Department of Mechanical and Aerospace Engineering

Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

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Copyright Declaration

Signed: Felix Katiki Kusaloka Date: 12 August 2022

Abstract

This research focused on technical parameters to penetrate the decarbonize the road transport sector in Zambia. The research was built around the solar powered mobility charging hub to service public charging of battery electric vehicles. This was particularly important as it gave both the technical requirements, environmental, and cost benefit factors in the adoption of electric mobility in the country to curb greenhouse gas emissions.

Through the literature reviewed, it was established that there were extremely low penetration levels of electric mobility vehicles in sub–Saharan Africa and for Zambia there were no registered electric vehicles at the time of this study. One of the reasons was the high purchasing cost of electric vehicles, and another reason was luck of incentivised policies and non-existence of mobility charging hubs. This research reviewed all available types of electric vehicles and their charging technologies and leveraged the technology and capital costs to drive interest from stakeholders to engage in the transition to electric vehicles.

Zambia's location 13.1339° S, 27.8493° E of the equator led to some interesting simulation results as the country enjoyed an annual sunshine of more than 2000hours. With this data, a 1m^2 solar photovoltaic panel simulation produced about 267kWh/yr and this was sufficient to charge an average electric vehicle with an average nominal battery capacity of 62kWh and a total demand of 73kWh/yr. It was also established that even when this hub was synchronized to the grid, it still drew an equivalent amount of energy as the electric vehicle demand of 73kWh/yr in an uncontrolled charging environment. When battery storage was introduced to the 267kWh/yr hub, it needed about 7kWh of battery nominal capacity to run the hub on a 24hours period. On the greenhouse gas emissions, it was found that over 2 tonnes of carbon dioxide were emitted by a single conventional gasoline vehicle per year.

Keywords: mobility charging hubs, solar, photovoltaic, electric vehicle, battery, grid, energy, kilowatt hour, carbon dioxide, emission

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1.0 Introduction

1.1 Research Background

The Zambian transport sector accounts for over 2% in national greenhouse gas emission (GHG) [1]. At global level sub–Saharan Africa is responsible for about 0.5% of carbon dioxide emissions, this is the lowest contribution by any continent and could be attributed to mainly lower levels of industrialization on the continent. Africa is one of the remaining continents which has not been fully exploited and if the environmental aspects are not nurtured now, it may be a huge task to turn back the clocks [2]. Sub Saharan Africa and Zambia in particular, is endowed with several natural resources such as minerals like cobalt a key component in Lithium-ion batteries. Zambia also has almost 12hours of sunlight throughout the day and all year round and this presents a huge opportunity to harness a renewable energy source in the form of solar energy. The introduction of mobility charging hubs in Zambia with the buffering of battery storage and or grid synchronization to support the transport sector is a promising pathway to transitioning the transport sector to a clean and sustainable energy environment which is also in line with the United Nations Sustainable Development Goals (SDGs) [3]. The SDGs that relate to this transition includes SDG 7 – Affordable and Clean Energy, SDG 9 – Industry, Innovation and Infrastructure, SDG 11 – Sustainable Cities and Communities and SDG 13 – Climate Action. The adoption of this technology in Zambia squarely carters for SDG number 13 as it will directly reduce GHG emissions from the transport sector.

Zambia is one of the sub-Saharan countries that has lagged behind in terms of decarbonizing the transport sector with South Africa and Kenya leading the way in introducing electric mobility vehicles[4]. However, despite this being the case, generally the roll out of electric vehicles is still in its infancy stage on the continent and is also somewhat hindered by high investment costs, political barriers, lack of infrastructure and social stereotypes among other aspects [5]. This research explores one of the ways to ease the acceleration of introduction of electric mobility vehicles and particularly examines the situation in Zambia as a case study.

The fuel for electric mobility vehicles is electrical energy which replaces fossil fuels petrol and diesel use in the conventional internal combustion engines (ICE) vehicles as electric vehicles rely on electric motors for propulsion[6]. The introduction of EVs implies more loads being introduced on the national grid which in the recent past has struggled to meet the loads especially with the increase in mining and exploration activities which led to perennial loadshedding in the country in the years 2014 to 2017. Using renewable energy which in this research would mainly imply solar photovoltaic (PV) energy resource is a sustainable way to decarbonize the transport sector. The idea of a solar photovoltaic powered public electric vehicle charging hub would not only encourage people to shift to electric mobility vehicles but would also reduce the carbon emission from the grid which would have come about by way of increasing the generation capacity of electricity to carter for the increased load from fossil fuel power generating stations.

Recently there have been discussions and memoranda signed between the governments of the republic of Zambia and the Democratic Republic of Congo (DRC) on the exploration of cobalt mining to fuel the adoption of electric vehicles through the manufacturing of car batteries [7]. This research prepares the grounds for the decarbonization pathway using one of the most abundant resources which is solar energy in Zambia [8]. This research examines the penetration of electric vehicles in sub-Saharan Africa and Zambia in particular. It also discusses the technology and types of electric vehicle, charging systems and infrastructure. The study zones in on the engineering feasibilities of possible energy system requirements to charge electric mobility vehicles in Zambia with an islanded microgrid and a grid connected microgrid. The main reason for such a diverse study is because not all places in Zambia may have access to the ZESCO national electricity grid and hence could be highly suitable for an islanded mobility hub microgrid especially in rural setup.

The research also briefly discusses the current state of the ZESCO national grid and its capability to take on more load alongside its traditional ever increasing mineral exploration and mining activities largest chunk of its current load. After much of the literature review, several software-based simulations were performed using Helioscope for the solar photovoltaic characteristic and Homer Pro for the entire charging hub system in determining the design structure and performance of the solar PV supported mobility charging hub. The research also looked at the key environments impacts of such a project on the greenhouse gas emissions footprint at national level with comparison to the grid imports in case of a grid connected mobility charging hub. The project was also costed to determine an underhand idea of how realistic it can be if implemented and or scaled up for implementation elsewhere.

1.2 Research Aims and Objectives

Climate change has affected most countries around the globe irrespective of their economic status or geographical location, it is therefore, imperative that all countries should begin to adopt new sustainable technologies in a quest to attain a carbon neutrality by 2050. The aim of this research was to assess the potential feasibility and characteristics of photovoltaic arrays and battery storage energy sources to support mobility charging hubs as an off-grid energy systems which can be installed in any location without needing grid connection. A solar PV and grid connected charging hub operational performance was also studied for cases where the hub was synchronized to the national grid. The research also endeavoured to weigh in on the current environmental impacts of the transport sector in Zambia and the contribution the results from this study could make in reducing greenhouse gases.

The dissertation also sought to review the level of the electric vehicle penetration in sub–Saharan Africa and of particular interest in Zambia. This is intended to form a framework on how to proceed in modelling an EV microgrid charging hub in an islanded mode and one connected to the ZESCO national electricity grid. Of particular interest in this research is that real data on solar radiation of Zambia was used to analyse the solar potential to support mobility charging hubs in the country.

The main objectives of this research have been crystalized as listed below as to,

i. Investigate the status quo of electric mobility vehicle penetration in sub-Saharan Africa and detail the types of current electric vehicles and available charging systems mechanisms,

ii. Study and evaluate existing alternatives of electric vehicle charging hubs technologies and their utilization characteristics,

iii. Model and analyse the characteristics of an off-grid PV and battery storage EV charging hub under the Zambian climate,

iv. Analyse the characteristics of a grid coupled PV and battery storage electric vehicle charging hub,

v. Evaluate the financial and environmental impacts of mobility charging hubs in the Zambian context,

vi. Discuss research findings and make conclusions of the results obtained.

One of the major contributions of this research objectives was the energy system with a realistic probabilistic EV charging characteristic analysis results which were done in such a way that they could easily be scaled up and replicated in various geographical locations in Zambia and beyond on the African continent. The idea was to also come up with a general perspective to implement mobility charging hubs supported by solar PVs, energy storage systems and where there is access to grid could replace the energy storage with grid depending on a several factors of which the main ones being the grids carbon footprint and the financial costs vis-a-vis energy storage system.

1.3 Research Methodology

The research methodology adopted in this dissertation were mainly in three folds. To contextualize the research, a tentative literature review was carried. The second stage was the simulation and analysis of a mobility charge to support an electric vehicle using the solar radiation of Zambia. To conclude, a discussion of the study and future studies to look at other sectors that could contribute to this study were made and lastly made some conclusions of the study with obtained results as set out in the research aims and objectives.

The literature review was based on bringing out the previous studies and technologies available in as far as mobility charging hubs, electric mobility vehicles and generally every aspect related to the topic under study to make mobility charging hubs feasible in Zambia. The literature review was tailored in such a way that an outlook on the penetration of electric vehicles in Sub Saharan Africa was undertaken with of course later shifting the concentration to Zambia as the case study. The reason for analysing what was happening at continental level was mainly to give a perspective of how Africa was fairing in transitioning to carbon neutral mobility as whole and not just as individual countries.

For better results to this study, an in-depth knowledge and previously published works and research of related mobility charging hubs were reviewed including the modern available electric mobility charging system technologies. This sectioned was also used as a structure to formulate an architectural configuration of what this research envisaged to realize its aims and objectives. Another component in the literature review was to bring to the fore the type of load that the mobility charging hubs was expected to support. This required background research on the types of electric vehicles and their charging systems and assess their suitability for application to this study. From the research it was realized that of particular interest was the battery electric vehicles and the light electric vehicles were the main contenders to suit for considerations in this study. The literature review was further extended to discuss the available types of battery technologies used in electric vehicles especially that Zambia is a mining country and does mine cobalt which is one of the components in Lithium-ion batteries.

The mobility charging hub was to be powered using solar photovoltaic, but through the quantitative literature review, it was observed that mobility charging hubs can either be solely PV powered or integrated with battery energy storage and or connected to the national grid. However, the national grid in Zambia was in the recent past experiencing loadshedding and the introduction of mobility charging hubs if connected to the grid would increase the current energy demand. Hence, an overview of the Zambian electricity generation and distribution sector was highlighted to give a picture of the national generation capacity and the existing power demand. The composition of the generation mix was also evaluated to assess the carbon footprint attributed to the power sector so as not to get into contention with the decarbonization of the transport sector which is the main core of this research.

Zambia is geographically located right below the equator bordering within the southern and eastern hemisphere. This geographical location presents an interesting potential in terms of solar photovoltaic energy production. This study expounded on this solar radiation potential and its ability to provide energy for servicing mobility charging hubs. The essence of these charging hubs was to charge the electric mobility vehicles starting from the one wheel all the way to the four-wheel vehicles. The literature review also analysed the feasibilities and possibilities of the types of electric mobilities that could be introduced in the country especially after careful study of the then current automobile trends in terms of purchasing pattern. Of particular interest was the large number in use of used petrol and diesel vehicles and how this would transform to importing used electric mobility vehicles.

The solar PV supported mobility charging hub design was best analysed through computer simulations using simulation software's that made use of predefined weather conditions as the solar radiation varies based on geographical locations. The method implemented in the simulation and results analysis of the charging hub were categorized in a step-by-step design starting with the modelling of a solar hub and scaling it down to a unity figure for ease uptake and application to any design. Figure 1 below depicts the technical research mobility charging hub design and analysis process that was undertaken to produce the research outcomes. The EV demand profile was made possible by aid of another software that generated a probabilistic electric vehicle demand profile for the most common electric vehicles on the roads in Glasgow city in the United Kingdom. All the assembled components which included the solar PV energy, the ZESCO grid connection and tariffs and battery energy storage facilities were modelled together to simulate the charging hub based on the set objectives of this research.

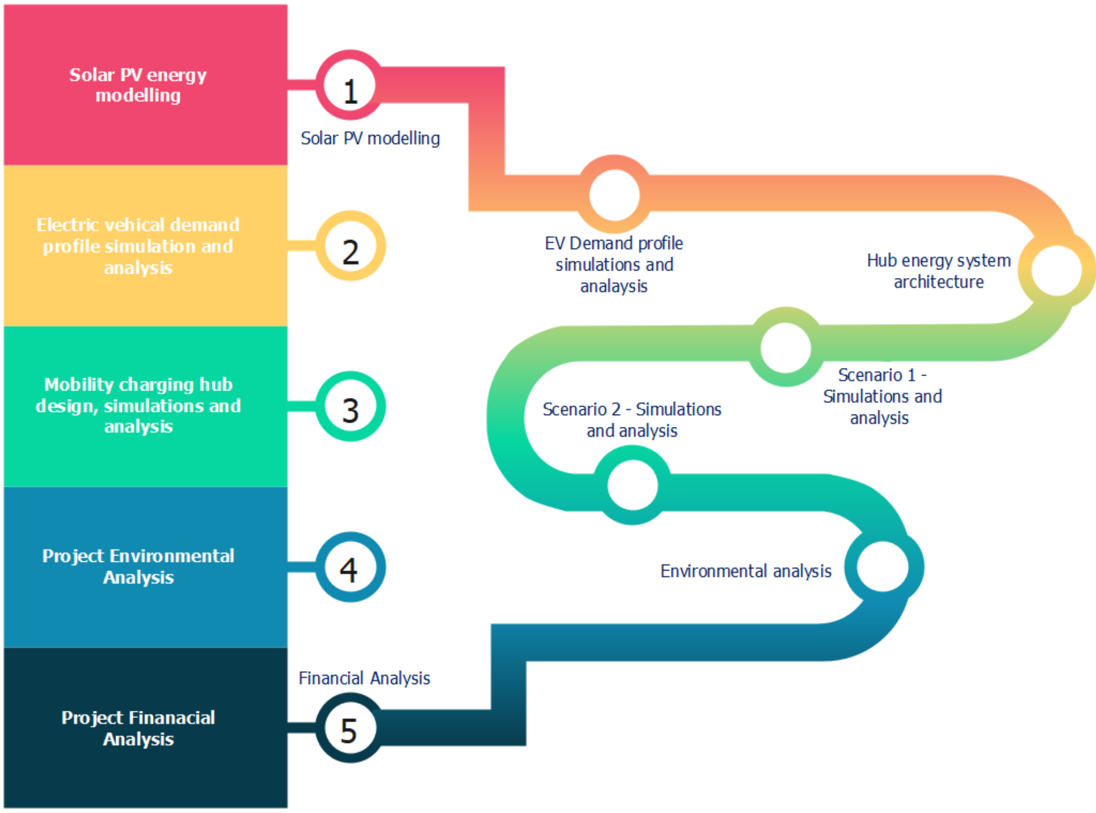


Figure 1: Project design, simulation, and results analysis structure (Source: Author's Analysis)

An environmental analysis was also carried out to evaluate the impact of introducing electric mobility vehicles would have on the Zambian national carbon footprint. This also included a summary of the capital expenditure requirements in a situation where this research was to be brought to fruition in its current form. This project also highlighted on assumptions made which consequently presented project limitations. The research was completed with a discussion and conclusions made with respect to attaining the set research aims and objectives and made remarks for possible areas of future studies.

2.0 Literature Review

2.1 Overview of Electric Vehicle Penetration in Sub Saharan Africa

Electric vehicle penetration in sub Saharan Africa was currently immature as compared to high income economies such as United States of America (USA), Europe and China who account for over 90% sales of EVs produced per year [9]. The main topic in sub–Saharan Africa for many years had been the improvement in the road infrastructure to accommodate more traffic, provision of walk ways and creation of cyclists lanes [10],[11] [12]. This has overshadowed the concentration on the type of vehicles on the roads in many of these countries. Sometimes this could be attributed to lack of policies in place to promote the transition to electric vehicles [13]. Another aspect to highlight is that most public transport which includes taxis, passenger busses and trucks in most sub Saharan African countries are privately owned, hence the transitioning to electric vehicles would also heavily rely on government policies and one of them could be through incentives [2], [14].

It has been projected that by 2035 all major automotive manufacturers will only be selling electric vehicles [4]. The main driving factor for the quest to transition from internal combustion engine (ICE) vehicles to EV is the target to attain carbon neutrality and save the climate from the continuation of production of carbon dioxide (C02) a gas responsible for climate change [15]. Sub Saharan Africa accounts for about 10% of the global greenhouse gas emissions and of this amount the transport sector contributes about 15% [16]. Sub Saharan Africa is mainly a consumer of second hand/used vehicles and many of these vehicles come from Japan, United Kingdom, and United States of America. Africa will need to push for a sustainable mobility system just as the rest of the world is drifting towards this or risk becoming the dumping site for the soon to be unwanted used ICE vehicles.

South Africa and Sudan are the current two Sub Saharan countries that have imposed a total ban on imported used cars whereas the others have imposed an age limit on importation of used cars. Zambia and a few others do not have any policy on importation of used vehicles apart from carbon tax surcharged when registering the vehicle [4]. Figure 2 below shows the sub-Saharan African countries with various legislations on the importation of second hand used vehicles and the average purchase price plus shipment of used vehicles to Africa.

Several African countries are making pronouncements towards the electrification of vehicles with South Africa leading the way. South Africa currently has over 1000 EVs on the road out of the over 12 million vehicles whereas Kenya has over 350 EVs out of over 2.2 million cars in that country[17]. Zambia and Democratic Republic of Congo (DRC) have also made pronouncements in putting in place legislation to promote EVs especially that the two countries hold a fair share of cobalt reserves, a mineral requirement in the production of Lithium-ion batteries [7]. Others include Kenya and Namibia who wish to increase the number of imports of electric vehicles by 2025 and 2030 respectively. Ghana, Rwanda, Mauritius, and Seychelles have even announced tax exemptions on the purchase of EVs.

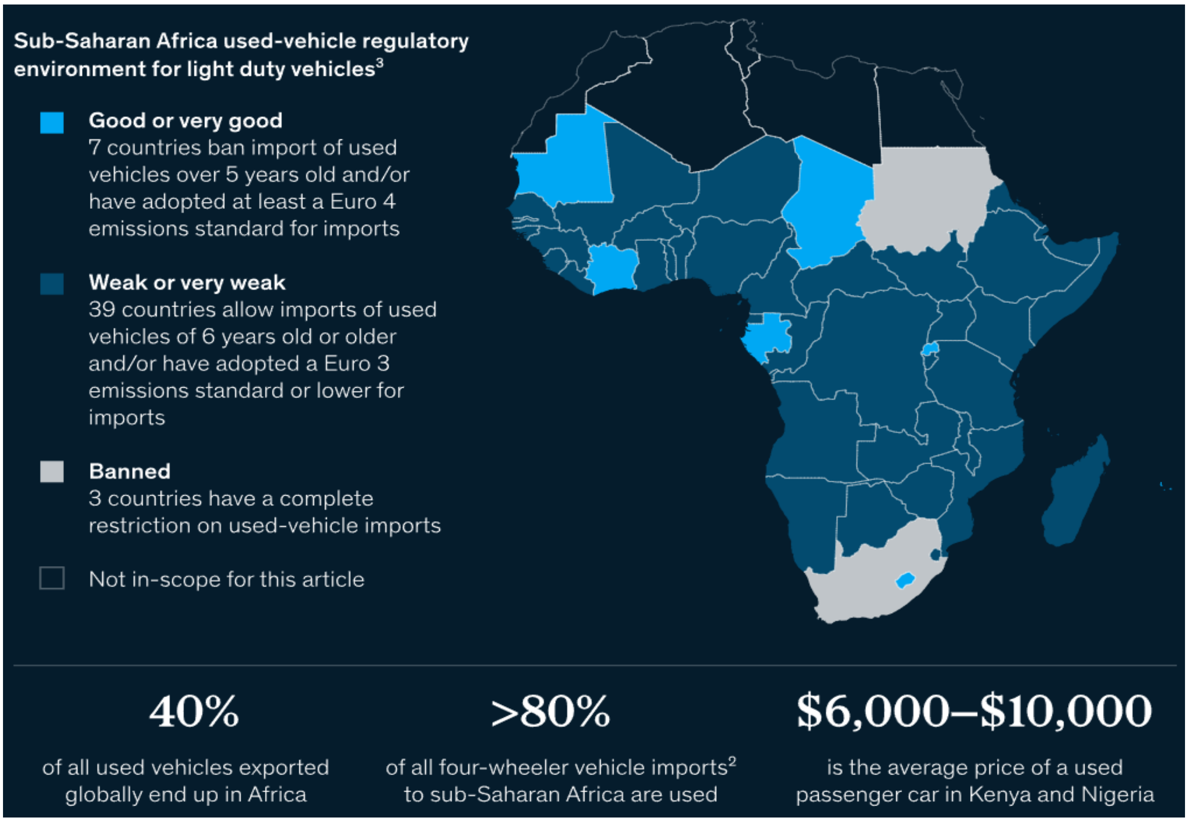


Figure 2: Sub Saharan African countries policies on importation of used vehicles [4]

Despite the interest in the adoption of EVs, there exists peculiar hindrances and challenges specifically for the African setup such as.

i. Electricity deficit and unreliable electricity supply to support EV charging loads,

ii. EVs are generally twice more expensive than ICE vehicles and for Africa which predominantly imports used vehicles this presents a huge challenge in EV affordability.

However, in Africa it seems the two-wheel electric vehicles will lead the race to decarbonizing the transport sector. The two-wheel vehicles belong to the class of bikes and scooters, but they are commonly found in East Africa and West Africa and commonly referred to as “boda boda” and “okada” respectively. These modes of mobility are mainly used as taxis to ferry people and cargo around cities. Electric two- wheelers use a small battery hence they can be easily charged using a micro or mini-grid and can also benefit from a battery swapping model as we have seen happening in Asia [18]. Already in Kenya some start-up companies have started assembling and building electric motorcycles tailored to meet the standards of the boda boda drivers with an average distance of 130km on a fully charged battery as compared to the ICE motorcycle costs per day. Rwanda has also embarked on a project to build battery swapping stations to enable motorcycle/motorbike drivers to swap depleted batteries with fully charged one on a go without any delays to their businesses.

Zambia has no statistically documented number of electric vehicles. Recently the Zambia Electricity Supply Corporation (ZESCO) Limited conducted a promotional roadshow at the 2022 Agricultural and Commercial Show of Zambia (ACSZ) just to drive interest from the general public in electric vehicles[19]. The only electric vehicles available worth mentioning could be the trolly assist dump trucks that only operate in the copper mine sites and there have been a few registered Hybrid Electric Vehicles (HEVs) but owing to the nature of self-charging in HEVs, they are currently not documented [20]. The average travel distance of vehicles in Zambia particularly in the capital city Lusaka is between 20 to 40km for private four-wheel vehicles and over 100km for commercial vehicles such as taxis and minibuses per day, this trend is like most sub-Saharan African countries as shown in Figure 3 below [4]. However, in Zambia motorbikes are not very popular in big cities like Lusaka, but in rural areas in the countryside these two-wheel motorbikes have found a niche as a preferred mode of transport for health workers, care givers, agricultural officers and indeed for the local people. Despite all these promising benefits the electric two-wheelers are still more expensive compared to the ICE one but could be cheaper in the long run due to the incurred costs of fuel and maintenance of ICEs within about a period of 5 years to reach a break-even point. Even though the upfront costs are high, the electric two-wheelers seem to supersede the four-wheel electric vehicles in adoption in sub–Saharan Africa. Figure 3 shows the probability and likelihood of electric vehicle adoption in sub-Saharan Africa.

Other sectors such as privately owned four-wheel vehicles and minibuses will also transition though at a rather slower rate because of the current trend in purchasing used cars. The status at the time of this study and perhaps even in the near future such as by 2030s, may still be rare to find large quantities of used four-wheel electric vehicles which could be cheaper than new ones for shipment to Africa. However, private and government institutions who usually buy new ICE could be the first ones to transition to EVs if certain incentives and charging facilities are made available because EVs have lower operating costs and hence convenient for doing business. One major concern about EVs is the lifespan of the batteries, traditionally used ICE vehicles tend to exceed 300,000km in Africa but could the trends in battery storage technologies retain a lifespan longer than that if indeed sub-Saharan Africa will transition to used EVs.

