daina, N., Figenbaum, E., Jakobsson, N., Jochem, P., Kinnear, N., Plötz, P., Pontes, J., Refa, N., Sprei, F., Turrentine, T. and Witkamp, B. (2018), “A review of consumer preferences of and interactions with electric vehicle charging infrastructure”, *Transportation Research Part D: Transport and Environment*, Vol. 62, pp. 508–523.

Hardman, S., Shiu, E. and Steinberger-Wilckens, R. (2016), “Comparing high-end and low-end early adopters of battery electric vehicles”, *Transportation Research Part A: Policy and Practice*, Vol. 88, pp. 40–57.

Hine, J. (2014), “Good Policies and Practices on Rural Transport inAfrica. Sub-Saharan Africa Transport Policy Program(SSATP), World Bank, Washington, DC, USA, WorkingPaper No. 100.”.

Hönig, R. and Gregor, W. (2018), “Electric propulsion for African fishermen”, available at: https://www.hbi-now.com/blog/electric-propulsion-for-african-fishermen/ (accessed 22 November 2019).

HOPPECKE (2013), “Accumulatorenwerke HOPPECKE Carl Zoellner & Sohn GmbH OPzS solar.power. Vented lead-acid battery for cyclic applications.”, available at: https://www.europe-solarstore.com/download/hoppecke/opzs/OPzS_solar.power_en.pdf (accessed 21-Sep-2019).

IBM (2010), “ILOG CPLEX Optimization Studio”, available at: http://www-01.ibm.com/software/integration/optimization/cplex-optimization-studio (accessed 02-July-2019).

IFRTD (2021), “Socio-Economic Impact Study into the Potential of E-Mobility for Improved Agricultural Value Chains and Income Opportunities in Lake Victoria Region, Kenya”.

Institute for Transportation and Development Policy (ITDP) (2021), “Kisumu Sustainable Mobility Plan”, available at: https://www.itdp.org/wp-content/uploads/2021/03/Kisumu-Sustainable-Mobility-Plan-210216.pdf (accessed 10-Dec-2021).

IRENA (2012), “Renewable Energy Cost Analysis - Concentrating Solar Power”, available at: https://irena.org/publications/2012/Jun/Renewable-Energy-Cost-Analysis---Concentrating-Solar-Power (accessed 29- Sep- 2019).

Jane, N.-K. (2020), “Design And Optimization of a Renewable Energy Based Smart Microgrid for Rural Electrification”, available at: https://www.research.manchester.ac.uk/portal/files/177286922/FULL_TEXT.PDF (accessed 02-April-2021).

K. Bataineh and D. Dalalah (2012), “Optimal Configuration for Design of Stand-Alone PV System”, Vol. 3 No. 2, pp. 139–147.

Kacira, M., Simsek, M., Babur, Y. and Demirkol, S. (2004), “Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey”, Vol. 29, pp. 1265–1275.

Kaunda, C.S., Kimambo, C.Z. and Nielsen, T.K. (2012), “Potential of Small-Scale Hydropower for Electricity Generation in Sub-Saharan Africa”, *ISRN Renewable Energy*, Vol. 2012 No. 2, pp. 1–15.

Kempton, W. (2016), “Electric vehicles: Driving range”, *Nature Energy*, Vol. 1 No. 9, p. 16131.

Kenya National Bureau of Statistics (2019), “Economic Survey 2019 Highlights. Nairobi: Kenya National Bureau of Statistics”, available at: https://s3-eu-west-1.amazonaws.com/s3.sourceafrica.net/documents/119074/Kenya-National-Bureau-of-Statistics-Economic.pdf (accessed 02-Feb-2021).

Kenya Power (2018), “Kenya leads East Africa peers in access to electricity”, available at: https://www.kplc.co.ke/content/item/2485/kenya-leads-east-africapeers-in-access-to-electricity (accessed 29-June-2019).

Klopp, J.M., “Towards a political economy of transportation policy and practice in Nairobi”, in *Urban forum*, Springer, pp. 1–21.

Klopp, J.M. and Cavoli, C.M. (2017), “The paratransit puzzle: minibus mapping and transportation planning in Maputo and Nairobi”, in Taylor & Francis Ltd.

KLOPP, J. and Mitullah, W. (2015), “Politics, policy and paratransit: A view from Nairobi”, in *Paratransit in African cities*, Routledge, pp. 95–115.

KNBS-Kenya National Bureau of Statistics (2019), “Kenya Population and Housing Census. Volume I: Population by County and Sub-County”, available at: Available online: https://www.knbs.or.ke/?wpdmpro=2019-kenya-population-and-housing-census-volume-i-population-by-county-and-sub-county (accessed 10-Dec-2020).

Knights Energy (2020), *Mbita Solar Hub Engineering Documentation*.

Kumar, A. (2011), “Understanding the Emerging Role of Motorcycles in African Cities A Political Economy Perspective. Sub-Saharan Africa Transport Policy Program (SSATP) discussion paper”, available at: https://openknowledge.worldbank.org/handle/10986/17804 (accessed 27 November 2019).

L. Eduardo (1994), *Solar electricity: engineering of photovoltaic systems*, Earthscan/James & James.

Lee, K., Brewer, E., Christiano, C., Meyo, F., Miguel, E., Podolsky, M., Rosa, J. and Wolfram, C. (2016), “Electrification for “Under Grid” households in Rural Kenya”, *Development Engineering*, Vol. 1, pp. 26–35.

Leon, F. and David, I. (2008), *Renewable Energy in Power Systems*, Wiley.

Liang, X., Tanyi, E. and Zou, X. (2014), “Charging electric cars from solar energy”, available at: http://www.divaportal.org/smash/record.jsf?pid=diva2%3A935136&dswid=-3475 (accessed 20 January 2018).

Liang, X. and Tanyi, E. and Zou, X. (2016), “Charging electric cars from solar energy”.

Lindiwe Bokopane, Kanzumba Kusakana and Herman Vermaak (2015), “Optimal energy management of an isolated electric Tuk-Tuk charging station powered by hybrid renewable systems”, *2015 International Conference on the Domestic Use of Energy (DUE)*, pp. 193–201.

Liu, Q. (2014), “Electric car with solar and wind energy may change the environment and economy: A tool for utilizing the renewable energy resource”, *Earth's Future*, Vol. 2 No. 1, pp. 7–13.

Lluc Canals Casals, Egoitz Martinez-Laserna, Beatriz Amante García and Nerea Nieto (2016), “Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction”, *Journal of Cleaner Production*, Vol. 127, pp. 425–437.

Lopez-Behar, D., Tran, M., Froese, T., Mayaud, J.R., Herrera, O.E. and Merida, W. (2019), “Charging infrastructure for electric vehicles in Multi-Unit Residential Buildings: Mapping feedbacks and policy recommendations”, *Energy Policy*, Vol. 126, pp. 444–451.

M. A. Ortega-Vazquez, F. Bouffard and V. Silva (2013), “Electric Vehicle Aggregator/System Operator Coordination for Charging Scheduling and Services Procurement”, *IEEE Transactions on Power Systems*, Vol. 28 No. 2, pp. 1806–1815.

M. G. Villalva, J. R. Gazoli and and E. Ruppert Filho (200), “Modeling and circuit-based simulation of photovoltaic arrays”, pp. 1244–1254.

M. Ishaq and U. H. Ibrahim (2013), “Design Of An Off Grid Photovoltaic System A Case Study Of Government Technical College Wudil Kano State”, Vol. 2 No. 12, pp. 175–181.