Feasibility of electric-vehicle adoption in sub-Saharan Africa High Medium Low

	Two-wheelers	Passenger cars (for personal use)	Passenger cars (for commercial use - taxis)	Light commercial vehicles	Minibuses
Primary use (commercial or personal)	*90% of all two-wheelers are for commercial use, traveling 90–130 km per day*	*Personal use, traveling 20–40 km per day*	*Commercial use (taxis), traveling up to 100 km per day*	*Commercial use, traveling over 100 km per day*	*Commercial use, traveling over 100 km per day*
Charging infrastructure required	*Battery swap stations or Level 1 at-home charging*	*Level 1 at-home charging sufficient in most cases*	*For some drivers and routes (traveling less than 100 km per day), Level 1 or 2 charging is sufficient DC fast charging required for full coverage*		
Ability to charge	*Drivers have time to make battery swaps, charge at home, or publicly charge*	*Most owners have access to electricity at home and are able to charge overnight*	*Able to charge overnight; limited time to charge during the day, which is required for going longer daily distances*		
Up-front cost of EV[1]/ICE[2]	*Current models are 30% more expensive, but R&D expected to bring down cost*	*Approximately 20–30% more expensive for new vehicles Used EVs not yet available so unable to compete with used ICE vehicles on purchase price*			
TCO[3] EV/ICE	*More favorable for EVs, even in countries with high electricity costs*				
Buy used/new	*Mostly new*	*Mostly used (>80% of all sales)*		*New and used*	*Mostly used*
Overall assessment					

Figure 3: Feasibility of electric vehicle adoption in sub-Saharan Africa [4]

Nevertheless, given the economic status of sub-Saharan African countries, there must be deliberate steps made to electrify the transport sector if indeed Africa is to achieve some of the UN Sustainable Development Goals by 2030 [3]. There is need to scale out EV charging infrastructure, promote local production and supply chain systems in the EV sector and consider some tax incentives targeted at everything EVs.

2.2 Charging Hub Characteristics and EV Charging Systems

With the advancement in technology, electric vehicles can be charged through several technologies such as Conductive, Induction, Capacitive techniques and using Radio frequency and laser powering technologies [21]. However, in this research the charging technology under study was based on the Conductive type.

There are several considerations taken with regards to charging hub characteristics. One of the aspects is the speed at which the charger charges the EV batteries, refer to Table 1 below. Tentatively, the type of charger installed largely depends on the location of the charging hub, for instance at home, residential or even hotel premises would be equipped with a slow charger whereas a shopping complex or restaurant would be equipped with a fast charger and this research will mainly focus on such public places like a shopping complex which would require a fast charger and better[22], [23]. Apart from the stationary mobility charging hubs, there are also several designs but with similar concept of portable charging hubs [24]. Energy costs for charging is another aspect to consider, it for this reason that residential locations are preferred for slow charger to make use of night charging facilities as many energy suppliers offer the lowest EV charging tariffs in the night. However, this research was premised on offsetting the daytime high tariffs for EV charging by introducing PVs and ESS to support EV charging as the most cost-efficient way in climates that experience sufficient solar radiation such as sub-Saharan Africa.

EV charging patterns can be quite unpredictable due to the unpredictability of drivers and more so EVs will usually get charged only after covering certain miles or kilometres depending on the type of EV and the available battery state of charge (SOC). The driving range of some of the common brands of EVs on the market today are listed below [25], [26].

i. Tesla S model range from 450 – 650km

ii. VW ID.3 model ranges from 340 – 540km

iii. Audi e-Tron model ranges from 280 – 430km

iv. Renault Zoe model ranges from 250 – 390km

v. Nissan Leaf model ranges from 220 – 380km

vi. Honda e ranges up to 150 – 220km

vii. Smart EQ for two people ranges up to 100km

As can be seen, some EVs compete quiet favourably with petrol/diesel ICE vehicles and if one's daily commuting is less than 100km then probably any type of electric vehicle would be ideal. Though one common trend is that many EVs would normally be charged when the SOC is around 40%. Researchers in this field have used several different algorithms to predict the charging pattern of EVs, the population of EVs per charger per 24hour period and the battery SOCs at start and end of every charge of each EV. The University of Strathclyde Energy and Research Unit (ESRU) developed a new electric vehicle load profile modelling tool used to predict the load profile for a public parking space to be serviced by the interaction between the grid, PV and batteries to simulate an EV charging hub model[27]. Other simulation software's used included HOMER and Monte Carlo method to determine the likelihood and EV demand tool profile by ESRU [18], [28].

Most electric vehicles use batteries which require timely recharging except for FCEVs that would also require refilling but with hydrogen which is mainly produced through electrolysis [29]. EV battery charging and electrolysis puts serious strain on the grid system which is also struggling to decarbonize. In the United Kingdom (UK), the electricity grid mainly supports electrical loads exclusively however, by early 2050, it is projected that the entire thermal load would have been electrified by replacing boilers with heat pumps as a measure to attain the carbon net zero 2050 target [30]. This would mean shifting the entire thermal load which is at present time largely served using natural gas to the electricity grid. Besides that, there would be an additional load due to EV charging. Photovoltaic solar PVs have attracted significant attention in being implemented to charge EVs. Nevertheless, PVs are intermittent as they do not produce sufficient power on a cloudy day and during dark periods like in the night. In this regard, the use of energy storage systems (ESS) such as batteries can be used to act as a buffer between EV charging stations and the electricity grid. Another incentive is the provision of lower EV charging tariffs by the energy suppliers such as Octopus Energy who offer "Octopus Go" tariffs in the nights for EV charging at the lowest tariff [31].

There have been several research proposals made on the implementation of an off-grid PV and Energy Storage Systems for EV charging however, what is peculiar in most these cases just like this one is the approach and methodology used to offer a solution [32], [33], [34]. Using solar to charge electric vehicles is one of the sure pathways to enhance renewable energy penetration in decarbonizing the transport sector [35]. This section focused on a standalone solar PV plus Energy Storage System Charging Station (CS). The configuration of a stand-alone or off-grid PV EV CS usually consisted of a standard or Maximum Power Point Trucking (MPPT) solar PV mounted either on a rooftop or car park shelter which is connected to a boost converter to the DC bus[36]. The function of the boost converter is to be matching the PV power output with the DC bus and provide control to utilizing the MPPT system of the PV panels. The Battery ESS is connected to the DC bus via a bi-directional DC/DC converter to provide continuous steady supply of power as the PVs power output usually fluctuates. The two quadrant DC/DC converter controls the charge and discharge processes of the lead-acid ESS batteries. This converter regulates the bus voltage due to the EV charging activities. Another DC/DC converter is connected to the DC bus for charging EVs lithium-ion batteries onboard the vehicles. Figure 4 below shows the equipment configuration for a micro-grid PV ESS EV CS.

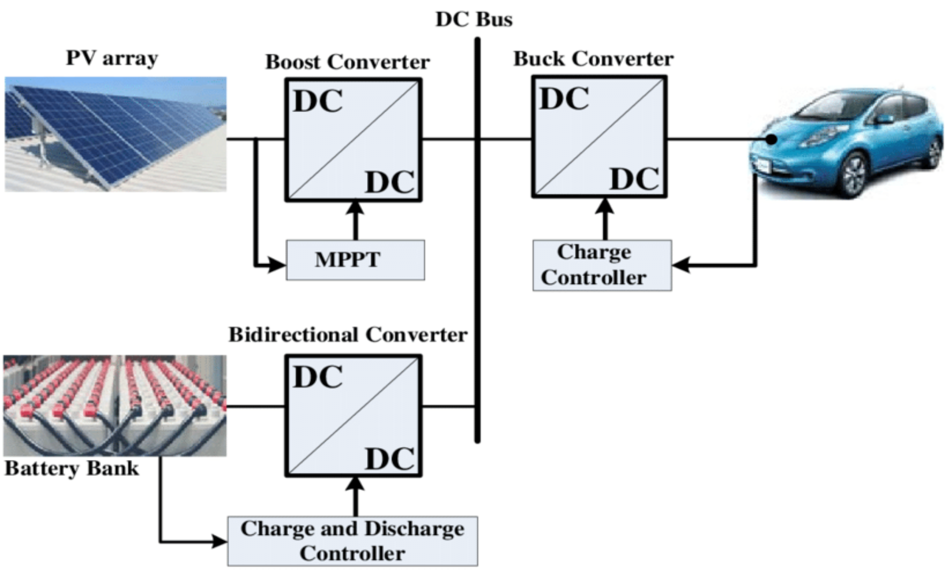


Figure 4: Off-grid PV and ESS EV charging station architecture [37]

Grid supported EV charging system is the conventional way of charging EVs and this would usually support all the 4 modes of EV charging depending on the cable used and type of charger installed at a particular station [32]. Figure 5 below shows the component configuration of a generic grid connected mobility charging hub. The charger modules are either single phase AC, three phase or the ultra-rapid DC charger as captioned in Table 1 above. Most of the current EV charging stations are exclusively connected to the grid. This type of configuration has however been realized to introduce some issues on the electricity grid hence the extension of solar PV and battery storage has been made to leverage the impact of EV charging on the grid [38].

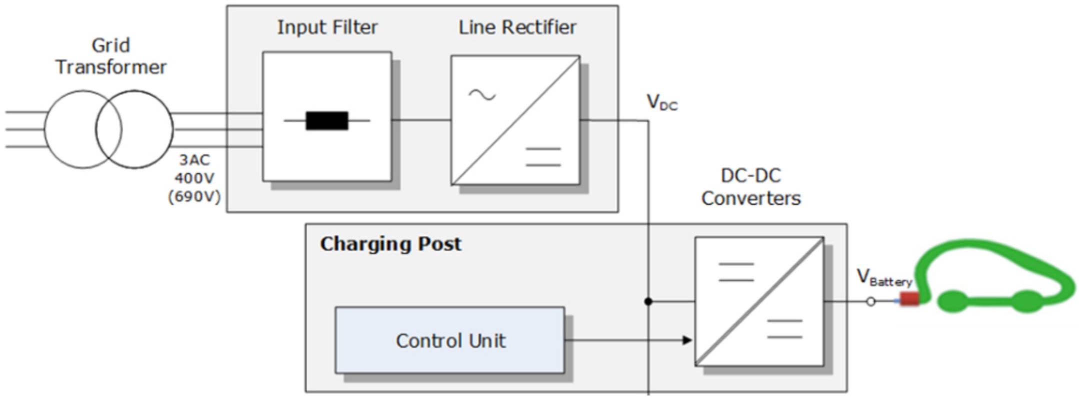


Figure 5: Grid supported EV charging station schematic [39]

2.3 Classification of Electric Mobility Vehicles

With the current plight to halt climate change, all forms of transport mobility are earmarked for-invention to stop the combustion of fossil fuels for mobility and shift to deploy environmentally friendly electric vehicles by the year 2050. Electric vehicles are mainly classified into four categories based on the source of energy to run the motors. These are Battery Electric Vehicles (BEV) which includes the Light Electric Vehicles (LEV), Plug-in Hybrid Electric Vehicles (PHEV), Hybrid Electric Vehicles (HEV) and Fuel Cell Electric Vehicles (FCEV) [6], [29], [40], [41]. Figure 6 below displays the common available types of mobility vehicles in use around the world.

The electric car mainly depicts the battery electric car and the plug-plug-in hybrid electric car as these both require external recharging at a charging hub. Hydrogen fuel cell electric vehicles are far more pronounced in electric buses due to the longer travel distance and quicker refilling times they offer. There also exists various forms of two-wheel electric mobilities and the display below mainly depicts the most common ones which is the electric motor bike. Another light electric vehicle perhaps not mentioned so far is the one-wheel mobility vehicles which are popular among the younger generations and are mostly used for fun.

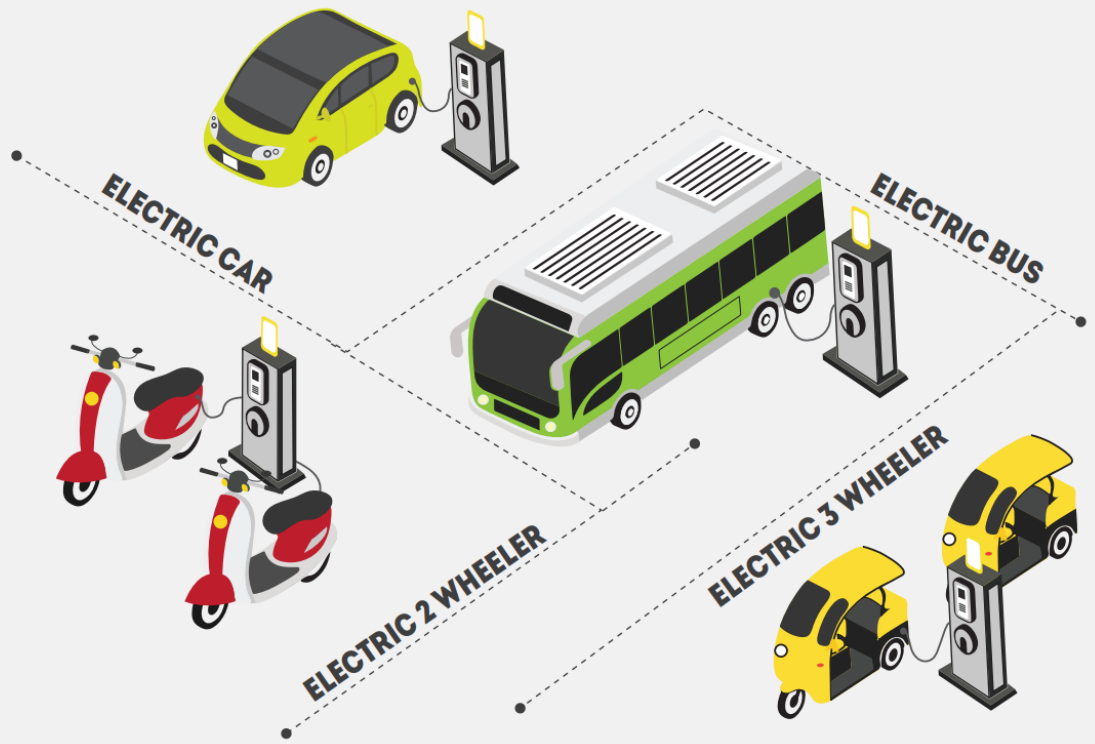


Figure 6: Common types of electric mobility vehicles[42], [43]

2.3.1 Battery Electric Vehicles (BEV)

Battery Electric Vehicles are naturally quieter to drive as they do not have a petrol or diesel internal combustion engine (ICE)[6], [44]. BEVs are either two-wheel or three or the most popular one four-wheel vehicles. They are powered using an onboard floor laid rechargeable battery used to run the motors to provide propulsion. Some BEVs have two motors while others only have one motor installed depending on the model and manufacturer[6], [44]. BEVs are usually unsophisticated to drive as they come with an automatic gearbox and regenerative braking system which allows the vehicle to recharge the batteries when applying brakes. An ordinary BEV can drive on a fully charged battery from about 100km to 600km[29]. The major advantage of BEVs is that they are environmentally friendly provided the energy used to recharge the batteries is clean then they can be classified to be 100% using renewable energy.

2.3.2 Light Electric Vehicles (LEV)

Electric vehicles are usually thought of just as the conventional four-wheel cars and yet the light electric vehicles are the largest electric fleet in the world, the population of LEVs in 2018 was at about 260 million as compared to the conventional electric cars which stood at 5.1 million globally. Recently these figures have shoot up with China alone recording over 300 million two-wheel electric mobility units on its roads [45]. Generally, the Light Electric Vehicles include the two-wheel, three wheel and any small vehicles with less than four wheels. The electric scooter, electric bikes, electric auto rickshaws all belong to this class of LEVs [6], [46]. Currently China is leading in the adoption of electric vehicles followed by Europe then the united States of America [46]. Among all the different types of LEVs, the two-wheel LEVs accounts for the largest population followed by the three-wheel electric vehicles and earlier stated, these are mostly popular in Asian countries. And because Africa imports most its vehicle from Asia, the LEVs are slowly also making it to the African countries especially in East and West sub-Saharan Africa.

2.3.3 Plug-in Hybrid Electric Vehicles (PHEV)

Another type of EV is the Plug-in Hybrid Electric Vehicle which has a combination of a petrol or diesel combustion engine and a medium sized battery which work together at different times to provide propulsion to the vehicle for mobility [29], [6]. The battery just like the case is in BEVs is supposed to be plugged in and charged before use. However, due the smaller size of the battery PHEVs only electrically drives for a relatively shorter distance of between 15 – 80km and after that obviously the battery would have discharged then the vehicles retain to function just like the traditional petrol or diesel vehicles provided there is fuel in the engine [41]. The choice to own a PHEV is in most cases based on average distance one drives. Usually, people who drive shorter distances would prefer PHEVs as they are cheaper than BEVs and are considered a transition to a fully electric car.

2.3.4 Hybrid Electric Vehicles (HEV)

Hybrid Electric Vehicles have a combination of a battery and a petrol or diesel engine however, the batteries on an HEV are self-charging [29], [6]. The vehicles do not need to be plugged into a charging hub instead the batteries charge automatically as the vehicle is being propelled using a petrol or diesel engine, as the vehicle is cruising, the combustion engines power a generator which subsequently stores energy in the batteries for later usage. The vehicle drive range on batteries is usually from between 20 – 40km [41]. In this same category, there exists a Mild Hybrid Electric Vehicle (MHEV). The concept is the same as the HEV however, in this case the battery does not propel the vehicles instead only aids power during start-stops and cruise control functionalities.

2.3.5 Fuel Cell Electric Vehicles (FCEV)

The Fuel Cell Electric Vehicle also known as Zero Emission Vehicle are powered by pure hydrogen[29], [6]. FCEVs employ the use of fuel cell technology where energy stored in the form of hydrogen is converted to electricity to propel the vehicle. This whole process happens onboard of the vehicle as the vehicle just requires refuelling of hydrogen like the traditional petrol or diesel ICE refuelling system. The electricity produced from the fuel cell is then used to drive the vehicle electric motors for propulsion. The distance the vehicle can travel is determined by the size of the hydrogen onboard storage tank and this also is used to size the power of the vehicles by appropriately sizing the propulsion motors based on the fuel cell size. The by-product of an FCEV is usually the expulsion of heat and water vapour which comes out through the exhaust pipe after the hydrogen molecule has combined with Oxygen molecule from the atmosphere and end up producing water as per the equation below.

$$H_2 + O_2 = H_2O \qquad 1$$

However, hydrogen is mainly now being produced by a process using methane and steam. Though there is an increase in production technology processes to produce hydrogen through electrolysis by splitting the water molecule into hydrogen gas and oxygen gas.

2.4 Types and Standards of Electric Vehicle Chargers

2.4.1 Conventional Electric Vehicles Charging Mechanisms

According to the International Electrotechnical Commission (IEC) standards, EV charging technologies have been classified into four distinct categories as illustrated in Table 1 below [37]. Some studies have further gone to determine the average energy consumption of an electric vehicle to be around 0.2kWh/km and this has been used to give an idea of the vehicle energy efficiency [21]. It is evident that a fast charger would draw more current more so a direct current (DC) charger would require DC power to rapidly charge an EV.

Table 1: IEC 61851-1 EV Charger Standard Categories[40], [21], [22], [47]

Charging Mode	**Charging Type**	**Maximum Current**	**Maximum Power**	**Maximum Charging Time for 50kWh**	**Kilometres from a 15min Charge**
Mode 1	Slow	16A, AC, Single Phase	3.7kW	14h	5km
Mode 2	Fast	32A, AC, Single Phase	7.4kW	7h	9km
		32A, AC, Three Phase	22kW	2h	27km
Mode 3	Rapid	62A, AC, Three Phase	43kW	1h	54km
Mode 4	Ultra-Rapid	400A, DC	200kW	15min	250km

Mode 1 is an ordinary slow charging system installed at household level socket type outlet, mode 2 is a fast charger either household for single phase but with higher current or three phase socket outlets with an in-cable protection mainly installed in commercial locations[28], [40]. Modes 3 and 4 are commercial installations and these are classified as rapid chargers with mode 3 requiring a specific three phase 62A socket outlet whereas mode 4 requiring an external charger for DC power output to charge the EV.

To charge an electric vehicle, one would also need to use a specific type of connecting cable and socket to plug into the charging hub and plug into the electric vehicle. These have been standardized to meet a certain level in quality and to make the roll out of the technology easier. There are mainly two types of electric vehicle charging cables on the market today and these includes, the Untethered and the Tethered cables. The untethered cable is part of the package that comes with the purchase of an EV, this is a portable cable which is so flexible in terms of usage as they can be used to charge any EV and plugged into any compatible charging hub and EV. It generally accompanies the vehicle and can be used to plug in and out of a charging hub or socket in case of a domestic charging point. The Tethered cables are usually permanently fixed to the charging hub, and these are likely to be phased out soon as new EVs could come with different type of adaptors. There are mainly four types of electric vehicle charger plugs currently in use globally. Figure 7below shows the commonly available car plugs. There are two types of AC plugs type and type 2 and another set of two DC type of plugs namely the Charge de Move (CHAdeMO) and the Combined Charging System (CCS)[47].

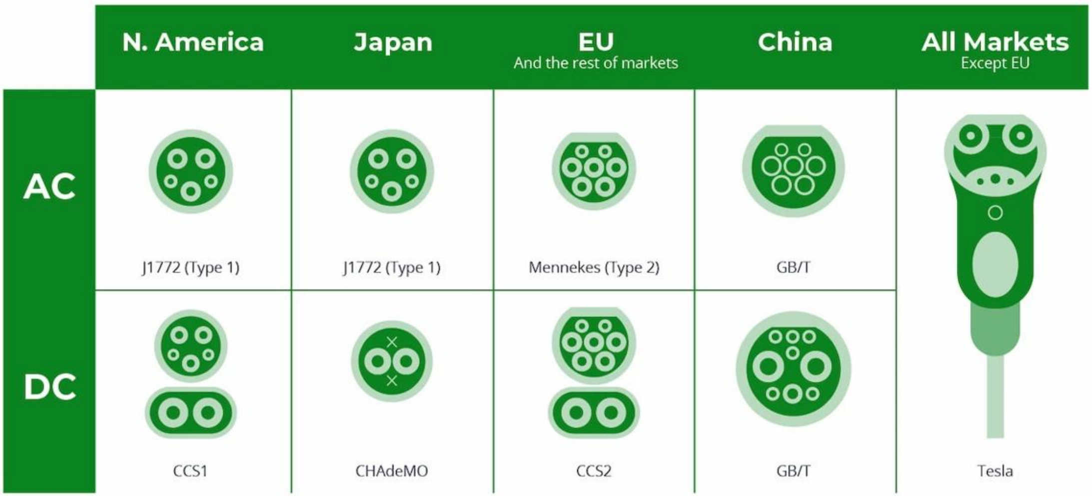


Figure 7: Electric Vehicle car plugs [48]

Type 1 or mode 1 plugs for EV charging cables are commonly found and used in Asian countries and North America. Most Asian and American car manufacturers conform to these standards of the AC type 1 plugs [48]. AC type 1 plugs the capability to charge an EV up to 7.4kW if charging an EV with such a capability of this rate. The other parts of the world which mainly consists of the rest of Europe and the United Kingdom, the standards in these places are slightly different hence it is extremely rare to find a type 1 AC charger in any of the public charging places [48].

On the other hand, the type 2 plugs seem to be the adopted standard in Europe and the United Kingdom by manufacturers such as BMW, VW, and Mercedes Benz. Type 2 is also compatible with almost all plug-in hybrid vehicles if they use the right cable for it. These are fast chargers of which at residential installations has a charge rate capability of 22kW and in some public places can even be installed for 43kW. This all depends on the grid capability and the vehicle charging power. Usually all Battery Electric Vehicles (BEV) are sold with a type 2 charging cable and socket and the plug-in hybrid vehicles usually also come with type 2 sockets so one just needs to find a location with a charger compatible with a type 2 socket.

The type 3 or model 3 electric vehicle charging plugs are often referred to as the Combined Charging System (CCS). These are used for rapid charging, and they are quite popular and most preferred to among EV users due to their faster rapid charging. They are also the most produced type by manufacturers in Europe and the

United Kingdom. The type 3 CCS connectors are capable to supply energy in the order of 25kWh up to 350kWh depending on the electric vehicle battery system design characteristics.

Mode 4 or type 4 plugs also referred to as the Charge de Move (CHAdeMO) are ultra – rapid usually installed in public places with DC charging connectors which have the capability to charge an electric vehicle above 80% under 40 minutes[40]. CHAdeMO plugs are compatible with most EVs available on the market today. Another advantage of CHAdeMO charger is their bidirectional power flow characteristics where apart from charging EVs, they can also transfer power from the EV to the electricity grid. This phenomenon is known as Vehicle to Grid (V2G). The advantage of being able to send back the EV battery stored energy to the grid if done in a controlled fashion would eventually help to shave the load or demand during peak periods.

2.4.2 Light Electric Vehicle Charging Mechanisms

The LEVs being in the same class as BEVs have similar charging mechanisms as shown in the sections above. There is always a source, which is an AC Charger usually supplied from the grid and a battery current regulator. The LEV chargers have AC/DC rectifiers which are designed to incorporate the power factor correction function and within the charger there is also another stage which is the DC/DC variable converter to produce a steady DC current output needed for charging. These chargers are quite small, they can be thought of being similar in size to laptop chargers, hence most of them are usually portable however, the bigger or heavier ones could be fixed to the charge point making them fixed to a charge point[49]. The chargers are also equipped with protection and communication circuitry at the sockets and this module is usually referred to as Electric Vehicle Service Equipment (EVSE) and it is through the EVSE that a charger is determined whether it is an AC or DC charger.

In the recent past there has been advancement in wireless electric vehicle charging but this has not yet been exploited conclusively especially in relation to charging LEVs and usually this technology does require the electric vehicle to have on board receiver coils to capture the wirelessly transferred energy signals[49]. LEVs just like all battery electric vehicles are charged via a conductive charging mechanism with a hardwired connecting cable between the EVSE and the LEV battery. The Batteries are either charger from inside the vehicle called plug-in charging or charged off the vehicle then put back into the LEV. However, it can be noted that unlike in conventional BEV where the heat, ventilation and air conditioning (HVAC) system is automatically switched on immediately the charger is connected to provide conditioned cooling to the battery system, LEVs do not have such facilities, and when for example using a fast charger, the faster the charging, the more heat is generated as this is a chemical process that produces heat as a by-product and hence, where there is no cooling this can result into sparks which can further lead to flames if left unattended to. This limits how fast an LEV can be charged when charging the battery on board. Nevertheless, considering the size of battery packs in LEVs which significantly smaller compared to electric vehicles, they can be removed and charged rapidly from an air-conditioned environment provided that the battery chemical composition does allow fast charging. Another interesting aspect of LEV battery pack is the ability to replace a discharged battery with a charged one and this phenomenon is referred to as battery swapping.

The charging mechanisms embedded in the EVSE is done at either constant current (CC), constant power (CP) or constant voltage (CV) and LEVs as earlier discussed especially in cases where the batteries are being charged while inside the vehicle is usually done at a slow pace using the constant current mode[49], [50]. The charging current is maintained at lower values usually between 10 to 30% of the LEV battery rated current and the charging is controlled in such a manner that it completely cuts off when the battery is fully charged to avoid overheating the batteries. A combination of constant current and constant voltage is usually implemented for LEV fast charging mode. In this mode the charging begins through the CC mode while monitoring the voltage levels and as the voltage difference reduces to a set point the EVSE switches to constant voltage mode.

Plug-in type of charging light electric vehicles is the most popular method. This involves a physical wired connection between the charger EVSE and the on-board LEV charger connection point and is in many cases of AC type. They are normally simple in design and compatible with residential and commercial power socket outlets and can either be fast charger or slow depending on the EVSE module being used with the slow charging taking between 4 to 10hours whereas the fast charging taking less than 2 hours to charge to full capacity. Lithium-ion batteries are usually faster to charge as compared to the Lead acid batteries, research has shown that Lead acid batteries take almost twice the time it would take if it were to charge a Lithium-ion battery. DC charging of LEVs is also possible however, this is mainly done off board and there is still research and development (R & D) under the IEC61851-3 standards going on in this regard among many manufacturers of light electric vehicles[49].

Battery swapping is another interesting and advantageous use of LEVs. Battery swapping basically involves removing the discharged battery or pack of batteries from the LEV and quickly replacing them with charged ones[22]. The removed discharged batteries are then charged individually or in case of a well-coordinated set up they are charged in a controlled environment where fast charging can even be achieved. The charging systems are the same as the methods described above. This has already been done in some Asian countries such as in India and Bangladesh where centralized LEV battery swapping facilities have been set up in various locations in the city for LEV users. Some of the advantages of battery swapping apart from saving on charging time are that they also allow for proper monitoring and maintenance of the batteries. Other possibilities are the potential within centralized battery swapping facility to act grid energy storage facilities though direction is still under several research to determine the feasibility of such an arrangement. Despite the numerous advantages of battery swapping there lies some hurdles as well. The cost of battery swapping, this lies in stocking several batteries as spares to be charged in readiness for swapping. Another drawback is the battery weight, manual swapping of batteries is only possible if the battery can be easily lifted by a single person. The higher the battery energy the heavier is the battery, take for instance the Lithium-ion batteries currently used in most LEVs contain between 120 and 250Wh/kg of specific energy. However, three-wheel vehicle batteries use batteries with higher capacity than the two wheel hence they weigh even much more and cannot be swapped manually except using hydraulic mechanisms which may complicate the battery swapping process.

2.5 Electric Vehicle Battery Energy Storage Technologies

Battery energy storage (BES) has replaced petrol and diesel in internal combustion engine vehicles and various forms of mobility including enhancement in bicycles as electric vehicles are now essentially powered by batteries for propulsion through the motors as already demonstrated in the earlier sections. However, despite making vehicles carbon free, batteries are composed of toxic waste of which if not properly disposed of or recycled at the end of their battery lifespan may pollute the environment[44]. There are several material compositions in battery energy storages which determines the types of batteries and their subsequent properties and characteristics thus influencing their applicable usage. To concisely discuss this subject, the electric vehicle battery energy storage was taken as subject of discussion and of course bearing in mind that the battery type that worked well for the electric vehicle would also work well for any other mobility vehicle too. This did not take into contrast the different types of energy storage for use on electric vehicles such as hydrogen fuel cells. The main topic of this study was focused on batteries as the sole source of energy and storage facility for the charging hub as well as the widely adopted method to power private electric vehicles.

2.5.1 Types of Batteries Used in Electric Vehicles

It is a no brainer that Lithium-ion batteries are the most common used type of batteries in most electric vehicles. However, there have been a lot of evolution in the battery energy storage leading to today’s wide use of Lithium-ion batteries. From the time Gaston Planté, a French Physicist who first invented a rechargeable lead-acid battery in 1859, many researchers have made several contributions in this sector to try to maximize the amount of energy that can be stored in a battery, cut down on the weight and production cost, devise ways to prolong battery life and subsequently recycle the batteries in a sustainable way.

Lead Acid Batteries

Lead acid batteries also referred to as Pb-acid batteries are the first generation of batteries which were mostly used in conventional ICE automobiles to run the starter motors and provided power to the vehicle electrical and electronic system such as lights, stereo system, wipers, etc[44]. The lead acid batteries were cheaper as compared to the recent type of batteries but had other engineering disadvantages such as low specific energy capacity, shorter life span, poor performance in cold weather and were generally bulky for use in EVs[5]. Even though advanced lead-acid batteries continue to be manufactured, these have mainly found use to power the auxiliary loads of electric vehicles and not the mobility part of EVs [51].

Nickel – Cadmium Batteries

Nickel – Cadmium (NiCd) batteries were used in electric vehicles in the early 1990s but were again phased out due to some technical glitches. The main advantages of nickel – cadmium batteries were their long lifespans which ranged between 1000 to 1500 cycles[44]. They are also known to have a high energy density content. However, the major drawback for nickel – cadmium batteries are the toxic nature of cadmium which had led to some countries like the European Union to prohibiting the use of NiCd batteries in electric vehicles as cadmium found to have detrimental environmental effects on humans, animals and generally the environment.

Nickel – Metal Hydride Batteries

The nickel – metal hydride batteries (Ni-MH) were much more successful as compared to the nickel – cadmium batteries mainly owing to the absence of the non-environmentally friendly metal cadmium in its accumulators [5]. In terms of production process, these were much like the NiCd batteries and had an advantage of not losing the memory effect when subjected to partial "charge - drain" cycles. The nickel – cadmium batteries were so designed that they had a high self-coefficient of discharge but unfortunately one of the drawbacks of these batteries was the low energy storage capabilities when compared to the latest battery technologies such as the Lithium-ion batteries. However, these batteries preceded the Nickel – Cadmium batteries in the usage in electric vehicles especially around the early 2000s.

Lithium – ion Batteries

The Lithium -ion batteries have evolved over time to become the most preferred batteries for application in modern electric vehicles. Tesla for instance, which is the largest manufacturer of electric vehicles has unreservedly adopted Lithium – ion batteries in their electric vehicle fleet. Some of the advantages of Lithium – ion batteries are their high energy density which gives them the ability to store large amounts of energy and they also offer a fair density to weight ratio as compared to other above-mentioned batteries[44]. Just like other competing battery technologies, Lithium -ion batteries also have some drawbacks which include overheating, limited life cycles and they are also very expensive to manufacture thereby further increasing the cost of electric vehicles where they have been used[5].

Solid – State Batteries

This type of batteries is currently at incubation level and undergoing laboratory research trials. The concept of solid – state batteries entail replacement of the battery electrolyte with a polymer like solid state substance. The main purpose is to try to further increase the amount of energy density beyond what is currently attainable in conventional electrolytic batteries such as in Lithium – ion batteries and the like. The technology also intends to control the temperature changes within the accumulator as the batteries undergo charging. Nevertheless, Lithium – ion batteries are still in use and most likely to be maintained as they currently offer the best option for use in electric vehicles for now and most likely even in the near future.

2.6 Overview of Electricity Infrastructure to Support Mobility

2.6.1 Status of the Zambia National Electricity Grid

The Zambia electricity sector is operated and owned by Zambia Electricity Supply Corporation (ZESCO) Limited which is a vertically integrated parastatal company. Zambia has total power generation capacity of 3,342.80MW with 88% being coming from renewable energy resources which constitutes mainly hydropower generation and a smaller quantity coming from solar photovoltaic farms. The remaining 12% is non-renewable energy sources which includes coal thermal plants and a Heavy Fuel Oil (HFO) thermal power plant. The Heavy Fuel Oil (HFO) is a bi-product of distillation and cracking process of crude oil which is produced by the Indeni Petroleum Oil refinery in Zambia and is combusted to produce steam to run the steam turbine just like in any conventional thermal power plant [52].

Zambia's largest industries are the copper mining industries, and these consequently are the largest consumers of more than 50% of the total power generated in the country [53]. Figure 8 below shows the exact distribution of the type of sources of power generation and their contribution to the national electricity grid as of the first quarter of the year 2022. It is imperative to also mention that all these stations are synchronized to the national grid. There are however, less than four pico-grids which are not synchronized to the national grid and are basically owned by private sector.

More than 60% of the total power generated is consumed by the mining companies and other medium to heavy industries leaving only 40% for the domestic and commercial consumption. With the introduction of EVs, this will imply that it will have to be accommodated in the 40% domestic supplies or 60% for commercial and industrial customers depending on the scale of the mobility charging hubs intended to be connected to the national grid.

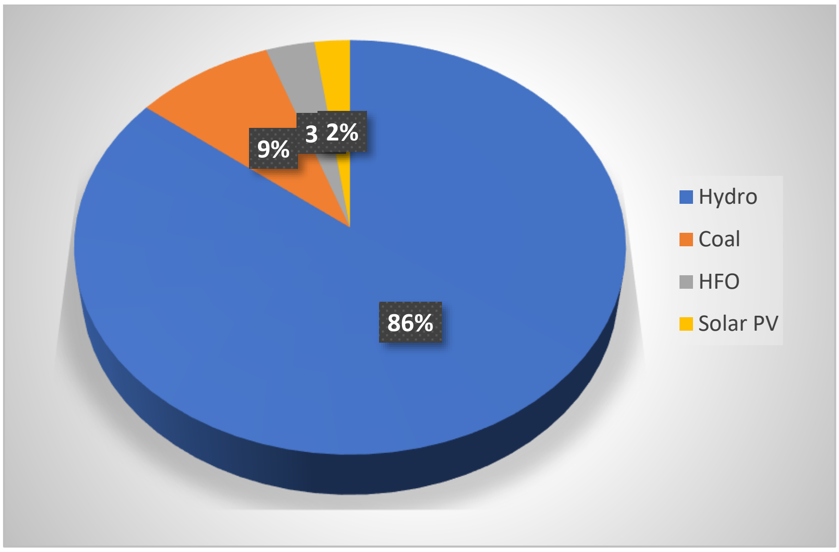


Figure 8: Zambia Installed Power Generation Capacity as of first quarter 2022 [53]

This scenario has the potential to strip the generation reserve capacity of the ZESCO Limited. As seen from many countries that have already rolled out electric vehicle public and private mobility charging hubs, they are usually connected at the distribution side of any power system and where to connect charging hubs in a network may pose power quality issues to the network especially if connected towards or at the end of radial feeders. In Zambia the distribution network is largely radial, though recently particularly in the capital city Lusaka, ZESCO Limited have been upgrading the Lusaka distribution network with new substations, and reinforcements of old substation under the Lusaka Transmission and Distribution Rehabilitation Project (LTDRP) to strengthen the network and mesh it up to provide sustainable reinforcements and improve on power quality and availability.

2.6.2 Impact of Electric Vehicle Charging on Distribution Network

Mobility charging hubs have a potential to present both negative and positive impacts on the distribution grid network. It must be mentioned that not long ago Zambia experienced long hours of loadshedding due to insufficient power generation between 2014 to around 2016 caused by severe droughts [54]. The nature of EVs is that they draw real power to charge the batteries and this scenario when it occurs beyond a certain threshold tends to present disturbances on the distribution network such as frequency deviations and voltage fluctuations[55]. If these disturbances are not well managed can cause system overload, destruction of electrical equipment's due to high voltages and the like [56]. Due to the non-linearity of DC loads, they tend to produce higher order odd harmonics such as the 3rd and 5th harmonics which distorts the power quality on the grid side, this could lead to increase in residual currents and voltages if not curtailed consequently compromising the protection system of the power system.

Researchers have also argued on the possibility of using the energy stored in electric vehicle batteries to inject this into the grid during energy deficit periods such as peak times. This phenomenon is referred to as Vehicle to Grid (V2G) [56], [57]. This has the potential to increase the utilities energy reserves and also lower the EV charging cost to the owners as they would be able to sell back some energy to the distribution network operator and in some instances even at a higher rate as it would be during peak times depending on the tariffs structure [58].

Electric vehicles draw real power, which is directly proportional to frequency, and frequency is the balancing measure between power supply and demand for real time utilization of electricity[55]. When EVs are connected to the grid for charging the frequency could drop if the cumulative chargers exceed a certain limit in a particular distribution network area [58]. Generally the rule of thumb is that if an additional load equivalent to the biggest generator in that power system grid is added or removed from the network, there tends to be a minimal frequency deviation for some milliseconds to seconds before the primary frequency control stabilizes that disturbance at the power stations by increasing real power output from the synchronized generators and if not sufficient import real power through dedicated interconnected tie-lines and if that fails the system controllers would have to synchronize another generator to stabilize the frequency. However, all this process should happen within seconds otherwise this situation would result in a major system disturbance and in weak systems like most of the grids in Sub-Saharan Africa, this would result in a total system blackout. In Zambia the biggest generator is 180MW, so in an unlikely case where the cumulative load of EVs were to be connected or disconnected from the grid, the above-described scenario would take place to stabilize the grid frequency. However, this is an extremely rare situation due to the low and slow penetration of EVs including in high-income countries like the UK let alone in Zambia where there is no EV charging facility at the time of this study.

Over and under Voltage fluctuations are another potential parameter that could be impacted by the introduction of EVs on any grid especially on radial distribution networks [58]. Research has shown that when EVs are charged from the radial end of the distribution networks they tend to cause voltage dips on the distribution network near to the affected location as voltage is mainly a localized problem and considering the huge amount of electricity EVs consume in a short space of time, the localities within which cumulative EVs would hook up to charge would experience voltage dips [38]. This would result in iron losses in the transformers due to increased loading on the local transformers.

2.6.3 Solar Energy Potential in Zambia

Zambia has a fair share of solar radiation owing to its geographical location being at a latitude of 13° 08' 25.26" S and a longitude of 27° 50' 57.50" E below the equator in the southern and eastern hemispheres. This geographical location can play a pivotal role in the introduction of mobility charging hubs that can be powered by solar photovoltaic energy system. Several research have been carried depicting potential sites for mass production of power using solar farms, this suggests that Zambia is on a renewable energy trajectory in the energy production mix to support the national grid [59], [60], [61], [62]. One of the obvious advantages of using PVs for electric vehicle public charging hubs was that this would avoid increasing the load on the national grid and where operated as a synchronized system would support the grid the hub would support the grid in cases of loss of generation from the power stations or transmission line faults [63]. The whole essence of propagating several cost and engineering efficient ways to introduce electric vehicle is aimed at reducing the national footprint of greenhouse emissions and in this case from the transport sector.

Zambia enjoys abundant solar radiation throughout the year with an annual average of about 2,000 to 3,000 hours of sunshine annually [8], [64]. According to the World Bank report conducted by Solargis in April 2019, the annual average solar direct normal irradiance (DNI) and the Global Horizontal Irradiance (GHI) recorded at various meteorological sites around the country was as shown in Table 2 below[8].

Table 2: Zambia annual recorded DNI and GHI [8]

Meteorological Station	Annual DNI [kWh/m2]	Annual GHI [kWh/m2]
Lusaka UNZA	1870	2005
Mount Makulu	1849	1984
Mochipapa	1954	2019
Longe	1978	2069
Misamfu	1734	2024
Mutanda	1746	1991

The world bank funded study produced a map of the total solar PV potential of power production for sub-Saharan African countries which included Zambia [8]. Figure 9below shows the Maps of Africa and Zambia with the mapping of solar potential in kilowatt hour per square meter. This data was based on an average of data collected over the years from 1997 to 2018.

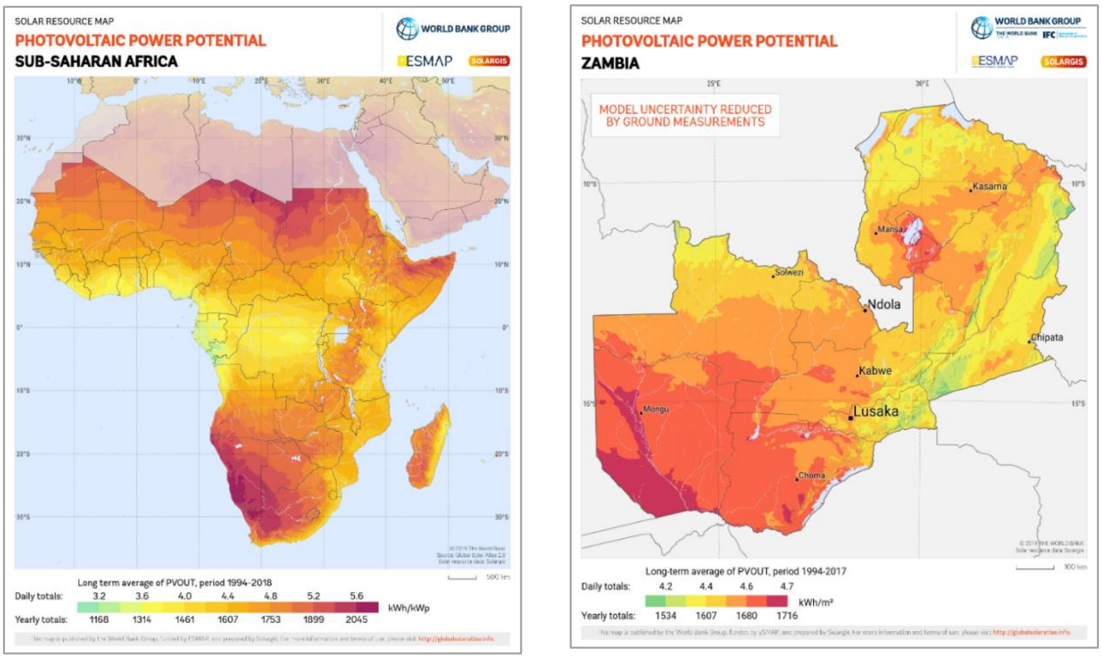


Figure 9: Photovoltaic Power Potential in Zambia sub Saharan Africa and particularly in Zambia too [8]

As can be seen there is generally an immense potential of solar PVs in Africa. In Zambia, it can be categorized to range from between 4.3kWh/m^2 to 5kWh/m^2 depending on which part of the country with the Western region yielding the highest solar energy potential.

2.7 Feasibility of Introduction of Electric Vehicles in Zambia

Zambia like many other sub - Saharan African countries purchases more of used or second-hand vehicles as compared to new vehicles mainly due to the issue of cost [5]. This trend is likely to continue and even increase as the high-income countries transition to fully electric cars soon[65], [15]. For instance, in the United Kingdom which is also among the exporters of used cars to Zambia, it is planned that by 2040 all vehicles would have transitioned to electric cars. This transition is likely to offload cheap petrol- and diesel-powered vehicles to Africa making the roll out of electric vehicles somewhat of a luxury venture. The transitioning to EVs if not managed holistically would simply shift the greenhouse gas emissions attributed to the transport sector from high-income countries to low-income countries who would take advantage to benefit from the sale of probably cheap and unwanted internal combustion engine vehicle in high-income countries.

With a projected decline in the manufacture of petrol and diesel vehicles, this will result in less and less ICE vehicles on the roads especially in high-income countries such as the United Kingdom. This scenario would consequently result in proliferation of electric vehicles on the global automotive market. Currently the cost of an electric vehicle is still perhaps twice more expensive as the ICE vehicle. In the UK the cheapest new electric car was slightly above £20,000 and a used electric car was also slightly above £5,000. It therefore implies that the cost of EVs is likely to stay relatively higher especially for low-income countries even after phasing out ICE vehicles. However, there is great hope in the cost of EVs going down owing to the cost reduction in batteries. There has been a significant reduction in the cost of electric vehicle batteries from $1000/kWh in 2016 to $128/kWh in 2022 and the cost is further expected to go down to even around $110/kWh in the coming years[66], [67]. This will in turn trickle down to many low-income countries like Zambia to able to still import used electric vehicles at a competitive price with comparison to the ICE vehicles. The main issue to further research on would be the adaptability of electric vehicles in the African environmental setup of not all good roads and relatively equatorial temperatures for the case of Zambia in determining the lifespan of a used and as well as new electric vehicles.

The EVs' most expensive component was the batteries, and it is the batteries that also determine the lifespan of an EV before any battery pack replacement if necessary is undertaken. Typical EV batteries would last up to 10 to 20 years and for the high-end Lithium-ion batteries such as those in Tesla EVs, the manufacturer claims that they can even last beyond 20 years thereby may not even be necessary to replace the battery at all. However, electric vehicle manufacturers do offer a 5 – 10 years warranty to their clients in case the vehicle batteries show some signs of performance distress against the expected set performance thresholds. The life span of an electric vehicle battery according to industry standard is determined or reached when the battery nominal capacity falls to below 80% because at this rating, the EV user will start noticing things such as a fall in range of the vehicle and other performance related aspects.

3.0 Model Design, Simulations and Analysis

3.1 Overview of Energy System Design

The analytical approach to this research involved making scalable deductions which could be used to roll out public EV charging facilities in Zambia. Computer modelling were extensively used in this study to carry out simulations and analysis to determine how much energy can be harnessed from a unity square meter of photovoltaic array in the study location and Lusaka was used as the site location for demonstration purposes to service one EV from this mobility charging hub. Further simulations were carried out to determine a design feasibility of a PV mobility charging hub as a stand-alone system, also as supported by battery energy storage system and alternatively with a grid connected charging hub.

Several software's were considered depending on the requirements of the project to select the most suitable and industry recommended software's to aid in carrying out the simulation of a mobility charging hub supported by solar PV, battery storage and the flexibility to incorporate the ZESCO electricity grid. The selection criteria mainly as mentioned above also included items such as user accessibility whether the software's were open source or required purchasing.