M. Villalva and J. Gazoli and E. Filho (2009), “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays”, Vol. 24 No. 5, pp. 1198–1208.

Macrotrends.net (2020), “Kenya Inflation Rate 1960-2020”, available at: https://www.macrotrends.net/countries/KEN/kenya/inflation-rate (accessed 29-Sep- 2020).

Maleki, A., Ameri, M. and Keynia, F. (2015), “Scrutiny of multifarious particle swarm optimization for finding the optimal size of a PV/wind/battery hybrid system”, *Renewable Energy*, Vol. 80, pp. 552–563.

Maleki, A. and Askarzadeh, A. (2014a), “Artificial bee swarm optimization for optimum sizing of a stand-alone PV/WT/FC hybrid system considering LPSP concept”, *Solar Energy*, Vol. 107, pp. 227–235.

Maleki, A. and Askarzadeh, A. (2014b), “Comparative study of artificial intelligence techniques for sizing of a hydrogen-based stand-alone photovoltaic/wind hybrid system”, *International Journal of Hydrogen Energy*, Vol. 39 No. 19, pp. 9973–9984.

Maleki, A. and Pourfayaz, F. (2015), “Optimal sizing of autonomous hybrid photovoltaic/wind/battery power system with LPSP technology by using evolutionary algorithms”, *Solar Energy*, Vol. 115, pp. 471–483.

Martin, E., Transport sector Climate Change team coordinator, Esther, G. and Climate Change focal person (2019), “Transport Sector Climate Change Annual Report: Performance and Implementation of Climate Change Actions”, available at: https://www.international-climate-initiative.com/fileadmin/Dokumente/2020/2019_Transport_Sector_Climate_Change_Annual_Report_Kenya.pdf (accessed 04-April-2021).

Martin, N. (2016), “How Solar Power Works - On-Grid, Off-Grid And Hybrid Systems”, available at: https://www.cleanenergyreviews.info/blog/2014/5/4/how-solar-works (accessed 09-August-2020).

MATLAB (2020), “App Designer”, available at: https://nl.mathworks.com/products/matlab/app-designer.html (accessed 8 June 2020).

Meteotest AG (2020), “Meteonorm Software Worldwide irradiation data”, available at: https://meteonorm.com/en/ (accessed 04-April-2020).

Ministry of Energy (2019), “Energy Sources Statistics”, available at: http://energy.go.ke/?p=516 (accessed 20-July-2020).

Ministry of Energy and Petroleum (2016), “Green Off-grid Solutions in Kenya. Presentation for the Off-grid Forum in Nairobi, 24th May 2016”.

Ministry of Transport and GIZ (2019), “ELECTRIC MOBILITY IN KENYA THE FACTS”, available at: https://www.changing-transport.org/wp-content/uploads/2019_Electric_Mobility_in_Kenya.pdf (accessed 22-July-2020).

Mueller, O.M. and Mueller, E.K. (2014), “Off-grid, low-cost, electrical sun-car system for developing countries.”, *IEEE Global Humanitarian Technology Conference (GHTC 2014)*, Vol. 34 No. 1, pp. 14–17.

Mueller, O.M. and Mueller, E.K. (2014), “Off-grid, low-cost, electrical sun-car system for developing countries”, *IEEE Global Humanitarian Technology Conference (GHTC 2014)*, Vol. 34 No. 1, pp. 14–17.

Mutonga, J. (2019), “‘EnDev’s RBF Facility for mini-grids: Experience from Kenya and Rwanda”, available at: https://minigrids.org/wp-content/uploads/2019/07/RBF_Mini-grids_Implementation_Kenya-Rwanda.pdf (accessed 22-Jun-2020).

N. Liu, Q. Chen, J. Liu, X. Lu, P. Li, J. Lei and J. Zhang (2015), “A Heuristic Operation Strategy for Commercial Building Microgrids Containing EVs and PV System”, *IEEE Transactions on Industrial Electronics*, Vol. 62 No. 4, pp. 2560–2570.

Nairobi City County (2019), *Transport Bill. Kenya Gazette Supplement No. 15, 5 December 2019.*

NCC-Nairobi City County (2015), “The Project on Integrated Urban Development Master Plan for the City of Nairobi in the Republic of Kenya. Final Report. Part III: The Master Plan”, available at: https://www.kpda.or.ke/documents/Policies/Final%20Report%20-%20The%20Project%20on%20Intergrated%20Urban%20Development%20Master%20Plan%20for%20Nairobi%20-%20Appendix.pdf (accessed 01-Feb-2021).

Nkurunziza, A., Zuidgeest, M., Brussel, M. and van den Bosch, F. (2012), “Spatial variation of transit service quality preferences in Dar-es-Salaam”, *Journal of Transport Geography*, Vol. 24, pp. 12–21.

Numbeo (2019), “Traffic Index 2019 Mid-Year”, available at: https://www.numbeo.com/traffic/in/Nairobi (accessed 31-Jan-2021).

Obura, F. (2019), “President Uhuru Kenyatta to commmission Lake Turkana Wind Power this week”, available at: https://www.standardmedia.co.ke/article/2001334107/uhuru-to-commission-africa-s-largest-wind-farm-in-marsabit (accessed 29-July-2019).

Ochieng, R. (2017), “URBAN SUSTAINABILITY REVIEW (USR) MBITA: HOMA BAY COUNTY”, available at: http://symbiocitykenya.org/wp-content/uploads/2017/12/USR-HomabayMbita-highres-SymbioCity.pdf (accessed 22-Nov-2019).

Olinto, P., Kathleen, B., Sobrado, C. and Uematsu, H. (2013), “The State ofthe Poor: Where Are the Poor, Where Is Extreme Poverty Harderto End, and What Is the

Current Profile of the World's Poor?The World Bank, Washington, DC, USA, Economic PremiseNumber 125".

Opibus (2021), "The first African electric motorcycle", available at: https://www.opibus.se/motorcycles (accessed 04-April-2021).

Park, E. and Kwon, S.J. (2016), "Renewable electricity generation systems for electric-powered taxis: The case of Daejeon metropolitan city", *Renewable and Sustainable Energy Reviews*, Vol. 58, pp. 1466–1474.

Patrick, C. (2014), "Design of rural photovoltaic water pumping systems and the potential of manual array tracking for a West-African village", No. 103, pp. 288–302.

Paul, S. and John, H. (2014), "Poverty and sustainable transport How transport affects poor people with policy implications for poverty reduction - A literature review", available at: https://sustainabledevelopment.un.org/content/documents/1767Poverty%20and%20sustainable%20transport.pdf (accessed 07-Sep-2019).

Paul, S. and John, H. (2020), "Rural Transport Services: Operational Characteristics and Options for Improvements.", available at: https://research4cap.org/ral/StarkeyHine-TRL-2020-IMPARTS-Phase3Report-ReCAP-GEN2136A-200702.pdf (accessed 01-Sep-2021).

Peter, L.L. and Yang, Y. (2019), "Urban planning historical review of master plans and the way towards a sustainable city: Dar es Salaam, Tanzania", *Frontiers of Architectural Research*, Vol. 8 No. 3, pp. 359–377.

Peterson, S.B. and Michalek, J.J. (2013), "Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption", *Energy Policy*, Vol. 52, pp. 429–438.