Helioscope was adopted as it has also been widely used in industry. Helioscope is a web based solar photovoltaic modelling tool which some striking features such as the capabilities to physically display the geographical location with its solar radiation data and all the features existing at any location in the world with the aid of tools such as google earth which has been incorporated into its application. This made it easier to visualise where to place the solar panels, use the location weather for the solar radiation and account or eliminate sites with significant shadings. Another aspect is the free one-month user accessibility which made it possible to familiarize and build hands on skill set working with the tool before making a financial commitment of purchasing the software license.

To be able to synchronize all the energy sources which included the solar PV, battery energy storage system and the grid and provide the electric vehicle load profile, Homer Pro was selected for this purpose. Homer Pro is one of the software packages which is offered by the Hybrid Optimization of Multiple Electric Renewables (HOMER). Homer Pro is a widely used software in both industry and academic to model micro grids starting from various projects such as islanded village renewable networks to grid connected microgrids. It incorporates most of the popular energy storage facilities and energy sources as well as perform financial analysis to assist with costing a microgrid project. Homer Pro like the case was with Helioscope also comes with a one month free for familiarization period before one finally purchases the license after exploring the software to satisfy themselves of its capabilities to perform what the user intended to use it for.

The electric vehicle load profiles were obtained through the simulation of the probabilistic EV load profiles using the Electric Vehicle demand profile tool developed by the University of Strathclyde Energy Research Unit (ESRU). The tool has so for been used in various EV study by the University and proven to be reliable. In this study, to generate the EV demand profile, all the 10 default electric vehicles in the tool were simulated to determine the annual energy demand and these 10 EVs were selected based on the most recent common types of EVs on the roads and as recorded from the various EV charging stations within the city of Glasgow as of end of year 2021.

3.2 Data Acquisition and Technical Analysis

3.2.1 PV Panel Model

The PV was first modelled in Helioscope to give a sense of the area of the PV panels required to produce a certain amount of energy and then translated this amount of energy as the rated PV output in Homer Pro. The initial idea was to model a $1m^2$ PV panel using the Zambian weather temperature, pressure and solar radiation as provided for in helioscope. However, it was not possible to model a $1m^2$ area of PV as the panel sizes used in the software were of minimum size of 2m x 1m. Another limitation was that the simulation could only run with a minimum of four solar panels. To solve this puzzle, the study was scaled up and instead modelled a 10m x 10m = $100m^2$ area as captioned in Figure 11 (b) below. The simulated $100m^2$ area of solar PV panels rated at 320W as per manufacturer specifications which cumulatively summated to 16kW produced 26.69MWh per year of PV energy with an annual loss of 11% as illustrated in Figure 11 (a) below.

The solar panels used in the helioscope simulation were the Trina solar panels and more details of the electrical description has been summarized in Table 3 below.

Table 3: Trina Solar photovoltaic panel electrical parameter description

DC Electrical Characteristics	Ratings
STC Power Rating	320W
PTC Power Rating	292W 1
STC Power per unit of area	15.3W/ft^2 (164.6W/m^2)
Peak Efficiency	16.46%
Power Tolerances	0%/+3%
Number of Cells	72
Nominal Voltage	not applicable
Imp	8.63A
Vmp	37.1V
Isc	9.15A
Voc	45.5V
NOCT	44°C
Temp. Coefficient of Isc	0.05%/K
Temp. Coefficient of Power	-0.41%/K
Temp. Coefficient of Voltage	-0.146V/K
Series Fuse Rating	15A
Maximum System Voltage	1000V

Figure 10 below shows the monthly PV energy production in the Zambian climate for an entire year based on the 100m^2 of solar PV panels. The solar panel arrays were set at 10° tilt as the Helioscope default tilt angle for carport racking landscape design and were assumably mounted facing north as the optimum orientation of photovoltaic arrays in the Southern hemisphere with an azimuth angle of 78.26143°. Refer to Figure 11 (b) for the solar panel and site arrangement display.

The Homer Pro photovoltaic power output *(P_{PV})* was calculated using the equation 2 shown below where; Y_{PV} in KW is the rated photovoltaic array panel power at standard test and conditions (STC), f_{PV} is the derating factor of the PV array, $\breve{G}_T$ in kW/m^2 is the time step solar radiation incident on the photovoltaic array, $\breve{G}_{T,\ STC}$ is actually 1kw/m^2 as the standard test conditions incident radiation, α_P representing the percentage temperature coefficient of power (%/°C), T_c being the existing cell temperature of the photovoltaic array in degrees Celsius and $T_{c,\ STC}$ is the photovoltaic array cell temperature at standard test conditions which is 25°C.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right] \qquad 2$$

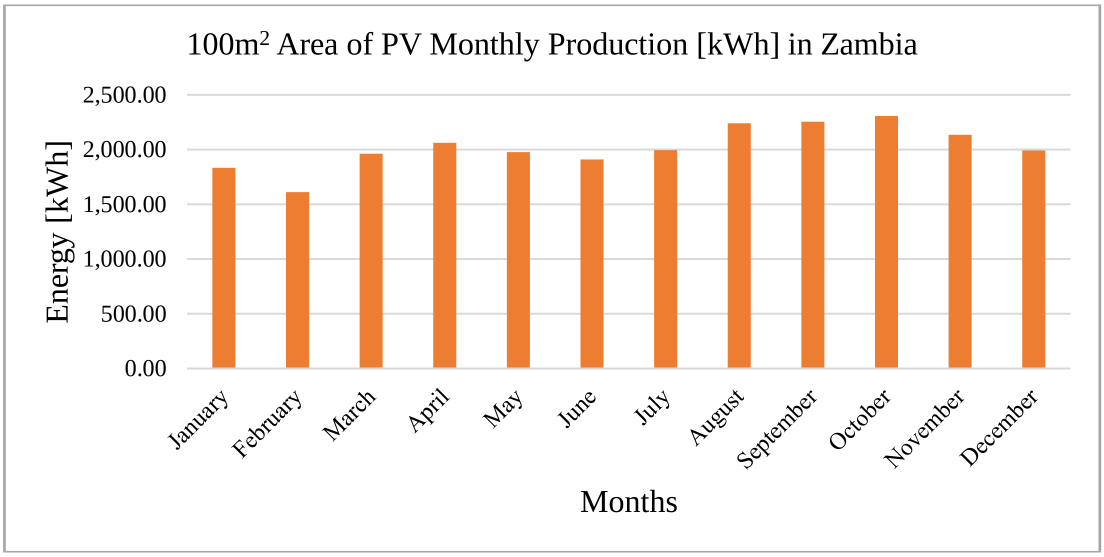
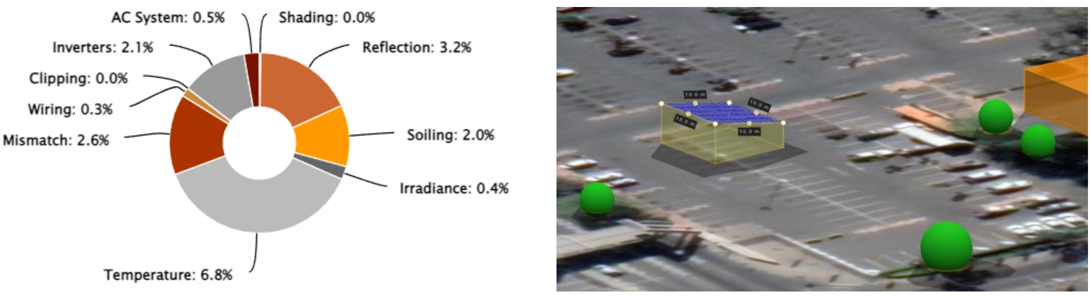


Figure 10: Helioscope simulated annual PV production from a 100m² area using Zambian weather (Source Author Analysis)



(a) *(b)*

Figure 11: (a) PV system losses and (b) Physical view of carpark solar PV array arrangement (Source Author Analysis)

The initial idea was to simulate for unity square are of solar PV panels, but since this was not attainable in the software, there was need to now scale down the 100m² to a 1m² solar PV area. Equation 3 below was used to illustrate the computations which were invoked in scaling down the PV system in Zambia for the mobility charging hub case study.

$$1sqrm\ PV = \frac{26690MWh/yr}{100m2} = 266.90kWh/yr \approx 267kWh/yr \qquad 3$$

Therefore, *Y*m² of PV = *Y* x 267kWh/yr, where *Y* is any given open area in Lusaka Zambia with no shading based on the conditions used in this study to model the photovoltaic array panels.

3.2.2 EV Demand Profile and Analysis

To simulate the characteristics of an electric vehicle charging hub, an EV demand charging tool which was developed by the Energy Systems Research University (ESRU) at the University of Strathclyde was used. The tool was calibrated based on the 2018 to 2021 collected electric vehicle data from the Transport Scotland database. This database mainly contained information such as the type of vehicle, battery capacity, the charger type, location, the start and end charge time of the EV, the date and charge capacity drawn by the EV and the cost incurred for charging. With this data, the EV demand tool was designed to able to calculate and produce results of charging demand in kilowatt hours at half hour intervals for 365days, the probability of a vehicle under study to charge on a particular day and the probable time of charging. It was also able to perform any queuing mechanisms in a case where the compatible charging hub point occupied and or assign a vehicle a compatible charge point.

Table 4 below shows the type and quantity of EVs that were considered for this study. A total of 100 EVs were simulated to determine the maximum annual energy demand required to charge the EVs. The quantities of each type of vehicle used in the study was based on a hypothesis of cost. The mini electric vehicle was allocated the highest number of EVs, and the rest were randomly selected.

Table 4: Simulation results summary (Source Author Analysis)

Item	Vehicle Type	Vehicle Class	Quantity	Battery Capacity (kWh)
1	Tesla Model 3	BEV	12	82
2	Kia e-Niro	BEV	10	64
3	VW ID.3	BEV	9	82
4	Nissan Leaf	BEV	9	62
5	Audi E-Tron	BEV	8	71
6	Hyundai Kona	BEV	9	64
7	MINI Electric	BEV	15	32.6
8	Renault Zoe	BEV	12	52
9	Vauxhall Corsa-e	BEV	9	50
10	MG ZS	BEV	7	44.5
	Total		100	

With the above electric vehicle distribution and the already inherent parameters in the EV Demand tool, the simulation results of the total annual energy demand recorded was given per hour calculation. To determine the actual one-hour interval measurements the energy formula shown in equation 4 below was devised and used for this purpose: With given 100 Electric Vehicles, the simulation results produced an equivalent electric vehicle annual energy demand of 7,304kWh/yr as total annual energy consumption to sustain public charging of the electric vehicles as selected from the EV demand simulation tool.

$$E = \sum_{i=1}^{n} Pi\ x\ C \ = \ [P1 + P2 + P3 + \cdots + Pn]\ x\ C \qquad 4$$

Where:
E = Annual energy (kWh/yr)
Pi = Total annual power (kW)
i = Number of days in a year
n = Upper limit of summation
C = hours = 0.5hrs

Therefore,

$$E = \sum_{i=1}^{n} Pi\ x\ C \ = 14608\ x\ 0.5 = 7304kWh/yr$$

Where:
P_i = 14608kW and
C = 0.5 hours

However, this study was based on the unity scale of simulations of PV 1m^2 production, and this was also matched with one EV. For the given energy for the 100 EVs, it was therefore necessary to scale this factor down to reflect a single vehicle. To obtain how much on average a single EV would use without simulating for a specific electric vehicle individually, it was found that one vehicle would require approximately 73.04kWh/yr from the mobility charging hub as shown in equation below:

$$1EV = \frac{7{,}304\text{kWh/yr}}{100\text{ EVs}} = 73.04kWh/yr$$

From section 3.2.1 the 1m^2 of PV array would approximately support EV charging up to a certain extent as shown in calculations below:

$$No.of\ EVs = \frac{1m2\ of\ PV}{EV\ Demand} = \frac{267\text{kWh/yr}}{73.04\text{kWh/yr}} = 3.65\ \approx 3$$

From the above computations, it ideally therefore meant that with controlled charging where EVs are restricted to charge at only specific times depending on the availability of solar radiation to produce energy from the PV arrays, Xm^2 of PV arrays was approximately equal to three times *(X)* electric vehicles implying that an Xm^2 of PV panels rated at 320W would be ideal to service (3 * *X)* electric vehicles. Conversely in an ideal situation where the load coincides with the PV production, 1 average EV would require about 0.33m^2 area of PV to fully be charging the EV according to the probabilistic predictive EV charging characteristics and demand profile tool used in this study. The three electric vehicles to be serviced by the 267kWh/yr charging hub was only possible if the charging times and queuing was controlled as there was zero charging energy during night times and low charging energy supply on cloudy days since the hub was solely powered by photovoltaic array panels. This was demonstrated during simulations as the 267kWh/yr PV supply would not meet the 3 EV annual demand due to varying charging times with the PV energy production times for the EV demand profile produced by the EV demand profile simulation tool. The charging times did not necessarily match with the production of PV energy as the vehicle would only charge depending on its state of charge (SOC) and or planned travel distance to be undertaken.

3.2.3 Mobility Charging Hub Modelling

The probability of an EV to charge cannot be empirically determined as an EV will only charge when it has run out of charge or ideally when its SOC is at a very low threshold and statistically many EV owners charge when their vehicles SOC is below 40%. However, solar PV power output is always available throughout the day light and dies off in the night and output is also reduced during cloudy periods of the day. Matching the EV charging time and solar PV availability is near to impossible and hence the requirement for an energy storage buffer system such as batteries or a grid connection to export the unused excess energy and consequently import from the grid when EV charging is required at times when there is no output from the PV terminals. Another alternative is to introduce controlled EV charging where EVs would only charge during the day when there is sufficient energy from PVs to avoid importing power from the grid during solar absence periods when an EV would turn up for charging. These could be some of the feasible pathways to introducing PV mobility charging hubs in Zambia and the sub-Saharan Africa at large.

To project this theory into perspective, a model was created in Homer Pro to simulate an EV charging hub in Zambia as shown in the graphical configurations in Figure 13 below. The annual energy output from the PV as earlier calculated above was set to

267kWh/yr, the grid imports/purchases was limited to the EV demand of not exceeding 73.04kWh/yr with unlimited export of energy from the mobility charging hub system to the grid. The battery energy storage system was left open ended for optimization by the software in trending the battery size per simulation in the various percentage contribution of the energy mix.

Load Profile Justification

To complete the setup, the mobility charging hub energy system required the load profile of which in this case involved an EV load profile with the above calculated average EV annual demand of 73.04kWh/yr. The Nissan Leaf load profile which gave the closest demand margin to the average of the 100 EVs under study of 72.9kWh/yr was imported into Homer Pro for simulation. Despite showing that the 267kWh/yr PV supply was sufficient to charge three EVs, this was not ideal in real life situation as the PV energy source was not there all the time and hence the only probable EV load profile sustainable and realistic for 267kWh/yr supply was one electric vehicle.

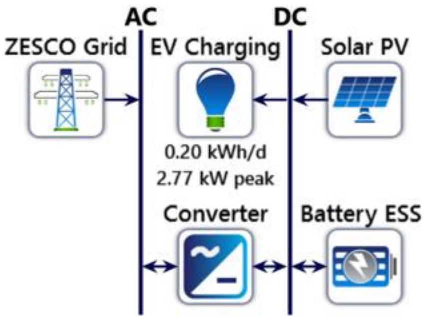


Figure 12: Mobility charging hub electrical components simulation configuration setup (Source: Author's Analysis Homer Pro)

The above shown electrical configuration setup made in the software was hence amplified in AutoCAD to show the single line schematic drawing for ease visualization and implementation as shown in Figure 13 below. The service panel gives an automatic flexibility of selecting the energy mix requirement depending on the available facilities. This design makes it possible to implement this project in several ways the implementers find feasible by using any of the following permutations listed below.

i. Islanded solar PV microgrid mobility charging hub,

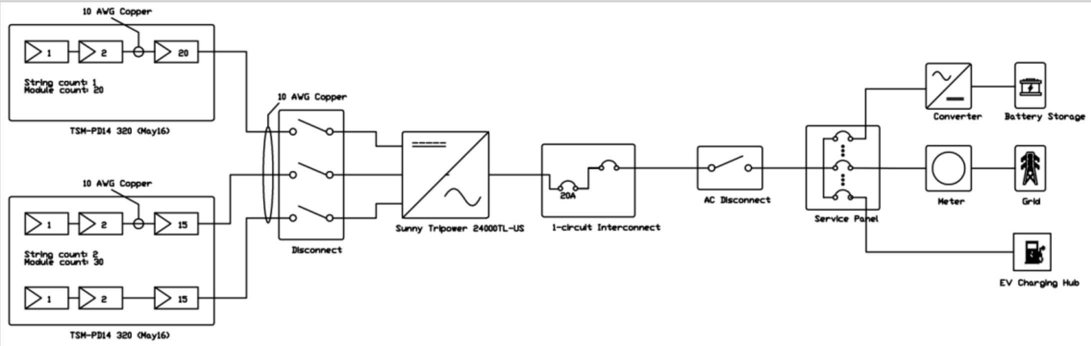
ii. Grid mobility supported charging hub,

iii. Islanded solar PV and battery storage microgrid mobility charging hub,

iv. Solar PV and grid supported mobility charging hub,

v. Solar PV, Battery storage and grid connected mobility charging hub.

However, for this study the focus is the PV mobility charging hub as could already have been noticed above that the annual PV output is fixed to a square meter of panels to support EV charging. The battery storage and grid connection alternatives are mainly on complimentary basis especially. These mainly come in play in a circumstance of uncontrolled EV charging.



Module Specifications	
50x Trina Solar TSM-PD14 320 (May16)	
STC Rating	320 W
Vmp	37.1 V
Imp	8.63 A
Voc	45.8 V
Isc	9.1 A

Inverter Specifications	
1x SMA Sunny Tripower 24000TL-US	
Max AC Power Rating	24.06 kW
Max Input Voltage	1,000 V

Wire Schedule		
Tier	Wire	Length
String	3x 10 AWG	48m

Figure 13: Electrical schematic drawing of the system architecture (Source: Author Analysis)

The simulations were done in two folds with the first concentrating solely on solar photovoltaic to charge the electric vehicle. The second scenario involved several simulations where all the three energy sources, the PVs, battery storage and the grid where optimized to size the battery requirement, determine the excess energy and energy export and import to and from the grid. The sections below detail the simulation procedures and results obtained.

Scenario 1

This was purely solar PV alone supplying power to meet the EV charging demand. As earlier shown in the above sections of 3.2.1 and 3.2.2, a $1m^2$ area was used as a sample space to produce energy from a solar PV which amounted to 267kWh/yr as further detailed in Appendix 7.1. The simulation's goal was to use this energy to meet the EV charging demand of 72.9kWh/yr as produced from the EV demand charging simulation tool. To determine the probability of a vehicle charging in a week, the tool would calculate the average characteristics of a vehicle to charge in a week based on the input data and then determine how often, the duration and what times the vehicle would charge per week. Figure 14 below shows a scatter plot for the number of times an EV visited the charging hub for recharging and as can be observed the EV only charged twice in that week of the month of January and only spent not more than 30 minutes charging on both days.

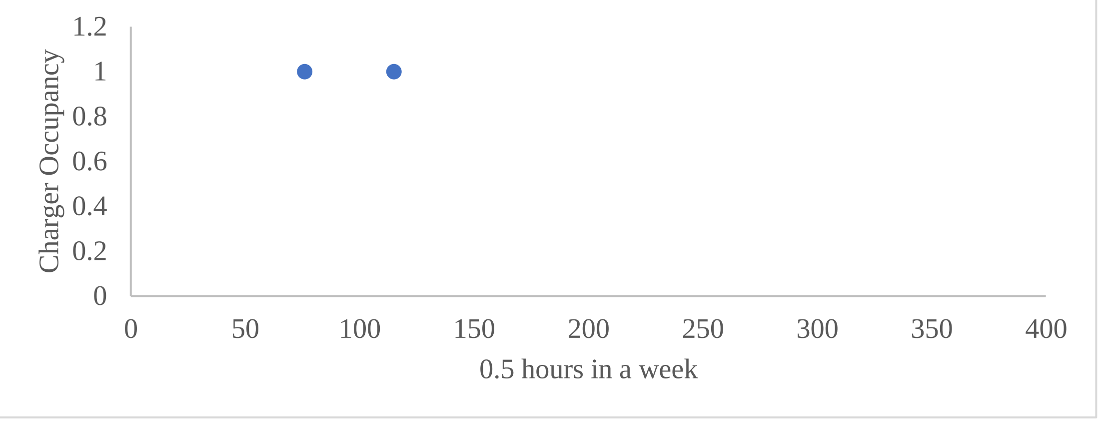


Figure 14: A 1 week EV charging hub activities (Source Author Analysis)

However, solar PV output is usually available all day throughout the year in Zambia as shown in

Figure 10 above. The amount of PV production of 73.04kWh/yr was sufficient to fully service the EV demand of 72.9kWh/yr whenever the EV required charging. But it must be noted that most of the times which in this case of just one EV about 190kWh/yr is excess energy from the PV was unused when the EV was not charging hence this extra energy could be used to charge light electrical vehicles such as motor bikes and scooters to mention but a few. A portion of it can also be used to provide local supply such as mobile phone charging facilities. This scenario is further observed looking at the over 12 months EV charging demand profile as shown in Figure 15 below.

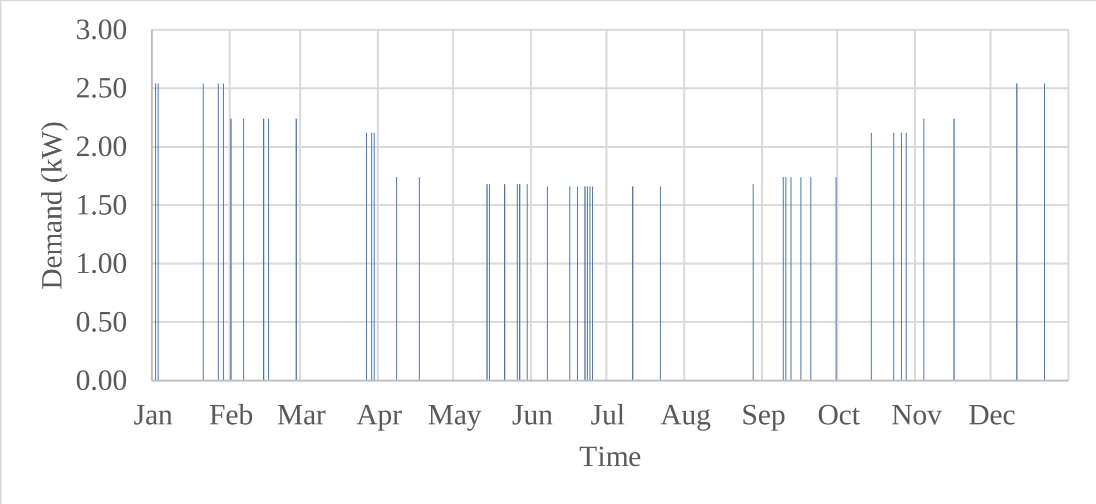


Figure 15: A one year Nissan Leaf battery electric vehicle charging demand profile (Source: Author's Analysis)

This scenario is a classic case where the EV is restricted to only charge during the day. If EV charging is required on a cloudy day or during night times, the hub would not be able to do so as the solar PV output is dependent of solar radiation and as such there maybe need to equip the hub with battery storage and or connect to the ZESCO electricity grid.

Scenario 2

With the EV demand set at 72.9kWh/yr for one vehicle and the solar PV output energy of 267kWh/yr, the grid and battery storage were introduced to play a role in the energy mix at the EV charging hub. Figure 16 below shows the results obtained from the simulations on the relationship between the grid energy imports and battery nominal capacity required to supplement the 267kWh/yr of PV energy production to charge a 72.9kWh/yr electric vehicle according to the probabilistic load profile produced during the EV demand profile simulation.

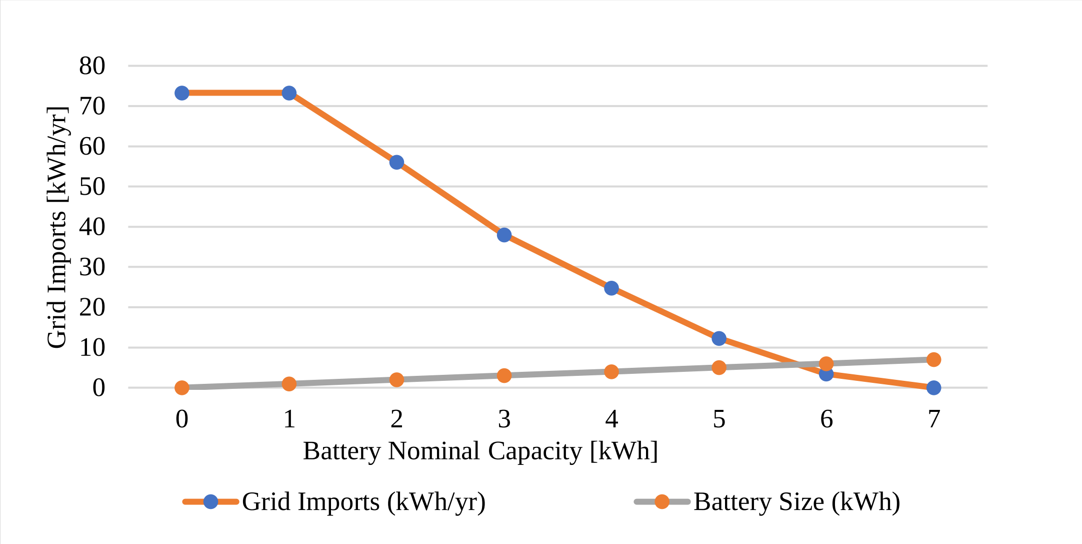


Figure 16: Graphs showing grid energy demand and nominal battery capacity necessary to supplement PV energy production to charge a unity electric vehicle in Zambian (Source Author Analysis)

The properties of the batteries used as energy storage in this study are as listed in Table 5 below. In this scenario, 8 simulations were carried until a break-even point between the grid energy supply and the battery storage capacity was attained. The overall entire system per simulation was incurring an approximate net loss of 16%. It was observed that when the charging hub was connected to the ZESCO electricity grid, the total import was almost equivalent to the EV energy demand with minor losses inclusive due to the converter and passive heat loss, at this stage, the EV charging hub would then function perfectly without any need of energy storage for excess energy or supply of deficit energy at periods of zero PV production. It was also observed that a 1kWh battery capacity could be introduced and the system would still perform in a similar fashion.

Table 5: Lithium-ion Battery Energy Storage Properties (Source: Authors' Analysis)

Properties	Ratings
Nominal Voltage	6V
Nominal Capacity	1kWh
Nominal Capacity	167Ah
Roundtrip Efficiency	90%
Maximum Charge Current	167Ah
Maximum Discharge Current	500A

Figure 16 above further demonstrates that as the battery nominal capacity was increased from 1 to 7kWh, the energy demand from the grid was seen to depreciate exponentially up to a break-even point where there was the least energy demand from the grid about 3kWh/yr with battery storage of slightly below 7kWh. After this crossover point the grid could be taken out and increased the battery capacity to 7kWh to supplement the PV during hours of poor to no power output. However, as the grid was introduced, it was also able to act as a buffer where excess energy from the hub was exported to the grid and when the grid was disconnected from the hub, there meant that the hub had excess energy to dispose of to any load. Figure 17 below shows how the excess energy comes about because of the mismatch of EV load with PV production and excess production from the PV.

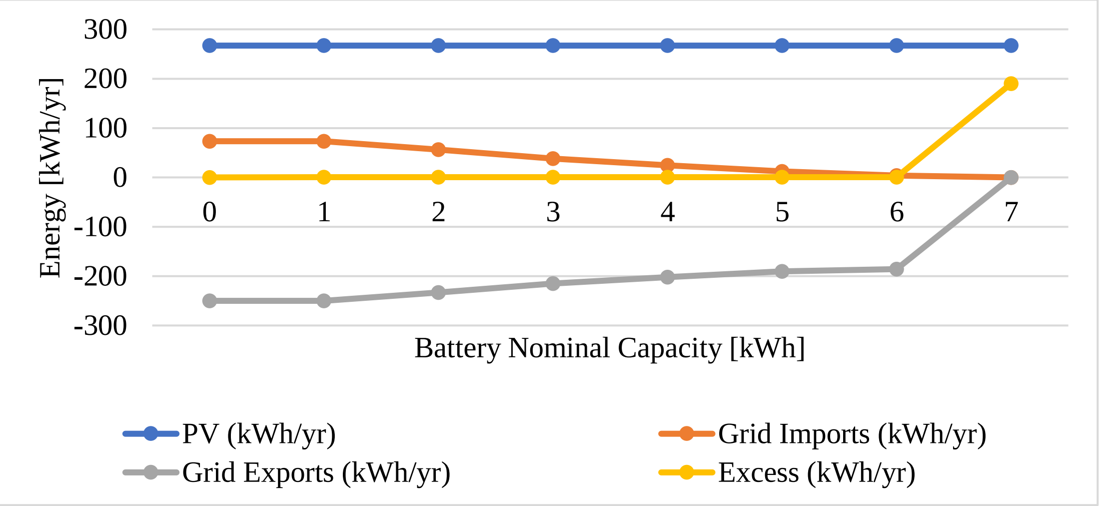


Figure 17: Graphs showing the annual energy trends from PV output, Grid imports and exports and excess energy to supplement the PV EV charging hub (Source: Authors' Analysis)

The PV energy output of 267kWh/yr and the EV annual demand of 72.9kWh/yr were fixed throughout the experiment in all the 7 scenarios. The brief description below further describes how and the interpretation of Figure 17 above.

Simulation 1

This case involved running the simulation with 267kWh/yr PV energy output synchronized to the ZESCO grid with a 72.90kWh/yr Nissan Leaf electric vehicle load profile. The simulation results output obtained showed a 73.3kWh/yr grid imports and a 250kWh/yr mobility charging hub solar PV export to the grid and satisfactorily met the EV demand with a 17% energy loss mainly due to converter losses. Refer to appendix 7.2 with the simulations raw data report.

Simulation 2

Scenario 2 was a build up to scenario one, in this case a new component was introduced in the form of a Lithium-ion battery energy storage to the mobility energy hub system. The ESS was made available, and the software algorithms had to optimize to determine the required battery size to fit in the current energy system. The results output gave a similar result as in scenario one with only one exception. The unique result in this case was the inclusion of a 1kWh battery energy storage as indicated in appendix 7.3.

Simulation 3

To trend the energy flow, the exports were reduced by about 7% resulting in a 233kWh/yr exports from 250kWh/yr recorded in scenario 2 and a subsequent decrease in grid imports from 73.3kWh/yr to 56kWh/yr. These adjustments saw an increase in battery nominal capacity from 1kWh to 2kWh. A full simulations results data was contained in appendix 7.4.

Simulation 4

This was another build up to scenario 3. A further 8% reduction in hub energy exports to the grid from 233kWh/yr to 215kWh/yr. This also produced a further reduction in grid imports from 56kWh/yr to 38kWh/yr and an additional battery nominal capacity of 1kWh bringing the cumulative total battery nominal capacity to 3kWh at this stage. Refer to appendix 7.5 for a detailed simulation results file.

Simulation 5

A further 5% reduction in grid exports was made as an input restrictive measure in Homer and the simulation results yielded yet another reduction in grid imports from 38kWh/yr to 25kWh/yr and a corresponding result in battery nominal capacity increasing from 3kWh to 4kWh. The grid exports were reduced from 215kWh/yr to 202kWh/yr to obtain the above results. An explicit simulation results was attached in appendix 7.6 below.

Simulation 6

This case also involved a further reduction in grid exports from 202kWh/yr as recorded in scenario 5 to 190kWh/yr. This simulation yielded a 12kWh/yr grid imports much lower than the figure recorded in scenario 5. There was also an increase in battery nominal capacity from 4kWh to 5kWh again with 17% energy loss just like in all the above scenarios so far mainly attributed to converter losses from AC bus to DC bus where the EV charging load was hooked onto as also shown in appendix 7.7 of the simulations results file.

Simulation 7

A further reduction in the mobility hub energy exports to the grid was made from about 190kWh/yr to 186kWh/yr. The solar PV just like in all the scenarios was still fixed at 267kWh/yr. This simulation yielded a further reduction in grid imports from 12kWh/yr to 3.5kWh/yr. It was in scenario 7 where for the first time in this experiment the battery nominal capacity was higher than the grid import. The battery capacity increased from 5kWh to 6kWh with a total energy loss of about 14% much less than in all the above simulations mainly due to the reduced amount of AC power being converted to DC power through the converter as the EV load was connected to the DC bus. Appendix 7.8 was also attached with the details of this simulation.

Simulation 8

Scenario 8 exploited the situation by completely decoupling the charging hub from the grid and then completely simulated the mobility hub purely on solar PV, and battery energy storage. This scenario simulation yielded a requirement of a 7kWh battery capacity together with a supply of 267kWh/yr of solar PV and much lower energy loss of 7kWh/yr mainly due to heat loss as the load was connected to the Dc bus hence there was no need for a converter in this scenario. However, this combination without grid connection but with a fixed solar PV energy supply produced excess energy amounting to 190kWh/yr. This excess energy could be delt with by supplying any other newly introduced loads to the charging hub such as electric bikes and the like. Another alternative would be to just switch off the solar PVs at certain periods when there is less or traffic at the charging hub. Refer to appendix 7.9 with this simulation full results file attached below.

To summarize the scenarios, it was observed that there was excess energy produced from the PV and hence, when the hub was synchronized to the ZESCO grid, this excess energy turned into export from the hub to the grid as seen by the grey line graph above. The way the charging hub operated in this study was in such a way that the hub would use the power generated by the PV to charge the EV only if the EV was charging during the day when there was reasonable output from the PV to meet the EV demand.

Corollary, if the EV reported to the hub to charge for instance in the night, the hub would import this charging energy from the grid as there would be no power generation from the solar PV. At the times that the hub had zero load which constituted most of the time as according to the probabilistic EV demand profile used, the PV power generated was exported to the grid and some of it was diverted to charge the battery storage in a situation where there is a battery storage as in scenarios 2 to 8. The battery similarly to the behaviour of the grid, the battery was able to meet the EV demand in times when the EV turned up for charging when there was no output from the solar PV. However, the batteries were limited to how much energy they can use to charge them and hence could not absorb all the excess energy from the solar PV due to its limited nominal capacity hence the rise to excess energy.

3.2 Environmental Impact Analysis

There are no motor vehicle manufacturing plants in Zambia, all the vehicles in Zambia are imported and majority of the motor vehicles are used cars imported from Japan. This perhaps has made it difficult to impose carbon dioxide emission cuts on vehicles in the country. However, in 2019 the government introduced the motor vehicle carbon surtax charge which is a recurring annual tax imposed on all motor vehicles and is varied depending on the engine displacement [68]. The idea was to use these resources to channel into areas that tackled to reduce biodiversity loss in a quest to counter reduce the greenhouse gas emissions [16].

Despite not having any measures to monitor CO2 emissions from vehicles, the government and motor vehicle owners rely on the motor vehicle manufacturer specifications. For instance, in Europe new cars are tested for compliance to the "Euro 6" emissions standards mainly against carbon monoxide (CO), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), particulate matter (PM) and Nitrogen oxide (NOx) emissions from car exhausts [69]. CO2 emissions is a responsibility tasked upon the car manufacturers. The main gases emitted from the combustion of hydrocarbons in internal combustion engine (ICE) vehicles are carbon dioxide (CO2) and methane (CH4) which is less harmful than CO2 but equally harmful about 25 times more harmful over a period exceeding 100 years [70].

Zambia has recorded a steady increase in the number of motor vehicles being imported into the country. This could be attributed to several factors such as increase in population and the increase in mining activities which has boosted the national gross domestic product (GDP). Figure 18 shows this trend over the last 10 years with the most recent update according to the Zambia Road Transport and Safety Agency (RTSA) being 853,909 motor vehicles by the end of 2020 [71].

Most of these motor vehicles are used vehicles especially those owned by private individuals and usually over 3 - 10 years old however, there are also a good number of new vehicles mostly owned by government departments and various private and public companies [71]. All these motor vehicles contribute to the national CO2 emissions footprint.

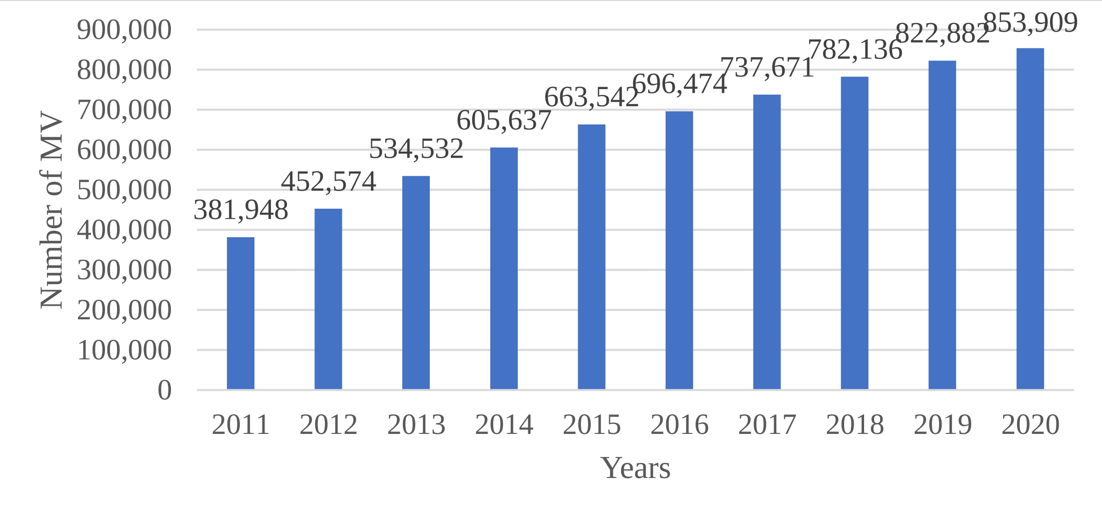


Figure 18: Cumulative number of ICE motor vehicles in Zambia [71]

According to the UK department of Transport, in 2014 the average carbon dioxide emissions from newly registered motor vehicles were measuring around 125g/km of CO2 [72]. Using this factor of 2014 and since most of the vehicles in Zambia were manufactured around this period it can be estimated that there is about 107tonnes/km of potential CO2 emissions emitted by all the vehicle should they all cover a kilometre each as shown in equation 5 calculations below.

$$CO2\ Emissions = Emissions\ per\ km \times No.of\ vehicles \qquad 5$$

$$CO2\ Emissions = \frac{125g}{km} \times\ 853{,}909 \approx 107tonnes/km$$

The introduction of electric vehicles would tend to leverage this 107tonnes/km of CO2 from motor vehicles and thus reduce the national carbon footprint. Nevertheless, as observed in sections above, the EV charging hub simulations did demonstrate various energy mix and one of them was the importation of power from the national grid. And currently the Zambian national grid is not 100% carbon free hence for there to be a sustainable decarbonization of various industries, the power sector would also require decarbonization of the power generation plants.

In Zambia the national grid is 88% decarbonized and the remaining 12% is power generated from coal thermal power plant and heavy Fuel Oil Power plant as illustrated in the pie chart in Figure 8 above. In this experiment the carbon dioxide factors considered per type of hydrocarbon fuel used were as shown in Table 6 below [73]. The total CO2 emission factor of 0.609 was used in the simulation and obtained 44.7kg/yr of CO2 emission when importing maximum power from the grid of about 73.3kWh/yr to support 1 EV charging for a year. Suffice to mention that the other sources of energy which includes solar PV and Battery Energy Storage systems were considered to emit zero CO2 emissions as they are environmentally friendly.

Table 6: Electricity source carbon dioxide scale factors and emissions results (Source: Author's Analysis)

Fuel	CO2 Kg/kWh	CO2 Emissions PV with Grid	CO2 Emissions PV with ESS
HFO	0.214		
Coal	0.395	44.7kg/yr	0
Hydro	0		
Total Factor	0.609		

To compare and validate the Homer Pro simulation of CO2 emissions results, equation 6 below was used to determine how much quantity of carbon dioxide emissions could have been produced from importing 73.3kWh/yr from the national grid to support the solar PV supported EV mobility charging hub in Zambia.

$$CO2\ emissions = (CO2\ kg/kWh) \times E(kWh/yr) \qquad 6$$

$$CO2\ emissions = (\frac{0.609kg}{kWh}) \times (\frac{73.3kWh}{yr})$$

$$CO2\ emissions = 44.64kg/yr/\text{EV}$$

The calculated figure was similar to the obtained figure from the software simulations, this was sufficient evidence to validate the software algorithm that it worked perfectly to produce the same quantity of 44.7kg/yr of carbon dioxide emissions from one electric vehicle under study.

To put this into the national picture of general CO2 emissions, it was necessary to make some contrast and comparisons on the sources of energy for ICE petrol and diesel vehicles as well as electric vehicle emissions charging through a mobility hub synchronized to the ZESCO grid with its current sources of energy mix. The overall average distance a motor vehicle covered in Zambia was taken to be 45.14km per day which translated into 16,476km/yr [74], [74]. Multiplying this distance with the average CO2 emissions per kilometre of 125g/km, this gave 2.06 tonnes of CO2 emissions per year per motor vehicle. From the derived figures, it was evident that despite introducing mobility hubs which were synchronized to the current ZESCO grid of which at the time of this study constituted 12% of power generated from fossil fuels, this would still tremendously reduce the amount of CO2 emissions from operating an internal combustion engine vehicle. Hence, grid supported mobility charging hub may not have any degrading environmental impact with the current ZESCO grid but may just affect the loading part on the already constrained grid.

The transport sector is not the only contributor of CO2 emissions, Figure 19 below depicts the major greenhouse gas emissions from the major contributing sectors in Zambia. The transport sector as can be seen accounted for about 2 million tonnes of annual CO2 emissions according the 2018 annual data statistics[1]. The largest contributor was of course the agricultural and forestry activities accounting for than 70% combined compared to other sectors. Nevertheless, the fight to reduce greenhouse gases is a holistic one hence no sector would be neglected if it made a significant contribution to the GHG emissions globally hence the drive to decarbonize the transport sector.

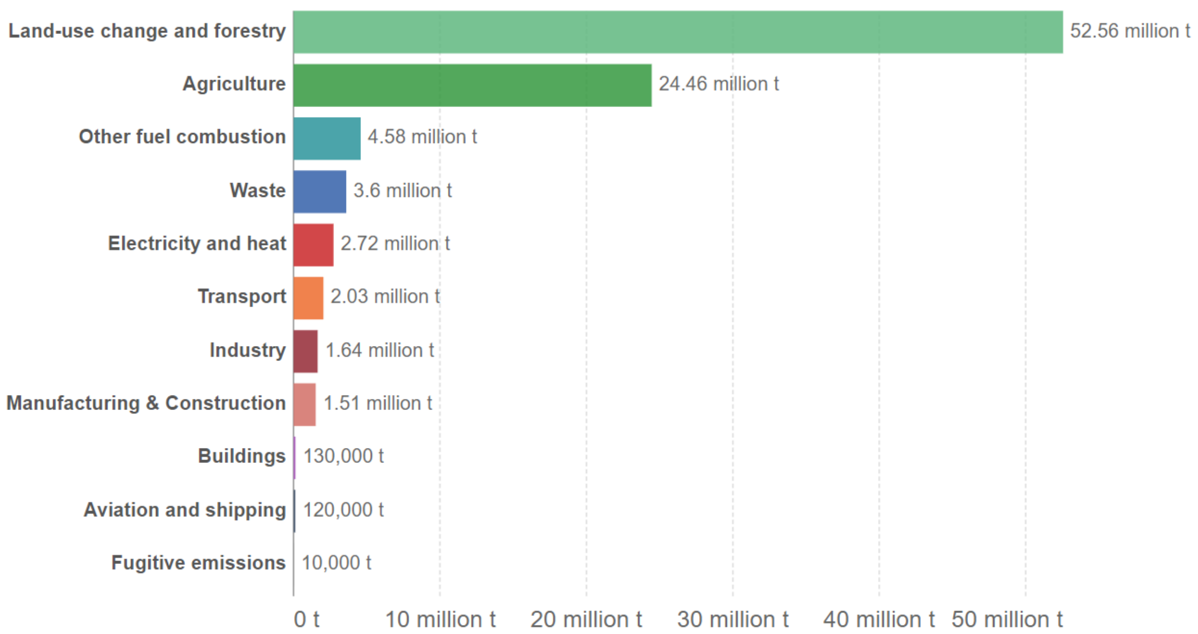


Figure 19: Greenhouse gas emissions by sector, Zambia, 2018[1]

At global level, Zambia like many other African countries apart from South Africa and Egypt were among the least GHG producers in the world. Figure 20 below shows the global annual share of carbon dioxide emissions for the year 2020. Africa was responsible for less than 5% of the global carbon dioxide emissions. Asia alone accounted for over 25% of carbon dioxide emissions and this was by far the largest percentage by any means measurable at global level.

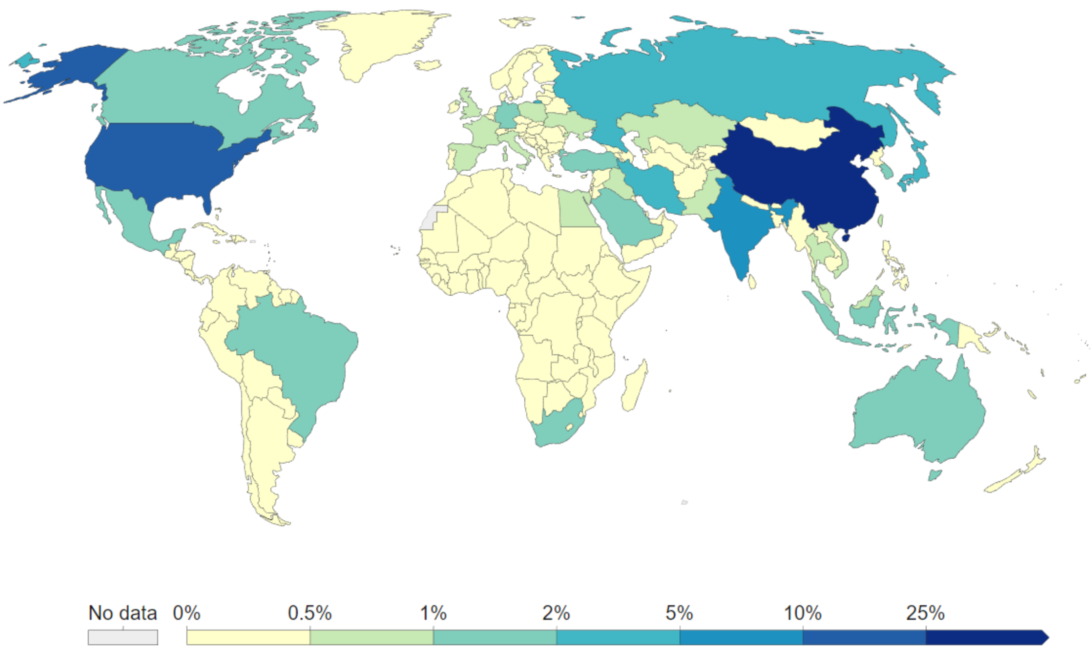


Figure 20: Annual share of global CO_2 emissions, 2020 [18]

3.3 Project Financial Analysis

ZESCO tariffs were recently revised upwards, and in this study, the new tariffs as implemented in 2022 were used to carry out the financial analysis for grid connection as well as daily energy usage. The tariffs implemented in Zambia are basically fixed according to bands of usage per month as shown in Table 7 below. The structure of energy tariffs is compoundable depending on the cumulative use of energy per calenda month. If one purchases 100 units at the beginning of any month, they would be charged at a rate of 2.81 cents GBP per kWh bringing the total purchase cost to £281 and if they run out of the purchased 100 units before the month ends the units will be charged at the next higher band rate which is at 3.5 cents GBP per kWh.

To summarize the costing of energy purchase in Zambia, the amount of units to be first bought in a new month is usually based on the amount of units being sought for and should there be an additional purchase of units within the same month regardless of the number of units being sought for, the energy purchase rate is translated to the next higher band than the previous rate the account holder was charged on when they first bought the units Table 7 below shows all the tariff calculations in use as of the second quarter of 2022 with 3% excise duty and 16% value added tax inclusive at an exchange rate of ZMW21 per £1 [75].