Porter, G. (2013), "TRANSPORT SERVICES AND THEIR IMPACT ON POVERTY AND GROWTH IN RURAL SUB-SAHARAN AFRICA", available at: https://assets.publishing.service.gov.uk/media/57a08a43ed915d3cfd00068c/AFCAP-GEN-060-J-Transport-Services-Poverty-and-Growth.pdf (accessed 29-Aug-2021).

Quddus, M.A., Kabli, M. and Marufuzzaman, M. (2019), "Modeling electric vehicle charging station expansion with an integration of renewable energy and Vehicle-to-Grid sources", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 128, pp. 251–279.

Remeredzai Joseph (2021), “CLEAN TRANSPORT. Electric Boda-Bodas Launch - A Promising Day For Electric Transportation In East Africa”, available at: https://cleantechnica.com/2021/03/02/electric-boda-bodas-launch-a-promising-day-for-electric-transportation-in-east-africa/ (accessed 10 March 2021).

Ricardo, B. and Manuel, M. (2011), “Economic and technical management of an aggregation agent for electric vehicles: a literature survey”.

Richardson, D.B. (2013), “Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration”, *Renewable and Sustainable Energy Reviews*, Vol. 19, pp. 247–254.

Ron, D. and Keith, P. (2017), “Vehicles for rural transport services in sub-Saharan Africa”, Volume 170 No. 6, pp. 321–327.

SERC - Strathmore University Energy Research Centre (2018), *WeHub Technical Performance Assessment Report.*, Kenya.

Shukla, A., Verma, K. and Kumar, R. (2019), “Impact of EV fast charging station on distribution system embedded with wind generation.”, pp. 4692–4697.

Shukla, A.K., Sudhakar, K. and Baredar, P. (2016), “Design, simulation and economic analysis of standalone roof top solar PV system in India”, Vol. 136, pp. 437–449.

Siemens Stiftung, “Testing E-Mobility Business Models at WE Hub Victoria Limited in Kenya”, available at: https://www.siemens-stiftung.org/wp-content/uploads/2022/04/study-mobilityafrica-siemensstiftung.pdf (accessed 01-June-2021).

Siemens Stiftung (2020a), “E-Mobility Solutions for Rural Sub-Saharan Africa: Leveraging Economic, Social and Environmental Change”, available at: https://www.siemens-stiftung.org/wp-content/uploads/medien/publikationen/publication-emobility-emobilitysolutionsforruralsubsaharanafrica-siemensstiftung.pdf (accessed 04-April-2021).

Siemens Stiftung (2020b), “WeTu Social business model with new technologies”, available at: https://www.siemens-stiftung.org/en/projects/wetu/ (accessed 02-August-2020).

Simiyu Sitati (2021), *REPORT ON THE MEASUREMENT CAMPAIGN E-MOBILITY FOR RURAL AFRICA*, MOI University, Kenya.

SLoCaT (2018), “Transport and Climate Change Global Status Report”, Partnership on Sustainable, Low Carbon Transport (SLoCaT), available at: http://slocat.net/sites/default/files/slocat_transport-and-climate-change-2018-web.pdf (accessed 3 August 2019).

SMA Solar Technology AG (2011), “Off-Grid Inverter SUNNY ISLAND 5048. Technical description”, available at: https://rexel-cdn.com/Products/SMA/SI5048U.pdf?i=216B015B-AA7E-4040-8D56-CE07DEC2145F (accessed 05-February-2020).

SMA Solar Technology AG (2015), “Operating manual SUNNY TRIPOWER 15000TL / 20000TL / 25000TL”, available at: https://www.sma.de/en/products/solarinverters/sunny-tripower-15000tl-20000tl-25000tl.html (accessed 04-April-2020).

Solar Energy International (2004), *Photovoltaics Design and Installation Manual.*, New Society Publishers.

SolarWorld (2005), “Sunmodule SW 220 Poly”, available at: http://www.iwr.de/solarworld/SWM_220_poly_05-8.pdf (accessed 10-Sep-2019).

Solcast (2020), “Solcast API Toolkit”, available at: https://toolkit.solcast.com.au/live-forecast (accessed 04-April-2020).

Søren, K., Poul-Erik, M. and Shimon, A. (2009), “The Economics of Wind Energy A report by the European Wind Energy Association”, available at: http://www.ewea.org/fileadmin/ewea_documents/documents/00_POLICY_document/Economics_of_Wind_Energy__March_2009_.pdf. (accessed 29- Sep- 2019).

Spertino, F., Di Leo, P. and Cocina, V. (2013), “Economic analysis of investment in the rooftop photovoltaic systems: A long-term research in the two main markets”, *Renewable and Sustainable Energy Reviews*, Vol. 28, pp. 531–540.

Starkey, P., Awadh, A., Kemptsop, G., Musonda, H. and Sirpé, G. (2007), “Rural Transport Services in Africa, Lessons from RapidAppraisal Surveys in Burkina Faso, Cameroon, Tanzaniaand Zambia. Sub-Saharan Africa Transport Policy Program(SSATP), Africa Region, The World Bank, Washington, DC,USA”.

Starkey, P., Njenga, P. and Kemptsop, G. (2013), “Rural Transport ServicesIndicators. International Forum for Rural Transport andDevelopment (IFRTD), for African Community AccessProgramme, London, UK, Final Report.”.

Starkey, P. and Njenge, P. (2010), “Improving sustainable rural transportservices: constraints, opportunities and research needs.Proceedings of the 1st AFCAP

Practitioners'Conference, AddisAbaba, Ethiopia.", available at: http://www.ruraltransport.info/RTSi/docs/Starkey-Njenga-2010-RuralTransportServicesAFCAP-ETworkshop.pdf (accessed 10-Sep-2021).

Szabó, S., Bódis K, Huld, T. and Moner-Girona, M. (2011), "Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension", Vol. 6 No. 3.

T. Khatib and W. Elmenreich (2016), *Modeling of Photovoltaic Systems Using MATLAB: Simplified Green Codes*, Wiley.

Talavera, D.L., Muñoz-Cerón, E., La Casa, J. de, Ortega, M.J. and Almonacid, G. (2011), "Energy and economic analysis for large-scale integration of small photovoltaic systems in buildings: The case of a public location in Southern Spain", *Renewable and Sustainable Energy Reviews*, Vol. 15 No. 9, pp. 4310–4319.

Thomas, D., Marie-Jeanne, K. and Murefu Barasa (2018), "The role of renewable energy minigrids in Kenya's electricity sector Evidence of a cost-competitive option for rural electrification and sustainable development", available at: https://newclimate.org/wp-content/uploads/2019/11/The-role-of-renewable-energy-mini-grids-in-Kenya%E2%80%99s-electricity-sector.pdf (accessed 05-July-2021).

Time and date (2020), "Moon Phases 2020 – Lunar Calendar for Mbita, Homa Bay, Kenya", available at: https://www.timeanddate.com/moon/phases/@187028?year=2020 (accessed 01-Jan-2021).

Tomonori, H., Yoshito, F., Samson Muuo, N., Chihiro, T. and Ibrahim, K. (2016), "Spatial Distributions of HIV Infection in an Endemic Area of Western Kenya: Guiding Information for Localized HIV Control and Prevention", Vol. 11 No. 2, pp. 1–14.

Tradingeconomics.com (29- Sep- 2019), *Kenya Interest Rate 2020*, available at: https://tradingeconomics.com/kenya/interest-rate.