Table 7: ZESCO 2022 Tariffs [75]

kWh or Units	Amount [ZMW]	Amount [£]	Tariff [£/kWh]
100	59	2.81	0.028
150	110	5.24	0.035
200	160	7.62	0.038
250	211	10.05	0.040
300	262	12.48	0.042
350	378	18.00	0.051
400	493	23.48	0.059
500	725	34.52	0.069
600	957	45.57	0.076
700	1198	57.05	0.081
800	1421	67.67	0.085
900	1653	78.71	0.087
1000	1884	89.71	0.090

The financial analysis was based on the simulated energy system of a unity PV area power output, grid, and ESS to supplement the PV EV charging hub to service one electric vehicle. The analysis used the worst-case scenario to compute the financial implications. Therefore, the grid import was taken to be the maximum grid purchases made according to the simulation results. The maximum energy imported from the grid to supplement the PV was found to be 73.3kWh/yr which falls within the 100 Units band under the 0.028£/kWh tariff.

The standard cost of grid connection to the charging hub with respect to the ZESCO new connection costing per 50 meter single phase underground cable was £753 and for a three-phase underground cable was £1,634 [76], [77]. With only one charger being considered it was prudent to use the connection cost of a single-phase underground cable in the financial analysis. The cost of battery energy storage was set at £550 with £10 maintenance fee and this was used in the simulation to come up with the capital expenditure (CAPEX) and operating expenditure (OPEX). The Converter was priced at £500 with an operating cost of £50. Table 8 below shows all the main parameters used to evaluate the cost implication for the energy mix used in simulating the PV mobility charging hub with grid supported microgrid and as an islanded microgrid. All the financial analysis were done using Homer Pro and were done in tandem with the energy simulations for scenario 2 simulations 0 and 7 for the grid connected microgrid and an islanded microgrid respectively.

Table 8: Energy mix cost implication (Source: Authors Analysis)

Description	PV + Grid	PV + Battery Storage	PV, Grid & Battery
CAPEX	£1,758	£4,094	£5,852
OPEX	£85.29	£180.70	£265.99

From Table 8 above the simulation results show that the grid connected PV EV charging hub had a lower CAPEX as compared to the PV and battery system. The overall combination of both the grid and battery storage further increased the capital investments and the operational cost.

4.0 Discussion

4.1 Research Discussion and Recommendations

Through the literature review process, it was found that similar studies have been undertaken before but in a totally different geographical environment which resulted in different results as compared to this research. One of the main unique aspects of this research was the sample space and the methodology used in establishing the research findings. It was established that Light Electric Vehicles were easily adopted in most of the sub-Saharan Africa as compared to the four-wheel electric vehicles with little or no mention of fuel cell electric vehicles. However, countries like South Africa are the front runners in the adoption of four-wheel electric vehicles in sub–Saharan Africa. The main contributing factor to this trend was just as the case in high-income countries, the cost to own an electric vehicle and the lack of EV charging infrastructure. Light Electric Vehicles were found to be cheaper and did not require new installations for recharging as an ordinary residential power socket outlet would still be used to plug in the LEV charger cable.

Interesting energy results were obtained from the simulations carried out in this research. Due to the favourable solar radiation experienced in Zambia, an almost rule of thumb was established where a $1m^2$ PV area of a 320W solar photovoltaic panel would sufficiently charge at least 3 electric vehicles. This implied that an off-grid micro grid of as little as one solar panel would service charging electric vehicles in Zambia. However, these results were wholly dependent on the availability of solar radiation hence a similar simulation in a different geographical local may yield different results. Another caution with this result were that this was only possible in a situation of controlled EV charging.

The results of this study also revealed that there was a huge bargain in the fight against climate change when the transport sector transitions from petrol and diesel vehicles to electric vehicles. It was established that a conventional gasoline vehicle produced over 2 tonnes of carbon dioxide emissions as compared to the zero-carbon emission EV charged from the solar PV or solar PV with Battery hub. If the EV was charged through a solar PV hub synchronized to the ZESCO grid with its current power generation mix, only about 44kg of CO2 emissions would be produced compared to the 2 tonnes from ICE vehicles. This research further demonstrates that electric vehicles with rooftop solar panels would hence perform well in Zambia considering the adequate vehicle roof space which is over a meter squared and the sufficient long hours of solar radiation experienced throughout the year.

4.2 Research Limitation

Zambia being a lower-income country was yet to register its first battery electric vehicle and this also resulted in lack of previous research studies done in relation to electric mobility charging hubs in Zambia. During the simulations there were a few assumptions made due to limitations in software capabilities and the variation in the nature and data to be analysed. Helioscope software for instance was unable to simulate a minimum of 1m2 of PV area except for a much bigger space. The electric vehicle load profile generation was based on a probabilistic EV demand tool which was calibrated against the data obtained from the Transport Department in Glasgow however, these profiles were not fixed just as the frequency and time of refuelling an ICE petrol or diesel vehicle cannot be classically determined. On the environmental impact assessment, the CO_2 emissions factor from petrol and diesel vehicle was that from 2014 based on the assumptions that majority of vehicles in Zambia were manufactured around that time.

The highlighted limitations had some impact on the results obtained. The helioscope simulation could be used directly if undertaken a design requiring more than a square meter of PV and this would not invoke manual calculations to scale down the obtained results. The load profile generation was particularly based on the EV traffic in the City of Glasgow. However, the unpredictability of EV charging times, duration, state of charge and EV type cannot be the same at any instance or in any location. Since this study was done for Zambia, it could have been better to use the Zambian EV data, unfortunately as earlier stated there are registered EVs in Zambia let alone charging hubs. The amount of CO_2 emissions could be different based on the CO_2 emissions factor used depending on the year of manufacture the vehicles under study were made. The financial analysis was mainly based on the energy calculations, it did not take into considerations the mobility charging hub modules in the cost calculations as these costs were a constant regardless of the energy source. However, all assumptions made had minimal to some extent negligible implications on the research results.

5.0 Conclusions

This research was mainly structured to cover the technical aspects of a mobility charging hub in Zambia to support the introduction of electric vehicles in that country. The set aims and objectives of this research were successfully achieved which included the feasibility of introducing a solar PV mobility charging hub in Zambia to support the introduction of electric mobility vehicles as the country prepares to transition the transport sector to carbon neutral system in line with the United Nations Sustainable Development Goals 2030 and the resolutions of the UN Conference of Parties (COP) 26. The study aimed at technical analysis of all the possible energy mix for the mobility hub with of course maintaining the solar PV energy source a constant but mixing it with battery energy storage as well as a synchronized charging hub to the Zambia national grid. The research also aimed at bringing out the information on the level of penetration electric mobility vehicles in sub-Saharan Africa including categorizing the highly or most favoured type of mobility vehicles, of much concentration was based on Zambia as this was the case study destination. The national carbon footprint in relation to mobility vehicles was also successfully analysed interestingly with the results obtained from the research findings from the emissions attributed to the transport sector.

With the aid of real data available at the location, this was used to carry out computer simulations and it was demonstrated that there was sufficient solar energy potential in Zambia to introduce solar PV mobility charging hubs. It was therefore, established that a unity square meter of PV was able to produce an average of 267kWh/yr where there was zero percent of radiation shading. It was also calculated through software simulations that an average electric vehicle would generally demand about 73kWh/yr of energy to keep an electric vehicle running. With these two obtained results, it was clear that a unity square meter of solar PV would successfully charge an EV if the charging was done in a controlled fashion when there was sufficient energy production from the PV as the PV gives no output during night and under extreme cloud cover. This further suggested that an off-grid mobility charging hub was feasible to operate in the Zambian climate. If synchronized to the national grid, the hub would normally import energy equivalent to the EV demand which in this case was about 73kWh/yr. The main reason for this was in case of uncontrolled charging where the EV turns up for charging even in the night or at any time, the hub would still have energy to charge the EV batteries. In the case of a solar PV and battery energy storage charging hub, the hub would require a 7kWh battery storage nominal capacity to service an average EV.

This prototype project was also analysed for capital investments and running costs. From the onset it was obvious that a solely solar PV mobility charging hub would cost the least mainly as this would only involve the cost of the PV panel, the mobility charging module and accessories. Between the battery energy storage and the grid connection plus grid operational costs, it was established that the PV charging hub incorporated with battery storage was much more expensive than the solar PV grid connected charging hub. The most expensive combination was the coagulation of a solar PV, Battery energy storage and grid connected microgrid charging hub. Based on cost and solar radiation potential, solar PV off grid mobility charging hubs would be most feasible for implementation in Zambia. On the other hand, electric vehicle rooftop solar PVs would also play a significant role in decarbonizing the transport sector as the EVs with rooftop solar panels maybe able to self-charge as they operate without driving to a charging hub. This pathway would also be able to eliminate about 2 tonnes of CO2 emissions from a single petrol or diesel vehicle on the roads in Zambia thereby reducing the national carbon footprint. Lastly this research further suggests that for future study, rooftop solar PVs on electric vehicles could be researched on to assess their feasibility for deployment in sub–Saharan Africa as this could be a ground-breaking technology most appropriate for most countries especially those near the equator.

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7.0 Appendices

Helioscope Solar PV Array Simulations Results Reports

7.1 *Helioscope Simulations Report*

HelioScope — Annual Production Report produced by Felix Kusaloka

Scale Up PV EV Charging Hub

Scale Up EV Charging, Lusaka Zambia

Report

Project Name	Scale Up EV Charging
Project Description	EV Charging Hup Scale Up
Project Address	Lusaka Zambia
Prepared By	Felix Kusaloka felix.kusaloka.2021@uni.strath.ac.uk

System Metrics

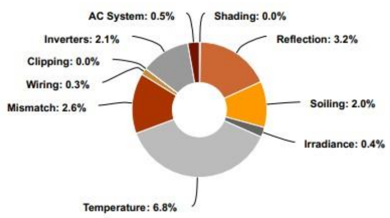
Design	Scale Up PV EV Charging Hub (Support copy)
Module DC Nameplate	16.0 kW
Inverter AC Nameplate	24.1 kW Load Ratio: 0.67
Annual Production	26.69 MWh
Performance Ratio	83.2%
kWh/kWp	1,668.3
Weather Dataset	TMY, 10km Grid, meteonorm (meteonorm)
Simulator Version	0e564ca985-fe0bd83782-144f525eb7-bfa47ce805

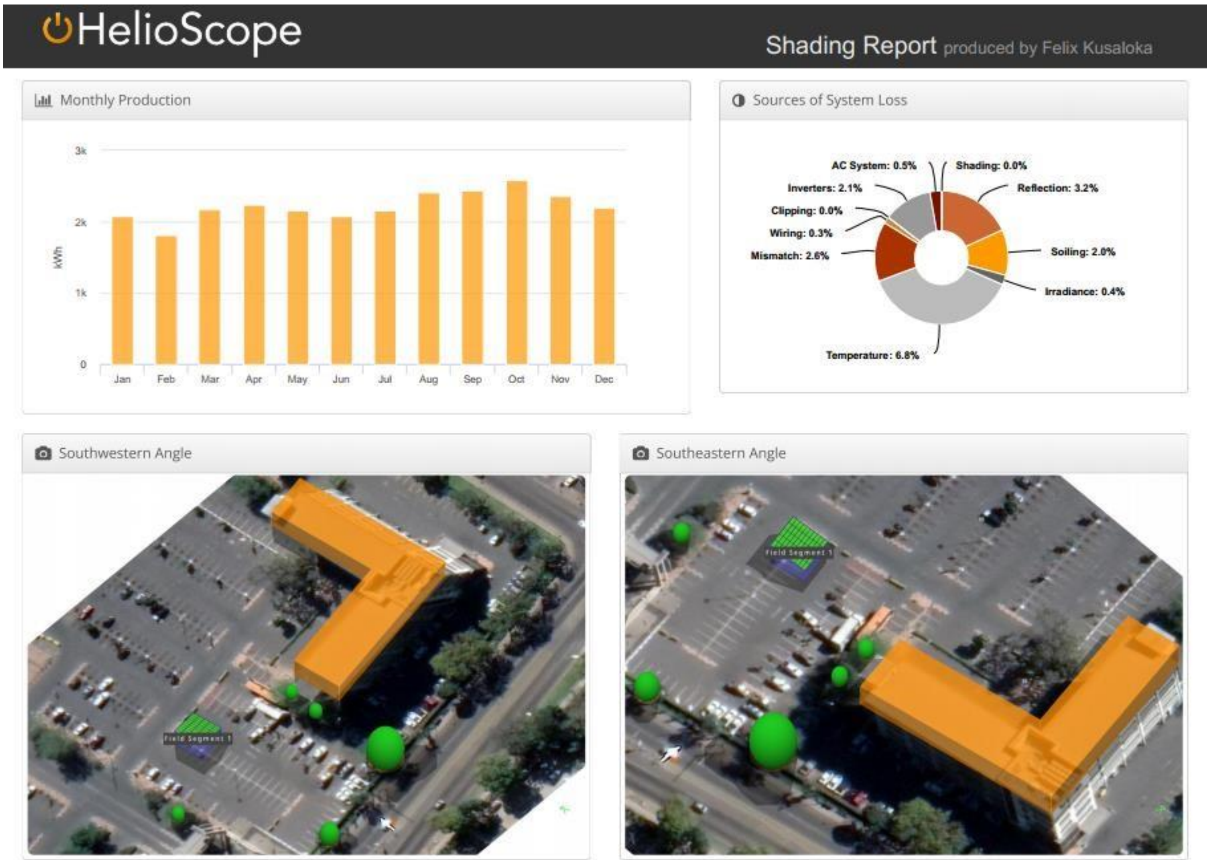
Project Location

Monthly Production

Month	GHI (kWh/m²)	POA (kWh/m²)	Shaded (kWh/m²)	Nameplate (kWh)	Grid (kWh)
January	156.4	157.3	157.2	2,383.7	2,079.7
February	139.1	137.9	137.9	2,093.4	1,816.8
March	162.9	164.2	164.1	2,492.0	2,175.5
April	164.4	166.4	166.4	2,528.0	2,233.5
May	156.9	160.0	160.0	2,419.1	2,154.1
June	148.4	152.2	152.2	2,295.3	2,075.2
July	154.1	158.3	158.3	2,391.9	2,156.8
August	176.2	179.7	179.6	2,729.0	2,415.2
September	183.7	186.2	186.2	2,839.8	2,445.2
October	199.1	198.5	198.5	3,026.0	2,590.9
November	182.1	179.6	179.5	2,729.2	2,354.4
December	164.9	165.4	165.3	2,503.8	2,195.2

Sources of System Loss




HelioScope
Shading Report produced by Felix Kusaloka
Monthly Production
3k
2k
1k
0
kWh
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Sources of System Loss
AC System: 0.5%
Shading: 0.0%
Inverters: 2.1%
Reflection: 3.2%
Clipping: 0.0%
Wiring: 0.3%
Mismatch: 2.6%
Soiling: 2.0%
Irradiance: 0.4%
Temperature: 6.8%
Southwestern Angle
Southeastern Angle

Homer Mobility Charging Hub Energy Systems' Simulations Results Reports

7.2 System Simulation Report

File: Simulation 0 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: *£2,861.04*

Levelized Cost of Energy (£/kWh): *£0.686*

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
System converter	System Converter	1.52	kW
Grid	Grid	999,999	kW
Dispatch strategy	HOMER Cycle Charging		

Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0.638	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	78.4
Grid Purchases	73.3	21.6

Total	340	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	22.6
Deferrable Load	0	0
Grid Sales	250	77.4
Total	323	100

PV: Generic flat plate PV

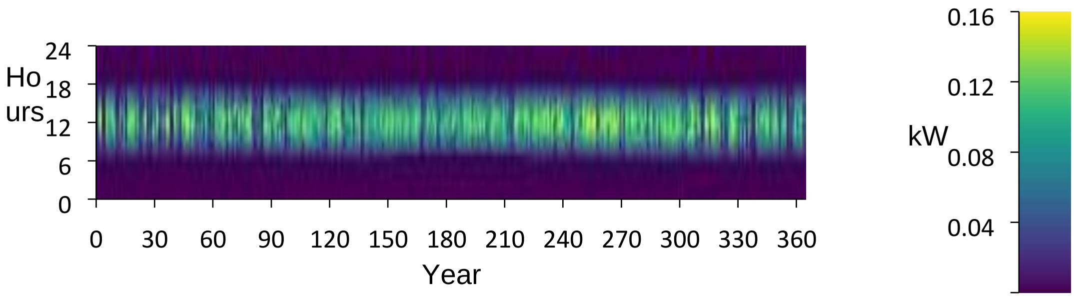
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	1.46	£0.00	£0.122
February	0	0	0	1.44	£0.00	£0.121
March	0	0	0	1.29	£0.00	£0.108
April	0	0	0	0.998	£0.00	£0.0838
May	0	0	0	0.998	£0.00	£0.0838
June	0	0	0	0.938	£0.00	£0.0788
July	0	0	0	0.909	£0.00	£0.0764
August	0	0	0	0.953	£0.00	£0.0801
September	0	0	0	0.998	£0.00	£0.0838
October	0	0	0	1.22	£0.00	£0.102
November	0	0	0	1.26	£0.00	£0.106
December	0	0	0	1.46	£0.00	£0.122
Annual	0	0	0	1.46	£0.00	£1.17

Grid rate: Rate

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	5.76	17.6	-11.8	0	-£0.0118	£0.00
February	9.05	16.1	-7.10	0	-£0.00710	£0.00
March	6.92	19.9	-13.0	0	-£0.0130	£0.00
April	4.79	20.6	-15.8	0	-£0.0158	£0.00
May	5.56	21.5	-16.0	0	-£0.0160	£0.00
June	3.67	20.5	-16.8	0	-£0.0168	£0.00
July	0.909	22.6	-21.7	0	-£0.0217	£0.00

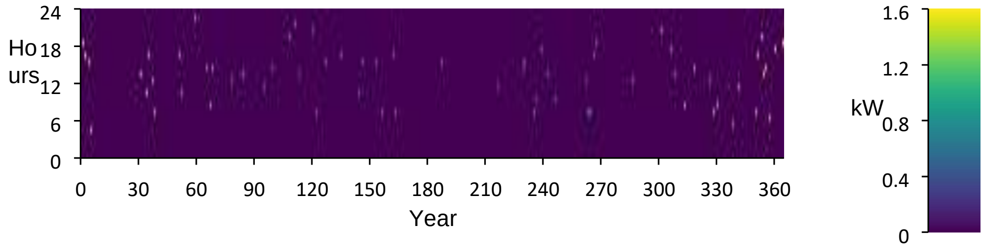
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
August	6.26	23.7	-17.4	0	-£0.0174	£0.00
September	5.59	23.6	-18.0	0	-£0.0180	£0.00
October	2.37	24.0	-21.6	0	-£0.0216	£0.00
November	8.35	21.1	-12.7	0	-£0.0127	£0.00
December	14.1	18.6	-4.50	0	-£0.00450	£0.00
Annual	73.3	250	-177	0	-£0.177	£0.00

Grid rate: All

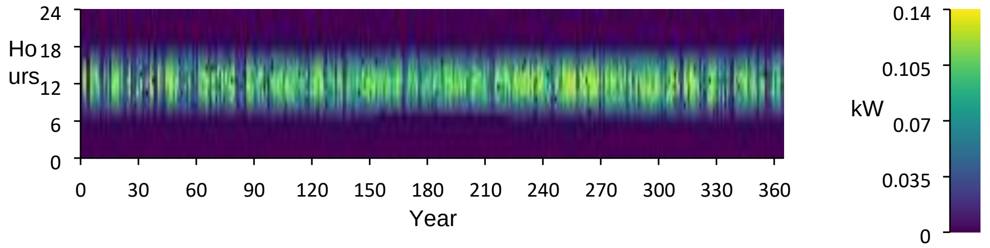
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	5.76	17.6	-11.8	1.46	-£0.0118	£0.122
February	9.05	16.1	-7.10	1.44	-£0.00710	£0.121
March	6.92	19.9	-13.0	1.29	-£0.0130	£0.108
April	4.79	20.6	-15.8	0.998	-£0.0158	£0.0838
May	5.56	21.5	-16.0	0.998	-£0.0160	£0.0838
June	3.67	20.5	-16.8	0.938	-£0.0168	£0.0788
July	0.909	22.6	-21.7	0.909	-£0.0217	£0.0764
August	6.26	23.7	-17.4	0.953	-£0.0174	£0.0801
September	5.59	23.6	-18.0	0.998	-£0.0180	£0.0838
October	2.37	24.0	-21.6	1.22	-£0.0216	£0.102
November	8.35	21.1	-12.7	1.26	-£0.0127	£0.106

December	14.1	18.6	-4.50	1.46	-£0.00450	£0.122
Annual	73.3	250	-177	1.46	-£0.177	£1.17

Energy Purchased From Grid (kW)



Energy Sold To Grid (kW)



Converter: System Converter

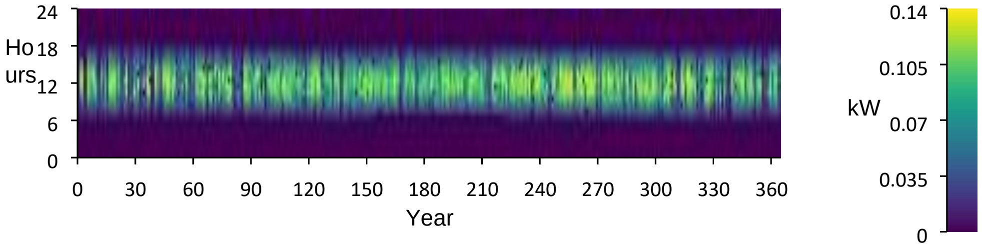
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	4,344	hrs/yr
Energy Out	250	kWh/yr
Energy In	263	kWh/yr
Losses	13.2	kWh/yr

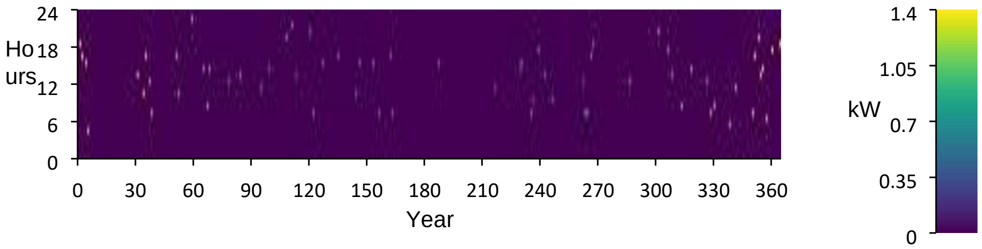
System Converter Statistics

Quantity	Value	Units
Capacity	1.52	kW
Mean Output	0.0285	kW
Minimum Output	0	kW
Maximum Output	0.130	kW
Capacity Factor	1.87	%

System Converter Inverter Output (kW)



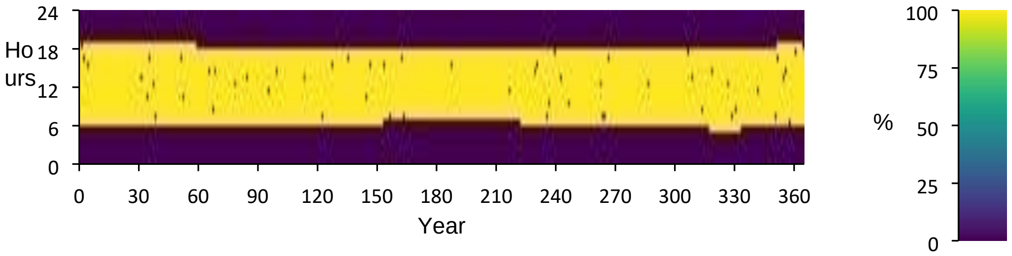
System Converter Rectifier Output (kW)



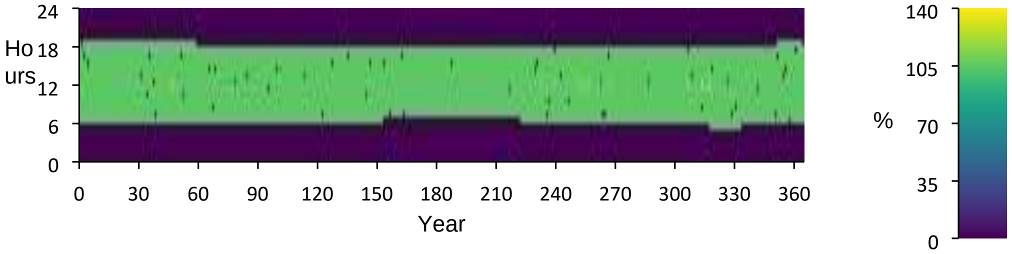
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	82.7	%
Total renewable production divided by generation	78.4	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	120	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