UEMI (2020a), "Kenya Profile", available at: http://www.uemi.net/nairobi---kenya.html (accessed 02-Feb-2021).

UEMI (2020b)), "Kenya Profile", available at: http://www.uemi.net/nairobi---kenya.html (accessed 10-April-2021).

UNEP (2018), "Africa Used Vehicle Report 2018", available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/25233/AfricaUsedVehicleReport.pdf?sequence=1&isAllowed=y (accessed 2 December 2020).

United Nations (2016), “The State of World’s Cities in 2016. Data Booklet”, available at: https://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2016_data_booklet.pdf (accessed 10-Jan-2021).

United Nations (2018), “The State of World’s Cities in 2018. Data Booklet.”, available at: https://www.un.org/en/events/citiesday/assets/pdf/the_worlds_cities_in_2018_data_booklet.pdf (accessed 10-Oct-2020).

United Nations (2019), “Department of Economic and Social Affairs, World Population Prospects 2019”.

US Energy Information Administration (2020), “Renewable Energy Explained”, available at: https://www.eia.gov/energyexplained/renewable-sources/ (accessed 05-Jun-2020).

Weiss, M., Cloos, K.C. and Helmers, E. (2020), “Energy efficiency trade-offs in small to large electric vehicles”, *Environmental Sciences Europe*, Vol. 32 No. 1, p. 46.

WeTu (2019), “Spotlight on (W)e-mobility at LBIIW in Kisumu”, available at: https://wetu.co.ke/2019/11/20/spotlight-on-we-mobility-at-lbiiw-in-kisumu/ (accessed 04-April-2021).

WeTu (2021), “Niwa lantern”, available at: https://twitter.com/WeTu_Kenya/media (accessed 04-April-2021).

Wi, Y.-M., Lee, J.-U. and Joo, S.-K. (2013), “Electric vehicle charging method for smart homes/buildings with a photovoltaic system”, *IEEE Transactions on Consumer Electronics*, Vol. 59 No. 2, pp. 323–328.

Wood, E.W., Rames, C.L., Muratori, M., Srinivasa Raghavan, S. and Melaina, M.W. (2017), *National Plug-In Electric Vehicle Infrastructure Analysis*, United States, available at: https://www.osti.gov/biblio/1393792.

World Bank (2017), “Project Appraisal Document-Dar Es Salaam Urban Transport Improvement Project.”, available at: http://documents1.worldbank.org/curated/en/794251489201242940/pdf/TZ-PAD-02162017.pdf (accessed 10-Aug-2020).

World Bank (2020), “Source: Global Solar Atlas 2.0, Solar resource data: Solargis Photovoltaic Electricity Potential Solar resource maps of Kenya”, available at: https://solargis.com/maps-and-gis-data/download/kenya (accessed 02-Mar-2021).

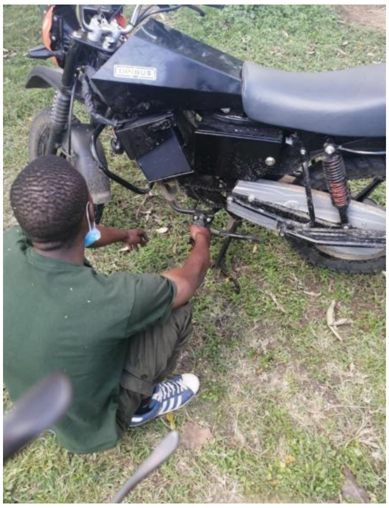
World Economic Forum (2018), “Electric Vehicles for Smarter Cities: The Future of Energy and Mobility”, available at: https://www.weforum.org/reports/electric-vehicles-for-smarter-cities-the-future-of-energy-and-mobility (accessed 12-August-2020).

Xin Li, L. Lopes and S. Williamson (2009), “On the suitability of plug-in hybrid electric vehicle (PHEV) charging infrastructures based on wind and solar energy”, *2009 IEEE Power & Energy Society General Meeting*, pp. 1–8.

Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z. and Wei, L. (2020), “World Cities Report 2020: The value of sustainable urbanization”.

Appendix

1.1 Glimpses of on-site measurement campaign



Picture A1: A technician servicing the e-bike at Homabay. The e-bikes were posing mechanical challenges. The technician had to be sent from Nairobi to address the problem,

Picture A2: The cargo bike GreenPack battery displayed

Picture A3: A student taking records (data) from the data logger

Picture A4: A student (Mike) test-riding an e-bike

Picture A5: Windsor hunter Fishing Lanterns being charged

Picture A6: Mr. Kifalu, Mike, Mangeti and Prof Sitati (taking photograph) inspecting the solar panels at Homa Bay Hub.

Picture A7: Solar panels on the roof of the *Mbita* hub

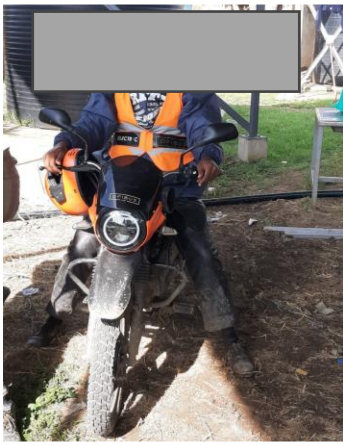
Picture A8: Inspection of the batteries, charging system and inverters at the *Mbita Hub*

Picture A9: Moi Team and Wetu team pause for a photograph at the Homa Bay Hub

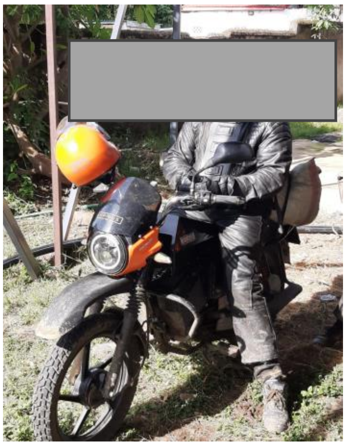
Picture A10: Moi Team and Wetu team pause for a photograph at the Homa Bay Hub

Picture A11: Cargo bike still under design and testing

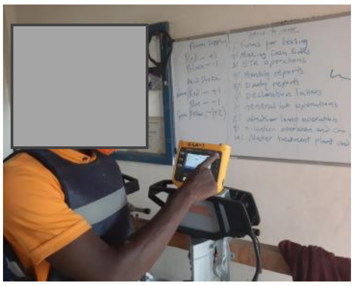
Picture A12: Energy Data logger used to take measurements at the Homa Bay hub



Picture A13: Rider getting ready for field measurement investigation



Picture A14: Rider getting ready for field measurement investigation



Picture A15: Rider taking energy readings from energy meter

1.2 Solar module datasheet

Bosch Solar Module c-Si M 60 | EU30117

Length [x]	Width [y]	Height [z]	Weight	Junction box	Plug connector type	Cable [l]	Front glass surface
1660.0	990.0	50.0	21	Spelsberg	MC4	–800 +1200	Structured

x, y, l in mm, ±2; z in mm, ±0.3; weight in kg ±0.5

Crystalline solar module	
Performance classes	**225 Wp, 230 Wp, 235 Wp, 240 Wp, 245 Wp**
Performance sorting	–0/+4.99 Wp
Structure	**Glass-foil laminate** ▸ Anodized aluminum frame ▸ Junction box (IP 65) with 3 bypass diodes ▸ Weather-resistant back sheet (white)
Cells	**60x monocrystalline solar cells** in 156 mm x 156 mm format
Mechanical load	**5400 Pa superimposed load, 2400 Pa suction load,** in accordance with IEC 61215 (extended test)