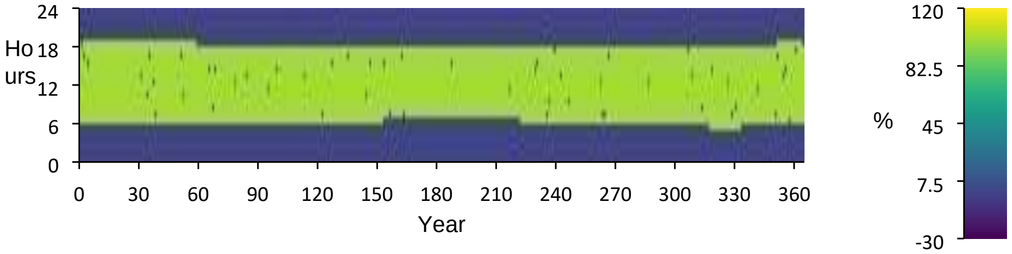
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



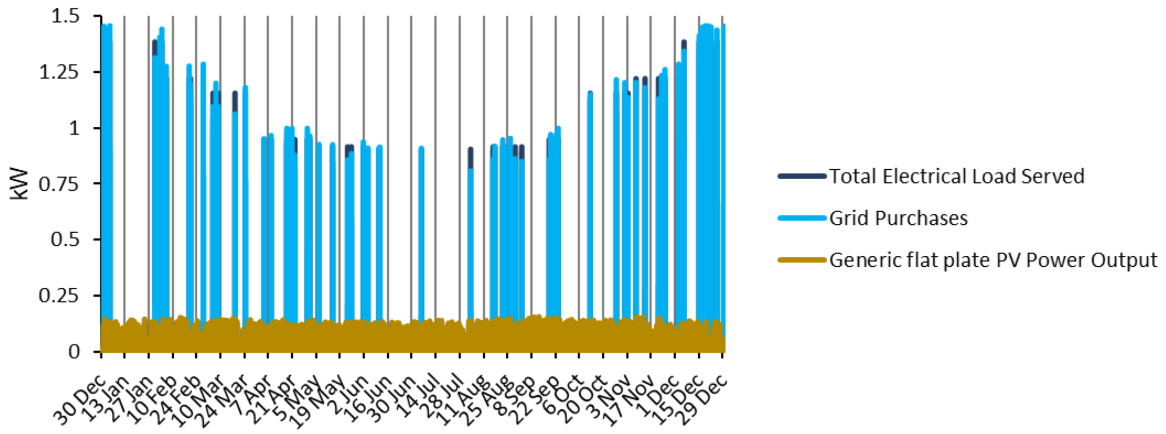
Compare Economics

IRR (%):**N/A**

Discounted payback (yr):**N/A**

Simple payback (yr):**N/A**

	Base System	**Proposed System**
Net Present Cost	£1,789	£2,861
CAPEX	£761.72	£1,758
OPEX	£79.50	£85.29
LCOE (per kWh)	£1.90	£0.686
CO2 Emitted (kg/yr)	46.7	44.7
Fuel Consumption (L/yr)	0	0



1.5
1.25
1
0.75
0.5
0.25
0
kW
30 Dec
13 Jan
27 Jan
10 Feb
24 Feb
10 Mar
24 Mar
7 Apr
21 Apr
5 May
19 May
2 Jun
16 Jun
30 Jun
14 Jul
28 Jul
11 Aug
25 Aug
8 Sep
22 Sep
6 Oct
20 Oct
3 Nov
17 Nov
1 Dec
15 Dec
29 Dec
Total Electrical Load Served
Grid Purchases
Generic flat plate PV Power Output

7.3 *System Simulation Report*

File: Simulation 1 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £3,655.12

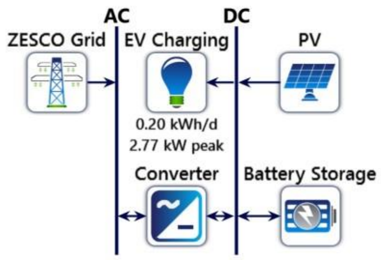
Levelized Cost of Energy (£/kWh): £0.876

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

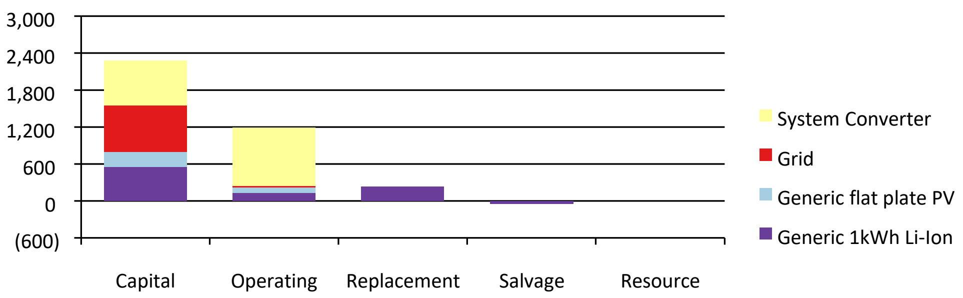
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	1	strings
System converter	System Converter	1.46	kW
Grid	Grid	2.00	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



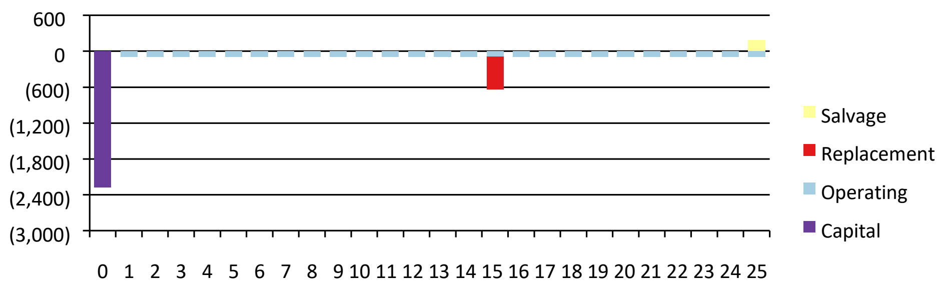
Net Present Costs

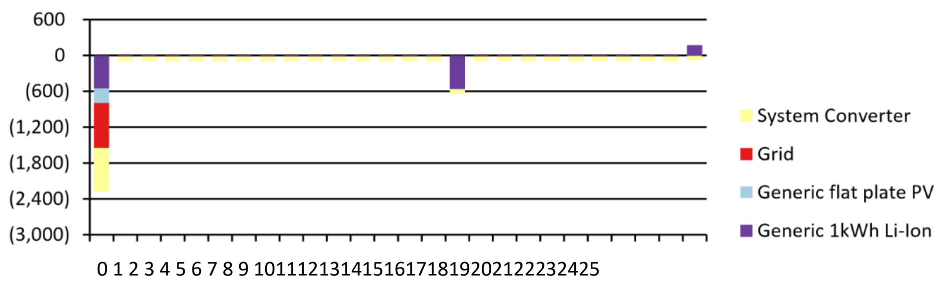
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£550.00	£129.28	£233.35	-£43.92	£0.00	£868.71
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79
Grid	£753.00	£12.83	£0.00	£0.00	£0.00	£765.83
System Converter	£729.17	£942.63	£0.00	£0.00	£0.00	£1,672
System	£2,276	£1,190	£233.35	-£43.92	£0.00	£3,655

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£42.54	£10.00	£18.05	-£3.40	£0.00	£67.20
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
Grid	£58.25	£0.992	£0.00	£0.00	£0.00	£59.24
System Converter	£56.40	£72.92	£0.00	£0.00	£0.00	£129.32
System	£176.05	£92.03	£18.05	-£3.40	£0.00	£282.74

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0.638	kWh/yr

Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	78.4
Grid Purchases	73.3	21.6
Total	340	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	22.6
Deferrable Load	0	0
Grid Sales	250	77.4
Total	323	100

PV: Generic flat plate PV

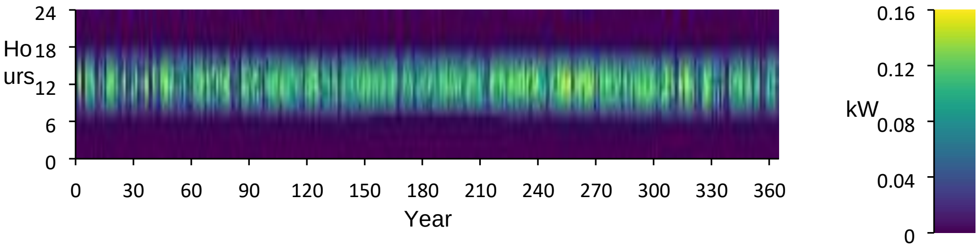
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	1.00	qty.
String Size	1.00	batteries
Strings in Parallel	1.00	strings
Bus Voltage	6.00	V

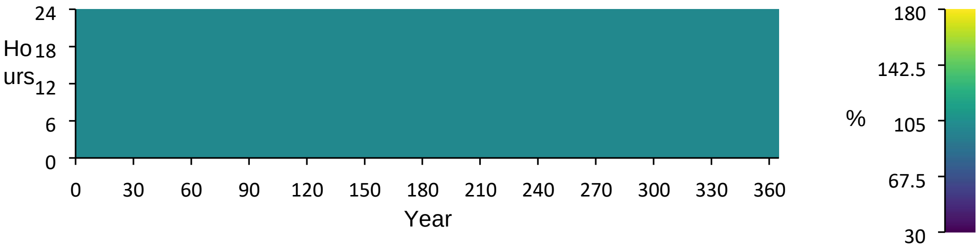
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	0	kWh/yr
Energy Out	0	kWh/yr
Storage Depletion	0	kWh/yr
Losses	0	kWh/yr
Annual Throughput	0	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	96.2	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	1.00	kWh
Usable Nominal Capacity	0.800	kWh
Lifetime Throughput	0	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

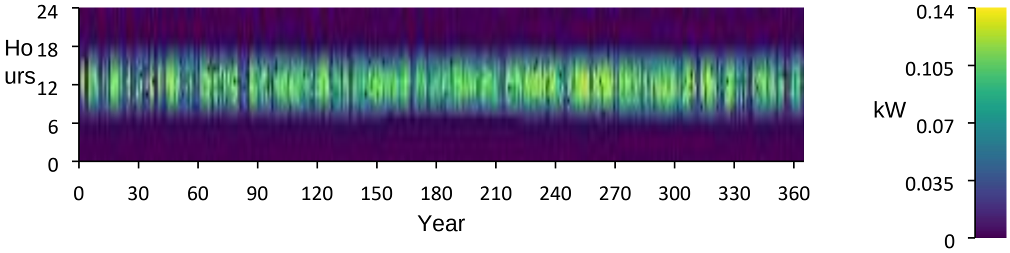
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	4,344	hrs/yr
Energy Out	250	kWh/yr
Energy In	263	kWh/yr
Losses	13.2	kWh/yr

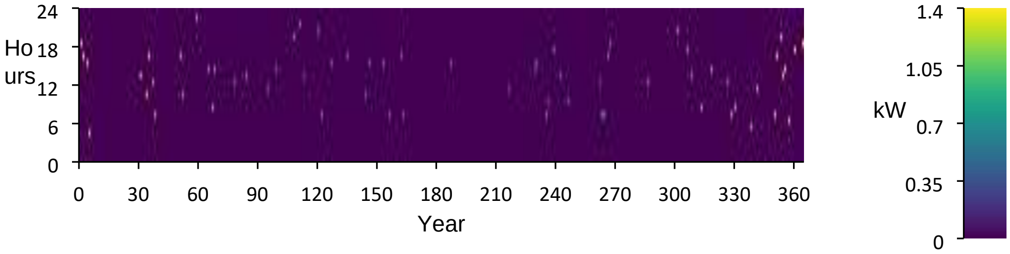
System Converter Statistics

Quantity	Value	Units
Capacity	1.46	kW
Mean Output	0.0285	kW
Minimum Output	0	kW
Maximum Output	0.130	kW
Capacity Factor	1.96	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	1.46	£0.00	£0.122
February	0	0	0	1.44	£0.00	£0.121

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
March	0	0	0	1.29	£0.00	£0.108
April	0	0	0	0.998	£0.00	£0.0838
May	0	0	0	0.998	£0.00	£0.0838
June	0	0	0	0.938	£0.00	£0.0788
July	0	0	0	0.909	£0.00	£0.0764
August	0	0	0	0.953	£0.00	£0.0801
September	0	0	0	0.998	£0.00	£0.0838
October	0	0	0	1.22	£0.00	£0.102
November	0	0	0	1.26	£0.00	£0.106
December	0	0	0	1.46	£0.00	£0.122
Annual	0	0	0	1.46	£0.00	£1.17

Grid rate: Rate

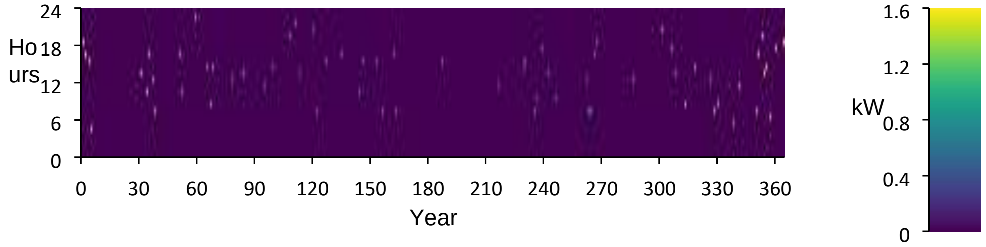
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	5.76	17.6	-11.8	0	-£0.0118	£0.00
February	9.05	16.1	-7.10	0	-£0.00710	£0.00
March	6.92	19.9	-13.0	0	-£0.0130	£0.00
April	4.79	20.6	-15.8	0	-£0.0158	£0.00
May	5.56	21.5	-16.0	0	-£0.0160	£0.00
June	3.67	20.5	-16.8	0	-£0.0168	£0.00
July	0.909	22.6	-21.7	0	-£0.0217	£0.00
August	6.26	23.7	-17.4	0	-£0.0174	£0.00
September	5.59	23.6	-18.0	0	-£0.0180	£0.00

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
October	2.37	24.0	-21.6	0	-£0.0216	£0.00
November	8.35	21.1	-12.7	0	-£0.0127	£0.00
December	14.1	18.6	-4.50	0	-£0.00450	£0.00
Annual	73.3	250	-177	0	-£0.177	£0.00

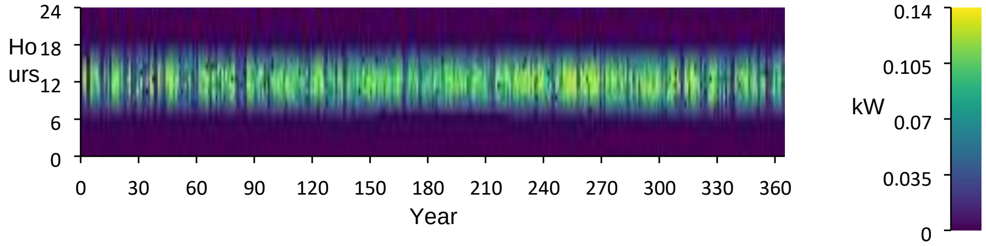
Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	5.76	17.6	-11.8	1.46	-£0.0118	£0.122
February	9.05	16.1	-7.10	1.44	-£0.00710	£0.121
March	6.92	19.9	-13.0	1.29	-£0.0130	£0.108
April	4.79	20.6	-15.8	0.998	-£0.0158	£0.0838
May	5.56	21.5	-16.0	0.998	-£0.0160	£0.0838
June	3.67	20.5	-16.8	0.938	-£0.0168	£0.0788
July	0.909	22.6	-21.7	0.909	-£0.0217	£0.0764
August	6.26	23.7	-17.4	0.953	-£0.0174	£0.0801
September	5.59	23.6	-18.0	0.998	-£0.0180	£0.0838
October	2.37	24.0	-21.6	1.22	-£0.0216	£0.102
November	8.35	21.1	-12.7	1.26	-£0.0127	£0.106
December	14.1	18.6	-4.50	1.46	-£0.00450	£0.122
Annual	73.3	250	-177	1.46	-£0.177	£1.17

Energy Purchased From Grid (kW)



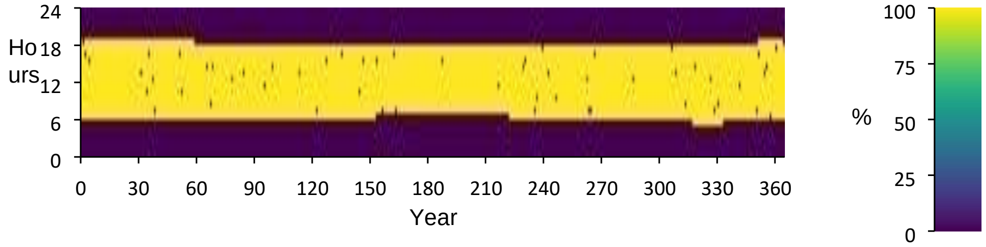
Energy Sold To Grid (kW)



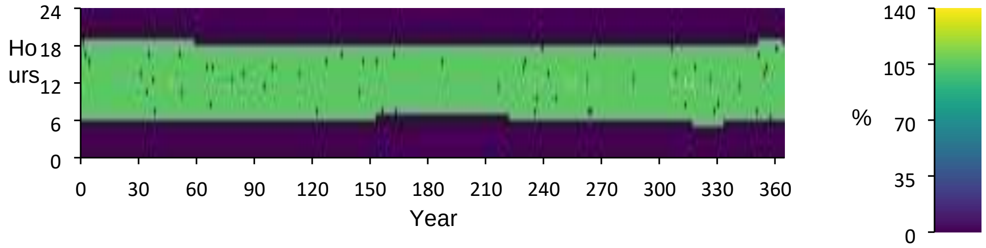
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	82.7	%
Total renewable production divided by generation	78.4	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	120	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

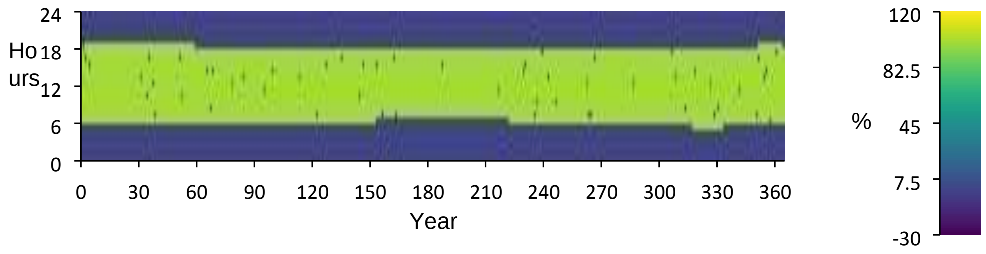
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

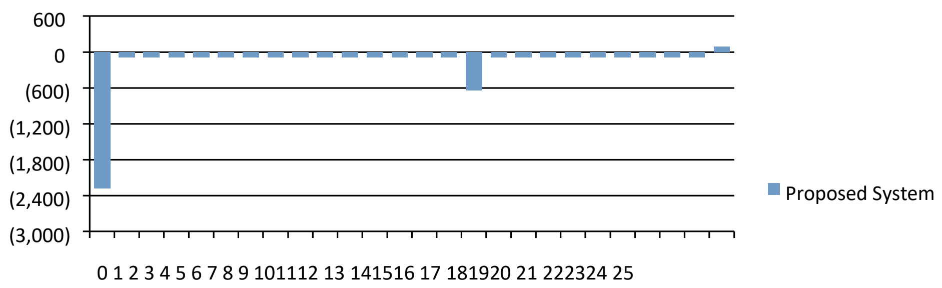
IRR (%):**N/A**

Discounted payback (yr):**N/A**

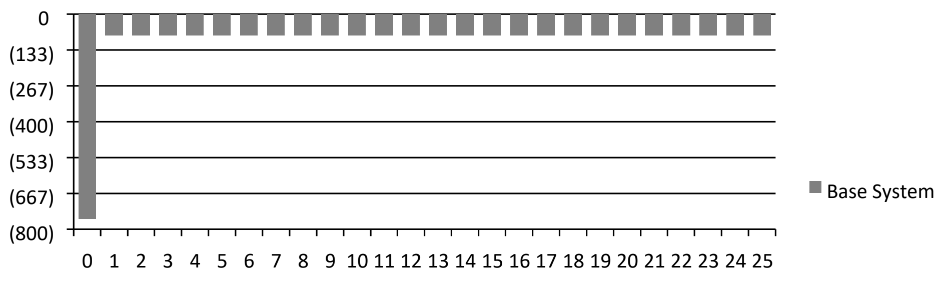
Simple payback (yr):**N/A**

	Base System	Proposed System
Net Present Cost	£1,789	£3,655
CAPEX	£761.72	£2,276
OPEX	£79.50	£106.69
LCOE (per kWh)	£1.90	£0.876
CO2 Emitted (kg/yr)	46.7	44.7
Fuel Consumption (L/yr)	0	0

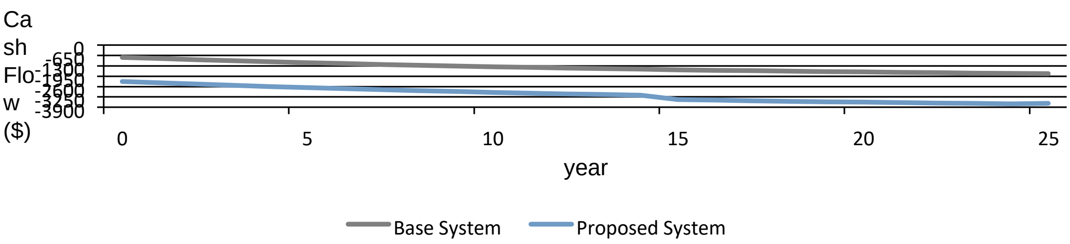
Proposed Annual Nominal Cash Flows



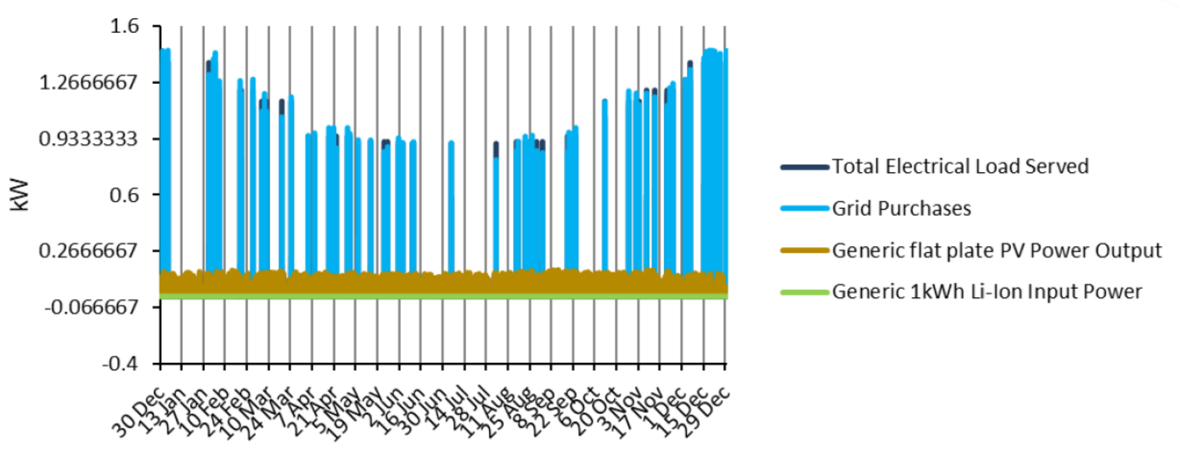
Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts:



7.4 System Simulation Report

File: Simulation 2 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £3,790.06