Electrical characteristics for STC[1]:

Designation	Pmpp [Wp]	Vmpp [V]	Impp [A]	Voc [V]	Isc [A]	Reverse-current load capacity [A]
M245 3BB	245	30.10	8.20	37.70	8.70	17
M240 3BB	240	30.00	8.10	37.40	8.60	17
M235 3BB	235	29.90	8.00	37.10	8.50	17
M230 3BB	230	29.70	7.90	37.00	8.40	17
M225 3BB	225	29.40	7.80	36.90	8.30	17

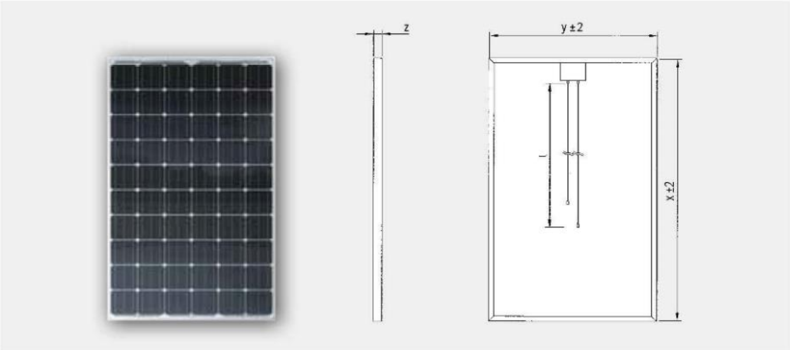
Reduction in module efficiency with decrease in irradiation level from 1000 W/m² to 200 W/m² (at 25 °C): –0.33 % (absolute); measuring tolerance Pmpp ±3 %

Electrical characteristics for NOCT[1]:

Designation	Pmpp [W]	Vmpp [V]	Voc [V]	Isc [A]
M245 3BB	177	27.07	34.09	6.92
M240 3BB	173	26.98	34.00	6.84
M235 3BB	169	26.87	33.89	6.76
M230 3BB	166	26.76	33.79	6.68
M225 3BB	162	26.55	33.49	6.60

NOCT: Normal Operation Cell Temperature 48.4 °C: Irradiation level 800 W/m², AM 1.5, temperature 20 °C, wind speed 1 m/s, electrical open circuit operation

Dimensions[2]:



[1] Electrical parameters are typical mean values from historical production data. No guarantee is made for the accuracy of this data for future production batches.

[2] Drawings are not to scale. For detailed dimensions and tolerances, see above.

Notes on assembly:
- See installation and operating manual at: www.bosch-solarenergy.com/products
- Horizontal and vertical assembly possible
- System voltage max. 1000 V
- Operating temperature range –40 to 85 °C

Weak light performance:

Intensity [W/m²]	Vmpp [%]	Impp [%]
800	0.0	–20
600	0.0	–40
400	–0.4	–60
200	–3.2	–80
100	–6.0	–90

The electrical data applies for 25 °C and AM 1.5.

Thermal characteristics:

Temperature coefficient	TK [%/K]
Pmpp	–0.46
Uoc	–0.32
Isc	0.032

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Robert-Bosch-Str. 1
99310 Arnstadt
Germany
Phone: +49 361 2195-0
Fax: +49 361 2195-1133
sales.se@de.bosch.com
www.bosch-solarenergy.com

Version: 01/2012

1.3 PV inverter datasheet

SUNNY TRIPOWER
15000TL / 20000TL / 25000TL

Efficient
- Maximum efficiency of 98.4%
- Yield increase without installation effort due to integrated shade management SMA ShadeFix

Safe
- DC surge arrester (SPD type II) can be integrated

Flexible
- DC input voltage of up to 1000 V
- Multistring capability for optimum system design
- Optional display

Innovative
- Cutting-edge grid management functions with Integrated Plant Control
- Reactive power available 24/7 (Q on Demand 24/7)

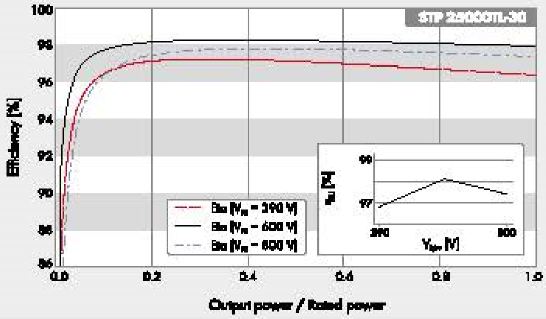
SUNNY TRIPOWER 15000TL / 20000TL / 25000TL

The versatile specialist for large-scale commercial plants and solar power plants

The Sunny Tripower is the ideal inverter for large-scale commercial and industrial plants. Not only does it deliver extraordinary high yields with an efficiency of 98.4%, but it also offers enormous design flexibility and compatibility with many PV modules thanks to its multistring capabilities and wide input voltage range.

The future is now: the Sunny Tripower comes with cutting-edge grid management functions such as Integrated Plant Control, which allows the inverter to regulate reactive power at the point of common coupling. Separate controllers are no longer needed, lowering system costs. Another new feature–reactive power provision on demand (Q on Demand 24/7).

Efficiency Curve



Accessory

RS485 interface
DM-485CB-10

Power Control Module
PWCMOD-10

DC surge arrester Typ II, inputs A and B
DCSPD KIT3-10

Multifunction relay
MFR 01-10

● Standard features ○ Optional features – Not available
Data at nominal conditions
Status: 02/2021

Technical Data	Sunny Tripower 15000TL	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)			
Max. generator power	27000 Wp	36000 Wp	45000 Wp
DC rated power	15330 W	20440 W	25550 W
Max. input voltage	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	240 V to 800 V / 600 V	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A	33 A / 33 A
Max. DC short-circuit current input A/input B	43 A / 43 A	43 A / 43 A	43 A / 43 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3	2 / A:3; B:3
Output (AC)			
Rated power (at 230 V, 50 Hz)	15000 W	20000 W	25000 W
Max. AC apparent power	15000 VA	20000 VA	25000 VA
AC nominal voltage		3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	
AC voltage range		180 V to 280 V	
AC grid frequency / range		50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz	
Rated power frequency / rated grid voltage		50 Hz / 230 V	
Max. output current / Rated output current	29 A / 21.7 A	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor		1 / 0 overexcited to 0 underexcited	
THD		≤ 3%	
Feed-in phases / connection phases		3 / 3	
Efficiency			
Max. efficiency / European Efficiency	98.4% / 98.0%	98.4% / 98.0%	98.3% / 98.1%
Protective devices			
DC-side disconnection device		●	
Ground fault monitoring / grid monitoring		● / ●	
DC surge arrester (Type II) can be integrated		○	
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated		● / ● / –	
All-pole sensitive residual-current monitoring unit		●	
Protection class (according to IEC 62109-1) / overvoltage category (according to IEC 62109-1)		I / AC: III; DC: II	
General data			
Dimensions (W / H / D)		661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)	
Weight		61 kg (134.48 lb)	
Operating temperature range		−25 °C to +60 °C (−13 °F to +140 °F)	
Noise emission (typical)		51 dB(A)	
Self-consumption (at night)		1 W	
Topology / cooling concept		Transformerless / Opticool	
Degree of protection (as per IEC 60529)		IP65	
Climatic category (according to IEC 60721-3-4)		4K4H	
Maximum permissible value for relative humidity (non-condensing)		100%	
Features / function / Accessories			
DC connection / AC connection		SUNCLIX / spring-cage terminal	
Display		○	
Interface: RS485, Speedwire/Webconnect		○ / ●	
Data interface: SMA Modbus / SunSpec Modbus		● / ●	
Multifunction relay / Power Control Module		○ / ○	
Shade management SMA ShadeFix / Integrated Plant Control / Q on Demand 24/7		● / ● / ●	
Off-Grid capable / SMA Fuel Save Controller compatible		● / ●	
Guarantee: 5 / 10 / 15 / 20 years		● / ○ / ○ / ○	
Certificates and permits (more available on request) * Does not apply to all national appendices of EN 50438		AS 4777, BDEW 2008, C10/11, CE, CEI 0-16, CEI 0-21, CNS 15382, CNS 15426, DEWA 2.0, DK1, DK2, EN 50549-1, EN 50549-2, G99/1, EN 50438:2013*, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, IS 16221-1/2, IS 16169, MEA 2013, NBR 16149, NEN EN 50438, NRS 097-2-1, PEA 2013, NTS, PPC, RD 1699/413, RD 661/2007, Res. n° 7:2013, SI 4777, TOR generator, UTE C 15-712-1, VDE 0126-1-1, VDE-AR-N 4105, VDE-AR-N 4110, VFR 2014	
Type designation	STP 15000TL-30	STP 20000TL-30	STP 25000TL-30

1.4 Battery inverter datasheet

SUNNY ISLAND 6.0H / 8.0H
FOR OFF-GRID AND ON-GRID APPLICATIONS

Flexible
- For self-consumption and battery backup systems in on-grid and off-grid applications
- All lead-acid and many lithium-ion batteries can be used
- Ideal for retrofits or modular expansions of single-phase and three-phase systems

Efficient
- Maximum efficiency of up to 96 %
- High efficiency of overall system
- Easy and fast installation and commissioning

Reliable
- Proven safety thanks to external certification
- Long battery service life thanks to intelligent battery management
- Reliable operation thanks to extreme overload capacity

SUNNY ISLAND 6.0H / 8.0H

The all-rounder for on-grid and off-grid

The Sunny Island 6.0H / 8.0H supports a wide range of on-grid and off-grid applications with compelling product features – from operation in remote off-grid areas to home energy management. Users can benefit from more than 25 years of SMA experience in the field of battery inverters. The high protection class, wide temperature range and exceptional overload capacity provide the kind of security needed for off-grid use. Intelligent load and energy management keeps the system running, even in critical situations. And being a core element in the SMA Flexible Storage System for new and existing PV systems, the Sunny Island 6.0H / 8.0H stores generated solar energy and works with the Sunny Home Manager to intelligently manage home energy consumption. The Quick Configuration Guide and intuitive user interface help ensure an easy, convenient installation in any application scenario. That makes the Sunny Island 6.0H / 8.0H the ultimate all-purpose product solution – for on-grid and off-grid.

SUNNY ISLAND 6.0H / 8.0H

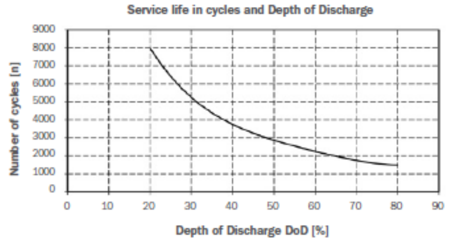
Technical Data	Sunny Island 6.0H	Sunny Island 8.0H
Operation on the utility grid or generator		
Rated grid voltage / AC voltage range	230 V / 172.5 V to 264.5 V	230 V / 172.5 V to 264.5 V
Rated grid frequency / permitted frequency range	50 Hz / 40 Hz to 70 Hz	50 Hz / 40 Hz to 70 Hz
Maximum AC current for increased self-consumption (grid operation)	20 A	26 A
Maximum AC power for increased self-consumption (grid operation)	4,6 kVA	6 kVA
Maximum AC input current	50 A	50 A
Maximum AC input power	11500 W	11500 W
Stand-alone or emergency power operation		
Rated grid voltage / AC voltage range	230 V / 202 V to 253 V	230 V / 202 V to 253 V
Rated frequency / frequency range (adjustable)	50 Hz / 45 Hz to 65 Hz	50 Hz / 45 Hz to 65 Hz
Rated power (at Unom, fnom / 25 °C / cos φ = 1)	4600 W	6000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	6000 W / 6800 W / 11000 W	8000 W / 9100 W / 11000 W
AC power at 45 °C permanently	3700 W	5430 W
Rated current / maximum output current (peak)	20 A / 120 A	26 A / 120 A
Total harmonic distortion output voltage / power factor at rated power	< 4 % / −1 to +1	< 4 % / −1 to +1
Battery DC input		
Rated input voltage / DC voltage range	48 V / 41 V to 63 V	48 V / 41 V to 63 V
Maximum battery charging current / rated DC charging current / DC discharging current	110 A / 90 A / 103 A	140 A / 115 A /130 A
Battery type / battery capacity (range)	Li-Ion*, FLA, VRLA / 100 Ah to 10000 Ah (lead-acid) 50 Ah to 10000 Ah (Li-Ion)	Li-Ion*, FLA, VRLA / 100 Ah to 10000 Ah (lead-acid) 50 Ah to 10000 Ah (Li-Ion)
Charge control	IUoU charge procedure with automatic full charge and equalization charge	
Efficiency / self-consumption of the device		
Maximum efficiency	95,8 %	95,8 %
No-load consumption / standby	25,8 W / 6,5 W	25,8 W / 6,5 W
Protective devices (inverter)		
AC short-circuit / AC overload	● / ●	● / ●
DC reverse polarity protection / DC fuse	– / –	– / –
Overtemperature / battery deep discharge	● / ●	● / ●
Overvoltage category as per IEC 60664-1	III	III
General data		
Dimensions (W / H / D)	467 mm / 612 mm / 242 mm (18.4 inch / 21.1 inch / 9.5 inch)	
Weight	63 kg (138.9 lb)	
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)	
Protection class as per IEC 62103	I	I
Climatic category as per IEC 60721	3K6	3K6
Degree of protection as per IEC 60529	IP54	IP54
Features / function		
Operation and display / multifunction relay	External via SRC-20 / 2	External via SRC-20 / 2
Three-phase systems / battery backup function	● / ●	● / ●
State of charge calculation / full charge / equalization charge	● / ● / ●	● / ● / ●
Battery temperature sensor / data cables	● / ●	● / ●
Certificates and approvals	www.SMA-Solar.com	www.SMA-Solar.com
Warranty	5 years	5 years
For off-grid applications		
Automatic rotating magnetic field detection / generator support	● / ●	● / ●
Parallel connection / Multicluster	● / ●	● / ●
Integrated soft start	●	●
Accessory		
For off-grid applications		
Battery fuse**	○	○
Interface SI-COMSMA (RS485) / SI-SYSCAN (Multicluster)	○ / ○	○ / ○
Interface SWDMSI-10 (Speedwire)	○	○
Sunny Island Charger SIC50-MPT** / SMA Cluster Controller	○ / ○	○ / ○
For on-grid applications		
Interface SI-COMSMA (RS485) / Interface SWDMSI-10 (Speedwire)	○ / ○	○ / ○
Sunny Home Manager / SMA Energy Meter / automatic transfer switch for battery backup**	○ / ○ / ○	○ / ○ / ○
● Standard features ○ Optional features – Not available * see „List of Approved Lithium-Ion Batteries" at www.SMA-Solar.com ** procurement via external supplier All specifications, last updated: October 2016		
Type designation	SI6.0H-11	SI8.0H-11

1.5 Battery hoppecke OPzS datasheet

Type overview

Capacities, dimensions and weights

Type	C_{100}/1.85 V Ah	C_{50}/1.85 V Ah	C_{24}/1.83 V Ah	C_{10}/1.80 V Ah	C_{5}/1.77 V Ah	max. Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
4 OPzS solar.power 280	280	265	245	213	182	17.1	4.5	105	208	420	A
5 OPzS solar.power 350	350	330	307	266	227	20.7	5.6	126	208	420	A
6 OPzS solar.power 420	420	395	370	320	273	24.6	6.7	147	208	420	A
5 OPzS solar.power 520	520	490	454	390	345	29.1	8.5	126	208	535	A
6 OPzS solar.power 620	620	585	542	468	414	34.1	10.1	147	208	535	A
7 OPzS solar.power 730	730	685	634	546	483	39.2	11.7	168	208	535	A
6 OPzS solar.power 910	910	860	797	686	590	46.1	13.3	147	208	710	A
7 OPzS solar.power 1070	1070	1002	930	801	691	59.1	16.7	215	193	710	B
8 OPzS solar.power 1220	1220	1145	1063	915	790	63.1	17.3	215	193	710	B
9 OPzS solar.power 1370	1370	1283	1192	1026	887	72.4	20.5	215	235	710	B
10 OPzS solar.power 1520	1520	1425	1325	1140	985	76.4	21.1	215	235	710	B
11 OPzS solar.power 1670	1670	1572	1459	1256	1086	86.6	25.2	215	277	710	B
12 OPzS solar.power 1820	1820	1715	1591	1370	1185	90.6	25.8	215	277	710	B
12 OPzS solar.power 2170	2170	2010	1843	1610	1400	110.4	32.7	215	277	855	B
14 OPzS solar.power 2540	2540	2349	2163	1881	1632	142.3	46.2	215	400	815	C
16 OPzS solar.power 2900	2900	2685	2472	2150	1865	150.9	45.9	215	400	815	C
18 OPzS solar.power 3250	3250	3015	2765	2412	2097	179.1	56.4	215	490	815	D
20 OPzS solar.power 3610	3610	3350	3072	2680	2330	187.3	55.7	215	490	815	D
22 OPzS solar.power 3980	3980	3685	3388	2952	2562	212.5	67.0	215	580	815	D
24 OPzS solar.power 4340	4340	4020	3696	3220	2795	221.2	66.4	215	580	815	D
26 OPzS solar.power 4700	4700	4355	4004	3488	3028	229.6	65.4	215	580	815	D

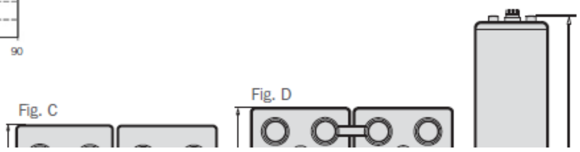


C_{100}, C_{50}, C_{24}, C_{10} and C_5 =
Capacity at 100 h, 50 h, 24 h, 10 h and 5 h discharge

* according to DIN 40736-1 data to be understood as maximum values

Fig. C

Fig. D



his brochure are based on state-of-the-art technology. Our products are subject to constant development. We therefore reserve the right to make changes.

1.6 Cargo bike battery

BETRIEBSHANDBUCH GREENPACK
V2.1 I November 2018

GreenPack
mobile energy solutions

TECHNISCHE DATEN

Der GreenPack Li-I 003 14S 10P

Technische Daten

GreeGreenPack-Typ	Type I
Zelltype	140 Stück Li-Ion 18650
Konfiguration	14S 10P
Nominale Spannung	48V
Entladeschlussspannung	42V
Ladeschlussspannung	58,8V
Spannungsfestigkeit	65 V DC
Kapazität / Energie	27,8 Ah / 1.400 Wh
Dauerstrom	25A
Maximaler Strom (3s max)	60 A
Zyklenzahl (80% Entladetiefe, 80% Restkapazität)	>1.000
Gewicht	9,5 kg
Betriebstemperatur (Laden)	0 °C bis + 45 °C
Betriebstemperatur (Entladen)	-20 °C bis + 60 °C
Abmessungen (HxBxT)	368 x 218 x 88 mm
Gehäuse Schutzart	IP 65
Kommunikation	CAN 2.0, 500 KBaud
Ladegerät	Li-Ion Batterie Ladegerät 8A
Ladezeit	3,5h
Sonstiges	- Batterie-Managementsystem mit Sicherheitsfeatures - interne Temperaturüberwachung - Clustering via externem Clustermanage-mentsystem

BETRIEBSHANDBUCH GREENPACK - SEITE 15

1.7 Niwa lantern datasheet

Certificate of Conformity

Low Voltage Directive 2014/35/EU

Holder of Certificate:	**NIWA - next energy products ltd.** **1903, Tamson Plaza, 161 Wai Yip Street, Kwun Tong, Hong Kong**
Cert. No./Report No.:	**LCZS17090046**
Product:	**LED portable lamp**
Model No.:	**Lago 600**
Parameters:	**Luminaire Rated Input : DC 5V, 6A(for lamp input)** **Power: 8W** **Used with Adaptor: 100-240Vac 50/60Hz, 30W** **Protection class: III** **Degree of protection: IP67(for portable lamp); IP20(for adaptor)**
Tested according To:	**EN 60598-2-4:1997** **EN 60598-1:2015** **EN 62031:2008+A1:2013+A2:2015**

Conclusion:

This Certificate of conformity is based on evaluation of a sample of the above mentioned product. Technical Report and documentation are at the License Holder's disposal. This is to certify that the Tested sample is in conformity with all revision of Annex I of Council Directive 2014/35/EU, in its latest amended version, referred to as the Low Voltage Directive. This certificate does not imply assessment of the series-production of the product and does not

1.8 LCoE for system with non-NLP load optimiser

System configuration	
Type	Solar System
Location	Mbita, Kenya
Number of modules	138.00
Module area in m²	231.84
Battery storage Capacity in kWh	104.00
Annual energy demand in kWh/a	27,200.00
Annual energy produced in kWh/a	37,700.00
Annual energy deficit in kWh/a	375.00

Investment costs	66,408.00 €
Solar array	27,600.00 €
Battery storage	23,650.00 €
Solar Inverter	5,158.00 €
Battery Inverter	6,000.00 €
Other components	3,000.00 €
Mounting	1,000.00 €

Operation and maintenance costs	
Operation-related costs in €/a	664.08
Electricity costs in €/kWh	0.00
Electricity costs in €/kWh to serve the 375 kWh deficit	0.00

Economic parameters	
Interest rate in %/a	7.00%
Inflation in %/a	4.69%
Discount rate in %/a	2.21%

LCOH	
Observation period in a	20
LCOH in €-Ct/kWh	**18.24**

t	M_t in €	$C_{recurrent}$ in €	$\Sigma C / (1+r)^t$	$E_t / (1+r)^t$
1	664.08		649.74	36886.10
2	664.08		635.72	36089.78
3	664.08		621.99	35310.64
4	664.08		608.56	34548.33
5	664.08		595.43	33802.47
6	664.08		582.57	33072.72
7	664.08		569.99	32358.72
8	664.08		557.69	31660.13
9	664.08		545.65	30976.63
10	664.08	27650.00	22762.33	30307.88
11	664.08		522.34	29653.57
12	664.08		511.07	29013.39
13	664.08		500.03	28387.02
14	664.08		489.24	27774.18
15	664.08		478.68	27174.57
16	664.08	4000.00	3289.34	26587.90
17	664.08		458.23	26013.90
18	664.08		448.34	25452.30
19	664.08		438.66	24902.81
20	664.08		429.19	24365.19
21	664.08		419.92	23839.17
22	664.08		410.86	23324.52
23	664.08		401.99	22820.97
24	664.08		393.31	22328.29
25	664.08		384.82	21846.25
26	664.08		376.51	21374.62
27	664.08		368.38	20913.16
28	664.08		360.43	20461.67
29	664.08		352.65	20019.93
30	664.08		345.03	19587.73
			34826.94	**555070.23**

1.9 LCoE for system with NLP load optimiser

System configuration	
Type	Solar System
Location	Mbita, Kenya
Number of modules	138.00
Module area in m²	231.84
Battery storage Capacity in kWh	90.00
Annual energy demand in kWh/a	31,300.00
Annual energy produced in kWh/a	37,700.00
Annual energy deficit in kWh/a	50.00

Investment costs	63,097.00 €
Solar array	27,600.00 €
Battery storage	20,339.00 €
Solar Inverter	5,158.00 €
Battery Inverter	6,000.00 €
Other components	3,000.00 €
Mounting	1,000.00 €

Operation and maintenance costs	
Operation-related costs in €/a	630.97
Electricity costs in €/kWh	0.00
Electricity costs in €/kWh to serve the 375 kWh deficit	0.00

Economic parameters	
Interest rate in %/a	7.00%
Inflation in %/a	4.69%
Discount rate in %/a	2.21%

LCOH	
Observation period in a	20
LCOH in €-Ct/kWh	**17.07**

t	M_t in €	$C_{recurrent}$ in €	$\Sigma C / (1+r)^t$	$E_t / (1+r)^t$
1	630.97		617.35	36886.10
2	630.97		604.02	36089.78
3	630.97		590.98	35310.64
4	630.97		578.22	34548.33
5	630.97		565.74	33802.47
6	630.97		553.53	33072.72
7	630.97		541.58	32358.72
8	630.97		529.88	31660.13
9	630.97		518.44	30976.63
10	630.97	24339.00	20073.92	30307.88
11	630.97		496.30	29653.57
12	630.97		485.59	29013.39
13	630.97		475.10	28387.02
14	630.97		464.85	27774.18
15	630.97		454.81	27174.57
16	630.97	4000.00	3265.99	26587.90
17	630.97		435.38	26013.90
18	630.97		425.99	25452.30
19	630.97		416.79	24902.81
20	630.97		407.79	24365.19
21	630.97		398.99	23839.17
22	630.97		390.37	23324.52
23	630.97		381.95	22820.97
24	630.97		373.70	22328.29
25	630.97		365.63	21846.25
26	630.97		357.74	21374.62
27	630.97		350.02	20913.16
28	630.97		342.46	20461.67
29	630.97		335.07	20019.93
30	630.97		327.83	19587.73
			31677.66	**555070.23**

1.10 Measurement investigation on *OpiBus* Bike

Date	Battery No.	Energy demand in kWh	Distance in km	Total weight in kg	Speed in km/h	Charging time in h	Charging capacity in kW	Energy demand in kWh/100km	Road surface
05.05.2021	1	2.0	56.1	78.0	55.0	3.2	0.6	3.6	Tarmac
05.05.2021	2	2.6	43.0	160.0	55.0	3.4	0.8	6.0	Tarmac
06.05.2021	3	2.3	39.2	88.0	45.0	3.0	0.8	6.0	Tarmac
06.05.2021	4	2.7	46.9	160.0	45.0	3.4	0.8	5.7	Tarmac
07.05.2021	5	2.6	42.9	160.0	45.0	2.9	0.9	6.1	Tarmac
08.05.2021	6	2.3	39.2	160.0	55.0	3.5	0.7	5.9	Tarmac
09.05.2021	7	2.6	39.6	212.0	55.0	3.4	0.8	6.7	Tarmac
10.05.2021	8	2.2	34.1	84.0	55.0	3.4	0.6	6.4	Without
11.05.2021	9	2.6	45.2	136.0	40.0	3.6	0.7	5.8	Without
11.05.2021	10	2.7	38.8	144.0	40.0	3.2	0.8	6.9	Without
12.05.2021	11	2.6	25.3	144.0	55.0	3.3	0.8	10.1	Without
13.05.2021	12	2.9	36.9	154.0	40.0	2.8	1.0	7.7	Without
13.05.2021	13	2.6	38.0	154.0	45.0	3.2	0.8	6.8	Without
	Ø	**2.5**	**40.4**	**141.1**	**48.5**	**3.2**	**0.8**	**6.4**	

1.11 Measurement investigation on *BodaWerk* Bike

Date	Battery No.	Energy demand in kWh	Distance in km	Total weight in kg	Speed in km/h	Charging time in h	Charging capacity in kW	Energy demand in kWh/100km	Road surface
14.12.20	1	2.1	59.3	84.3	30	2.1	1.0	3.5	Tarmac
15.12.20	2	0.7	18.0	84.3	30	1.2	0.6	3.9	Tarmac
16.12.20	3	2.0	46.6	64	47	1.9	1.1	4.3	Tarmac
17.12.20	4	2.4	54.3	64	45	2.4	1.0	4.4	Tarmac
18.12.20	5	2.2	62.4	74	45	2.1	1.0	3.6	Tarmac
	Ø	**1.9**	**48.1**	**74.1**	**39.4**	**1.9**	**0.9**	**3.9**	

1.12 Measurement investigation on *AnywhereBerlin Cargo* Bike

Date	Battery No.	Energy demand in kWh	Distance in km	Total weight in kg	Speed in km/h	Charging time in h	Charging capacity in kW	Energy demand in kWh/100km	Road surface
12.11.20	2	1.1	10.5	210	24	5.7	0.2	10.2	Mixed
12.12.20	1	1.2	33.0	70	23	5.8	0.2	3.5	Tarmac
13.12.20	2	1.0	36.0	70	23	5.3	0.2	2.7	Tarmac
14.12.20	1	1.0	35.3	70	24	5.2	0.2	2.9	Tarmac
15.12.20	2	1.0	31.5	70	24	5.3	0.2	3.3	Tarmac
16.12.20	1	1.0	33.3	70	24	4.8	0.2	3.0	Tarmac
17.12.20	2	1.1	30.6	118.05	20	5.4	0.2	3.4	Tarmac
18.12.20	1	1.1	22.0	140.4	21	5.4	0.2	4.8	Tarmac
	Ø	**1.0**	**29.0**	**102.3**	**22.9**	**5.4**	**0.2**	**4.2**	

1.13 Declaration of Authorship

I hereby attest that this research and the materials I submit for evaluation in order to receive the title of "Doctor of Philosophy" were written by me and are totally original. To the best of my knowledge, I took reasonable precautions to ensure that the work is original and does not violate any copyright laws. Throughout the text of this paper, no one else's work has been used without proper acknowledgement and citation.

Signed:

Date: 01.08.2023