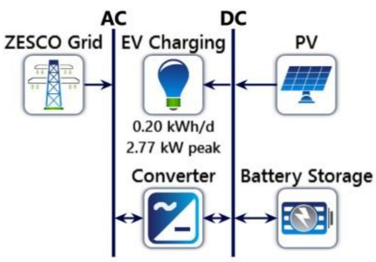
Levelized Cost of Energy (£/kWh): £0.958

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

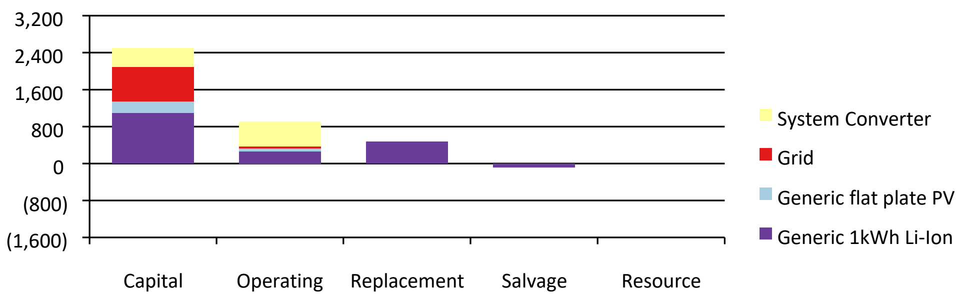
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	2	strings
System converter	System Converter	0.822	kW
Grid	Grid	1.00	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



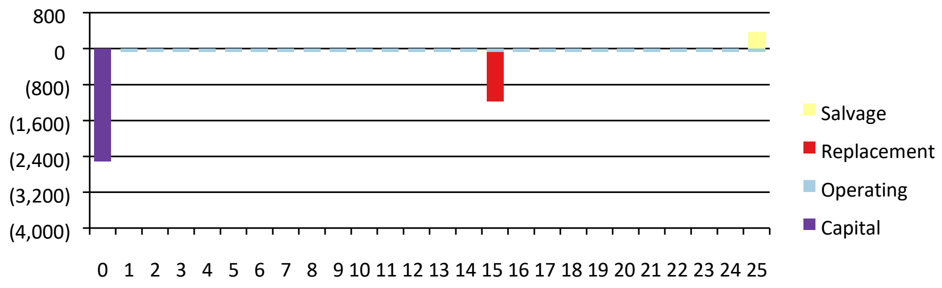
Net Present Costs

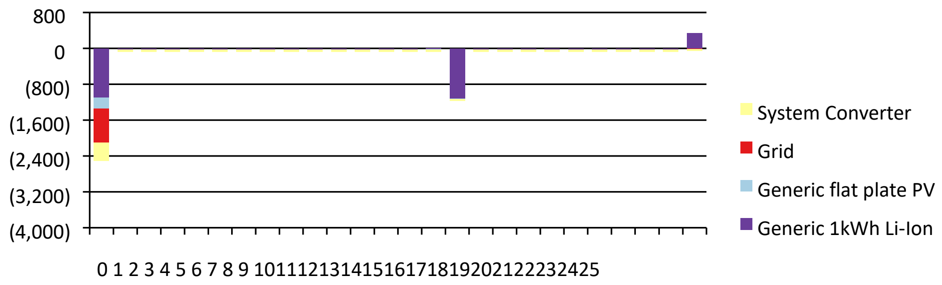
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£1,100	£258.55	£466.70	-£87.84	£0.00	£1,737
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79
Grid	£753.00	£8.98	£0.00	£0.00	£0.00	£761.98
System Converter	£410.81	£531.07	£0.00	£0.00	£0.00	£941.88
System	£2,508	£903.64	£466.70	-£87.84	£0.00	£3,790

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£85.09	£20.00	£36.10	-£6.79	£0.00	£134.40
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
Grid	£58.25	£0.695	£0.00	£0.00	£0.00	£58.94
System Converter	£31.78	£41.08	£0.00	£0.00	£0.00	£72.86
System	£193.97	£69.90	£36.10	-£6.79	£0.00	£293.18

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0.591	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	82.6
Grid Purchases	56.1	17.4
Total	323	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	23.8
Deferrable Load	0	0
Grid Sales	233	76.2
Total	306	100

PV: Generic flat plate PV

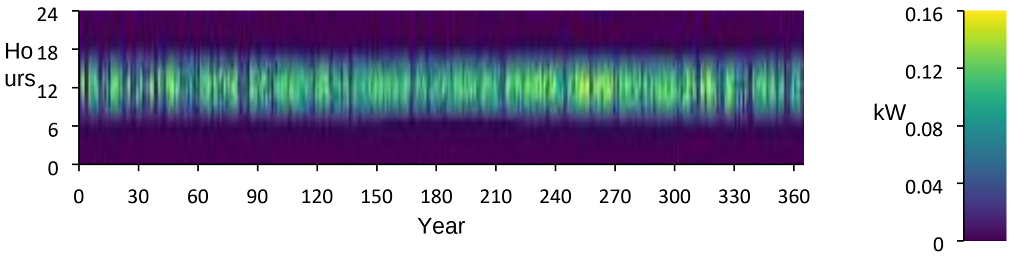
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	2.00	qty.
String Size	1.00	batteries
Strings in Parallel	2.00	strings
Bus Voltage	6.00	V

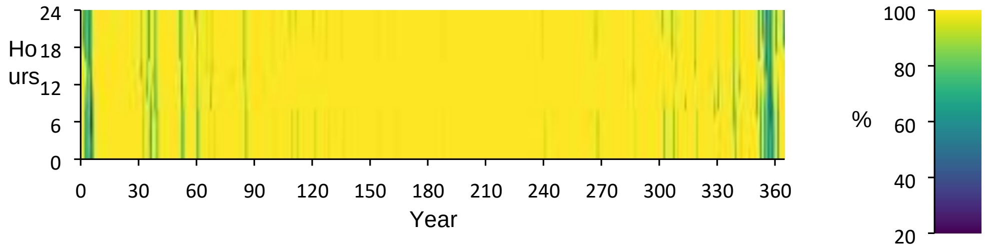
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	17.5	kWh/yr
Energy Out	16.3	kWh/yr
Storage Depletion	0.591	kWh/yr
Losses	1.78	kWh/yr
Annual Throughput	17.2	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	192	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	2.00	kWh
Usable Nominal Capacity	1.60	kWh
Lifetime Throughput	258	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

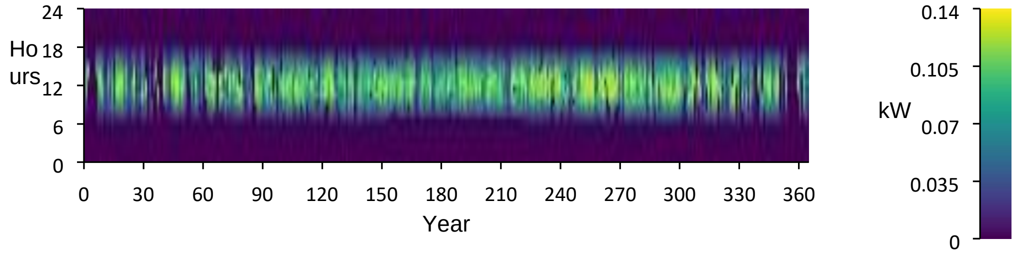
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	3,939	hrs/yr
Energy Out	233	kWh/yr
Energy In	246	kWh/yr
Losses	12.3	kWh/yr

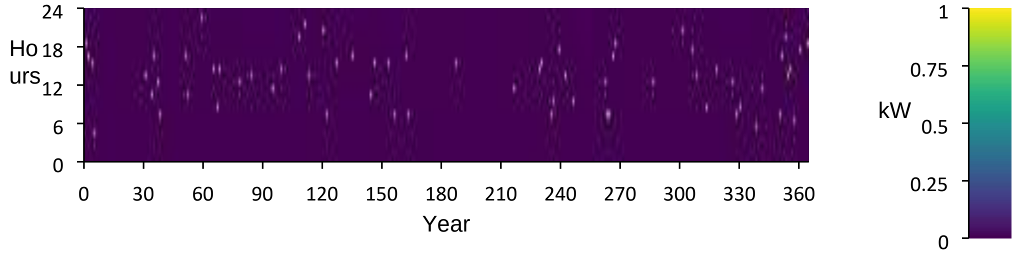
System Converter Statistics

Quantity	Value	Units
Capacity	0.822	kW
Mean Output	0.0266	kW
Minimum Output	0	kW
Maximum Output	0.130	kW
Capacity Factor	3.24	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0.865	£0.00	£0.0726
February	0	0	0	0.865	£0.00	£0.0726
March	0	0	0	0.865	£0.00	£0.0726
April	0	0	0	0.865	£0.00	£0.0726
May	0	0	0	0.865	£0.00	£0.0726
June	0	0	0	0.865	£0.00	£0.0726
July	0	0	0	0.865	£0.00	£0.0726
August	0	0	0	0.865	£0.00	£0.0726
September	0	0	0	0.865	£0.00	£0.0726
October	0	0	0	0.865	£0.00	£0.0726
November	0	0	0	0.865	£0.00	£0.0726
December	0	0	0	0.865	£0.00	£0.0726
Annual	0	0	0	0.865	£0.00	£0.872

Grid rate: Rate

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	3.46	15.3	-11.8	0	-£0.0118	£0.00
February	6.05	13.2	-7.10	0	-£0.00710	£0.00
March	5.19	18.2	-13.0	0	-£0.0130	£0.00
April	4.32	20.2	-15.8	0	-£0.0158	£0.00
May	5.18	21.2	-16.0	0	-£0.0160	£0.00
June	3.46	20.3	-16.8	0	-£0.0168	£0.00
July	0.865	22.5	-21.7	0	-£0.0217	£0.00

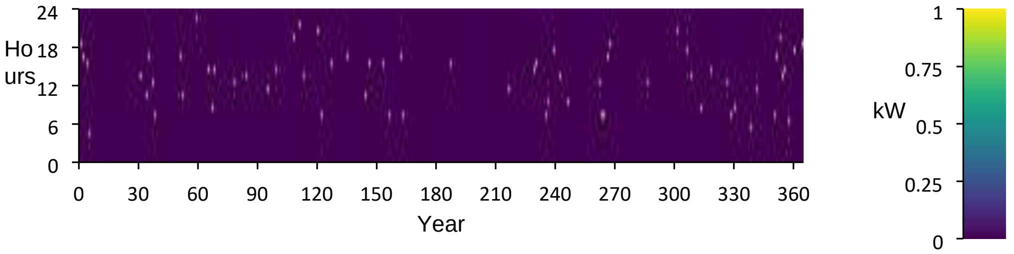
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
August	5.99	23.4	-17.4	0	-£0.0174	£0.00
September	5.17	23.2	-18.0	0	-£0.0180	£0.00
October	1.73	23.4	-21.6	0	-£0.0216	£0.00
November	6.05	18.8	-12.7	0	-£0.0127	£0.00
December	8.65	13.7	-5.07	0	-£0.00507	£0.00
Annual	56.1	233	-177	0	-£0.177	£0.00

Grid rate: All

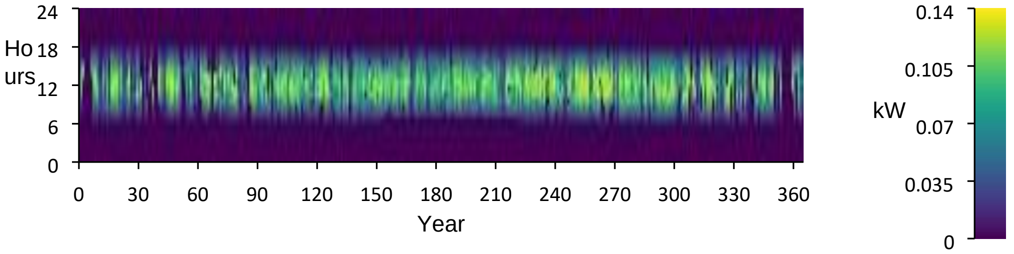
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	3.46	15.3	-11.8	0.865	-£0.0118	£0.0726
February	6.05	13.2	-7.10	0.865	-£0.00710	£0.0726
March	5.19	18.2	-13.0	0.865	-£0.0130	£0.0726
April	4.32	20.2	-15.8	0.865	-£0.0158	£0.0726
May	5.18	21.2	-16.0	0.865	-£0.0160	£0.0726
June	3.46	20.3	-16.8	0.865	-£0.0168	£0.0726
July	0.865	22.5	-21.7	0.865	-£0.0217	£0.0726
August	5.99	23.4	-17.4	0.865	-£0.0174	£0.0726
September	5.17	23.2	-18.0	0.865	-£0.0180	£0.0726
October	1.73	23.4	-21.6	0.865	-£0.0216	£0.0726
November	6.05	18.8	-12.7	0.865	-£0.0127	£0.0726

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
December	8.65	13.7	-5.07	0.865	-£0.00507	£0.0726
Annual	56.1	233	-177	0.865	-£0.177	£0.872

Energy Purchased From Grid (kW)



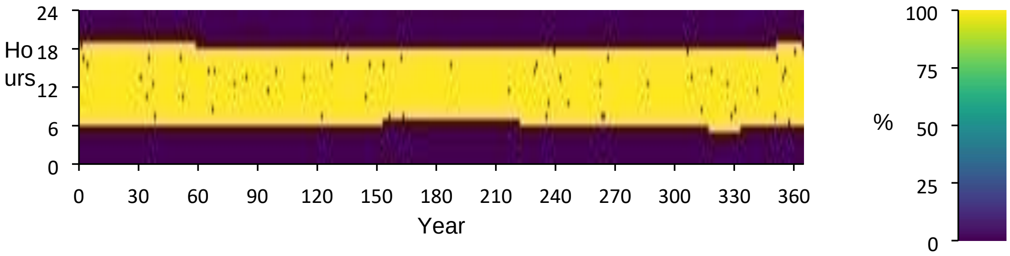
Energy Sold To Grid (kW)



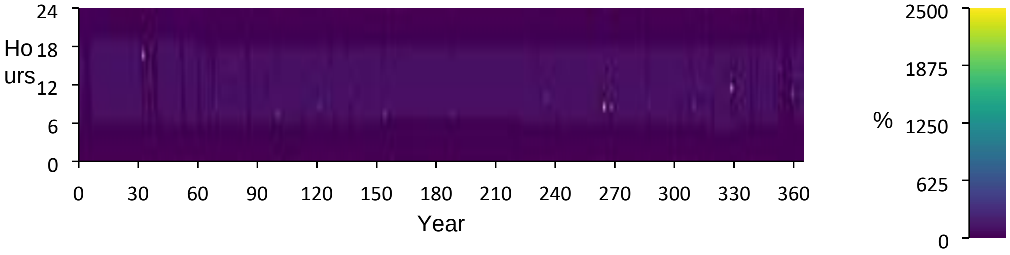
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	87.2	%
Total renewable production divided by generation	82.6	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	2,464	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

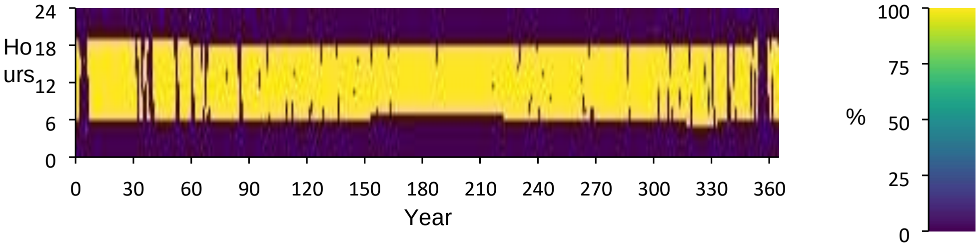
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

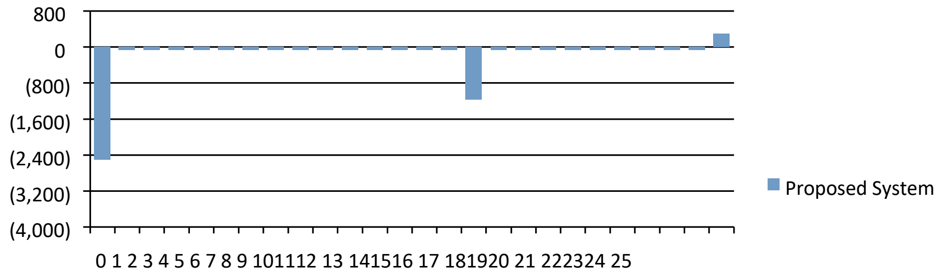
IRR (%):**N/A**

Discounted payback (yr):**N/A**

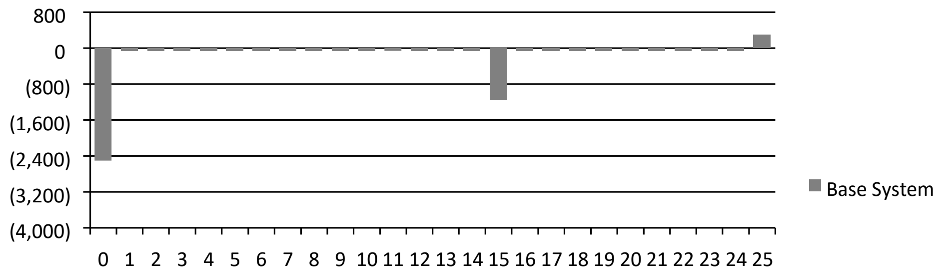
Simple payback (yr):**N/A**

	Base System	Proposed System
Net Present Cost	£3,790	£3,790
CAPEX	£2,508	£2,508
OPEX	£99.21	£99.21
LCOE (per kWh)	£0.958	£0.958
CO2 Emitted (kg/yr)	34.2	34.2
Fuel Consumption (L/yr)	0	0

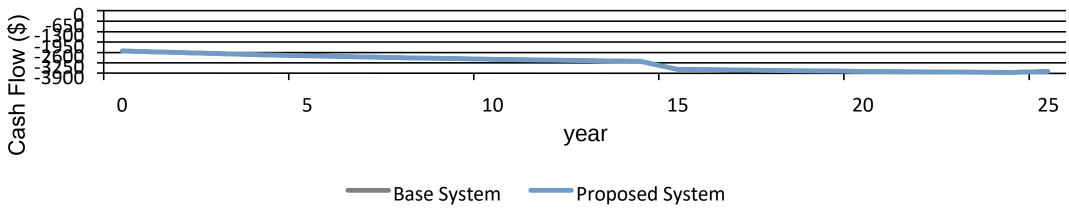
Proposed Annual Nominal Cash Flows



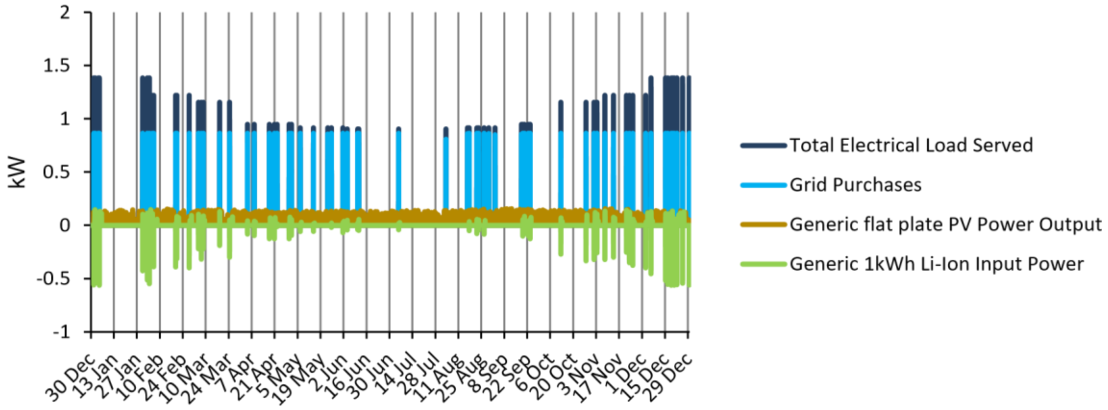
Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts:



7.5 System Simulation Report

File: Simulation 3 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £4,350.11

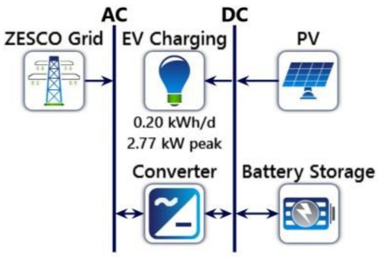
Levelized Cost of Energy (£/kWh): £1.17

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

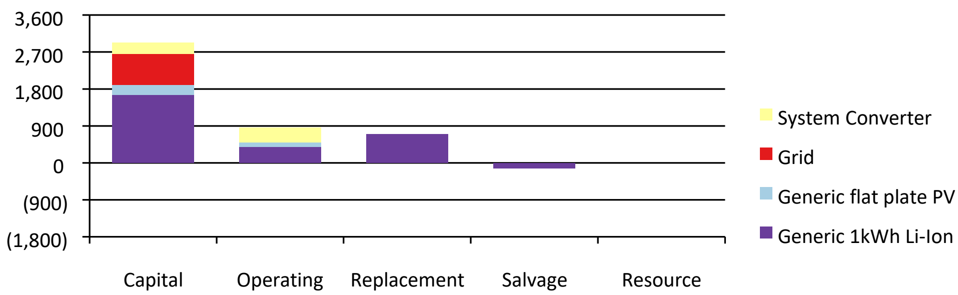
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	3	strings
System converter	System Converter	0.556	kW
Grid	Grid	0.700	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



Net Present Costs

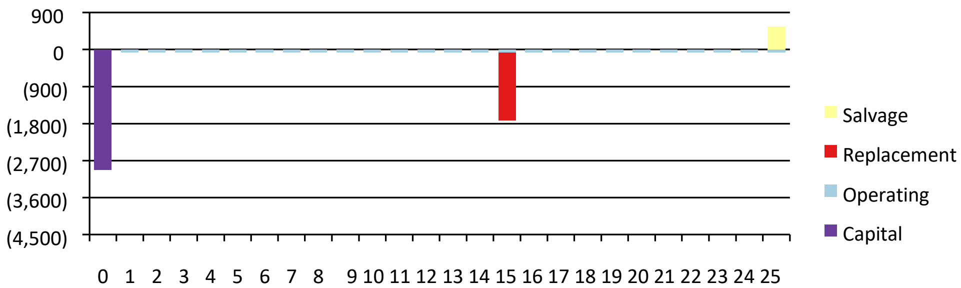
Name	Capital	Operating	Replacement	Salvage	Resource	Total

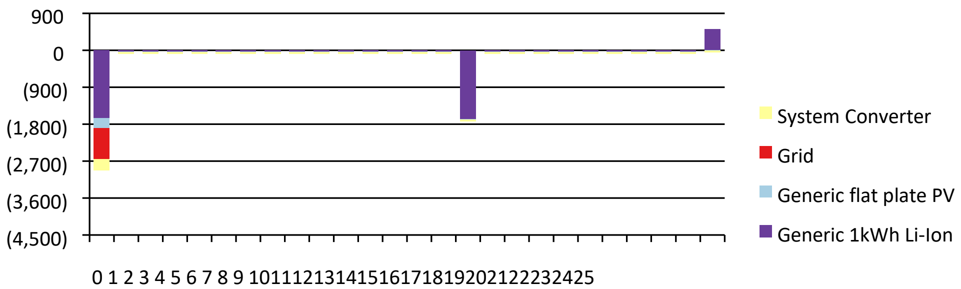
Generic 1kWh Li-Ion	£1,650	£387.83	£700.05	-£131.76	£0.00	£2,606
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79
Grid	£753.00	£5.33	£0.00	£0.00	£0.00	£758.33
System Converter	£277.78	£359.10	£0.00	£0.00	£0.00	£636.88
System	£2,925	£857.29	£700.05	-£131.76	£0.00	£4,350

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£127.63	£30.00	£54.15	-£10.19	£0.00	£201.59
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
Grid	£58.25	£0.412	£0.00	£0.00	£0.00	£58.66
System Converter	£21.49	£27.78	£0.00	£0.00	£0.00	£49.27
System	£226.23	£66.31	£54.15	-£10.19	£0.00	£336.50

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0.535	kWh/yr

Quantity	Value	Units
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0.0350	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	87.5
Grid Purchases	38.0	12.5
Total	305	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	25.3
Deferrable Load	0	0
Grid Sales	215	74.7
Total	288	100

PV: Generic flat plate PV

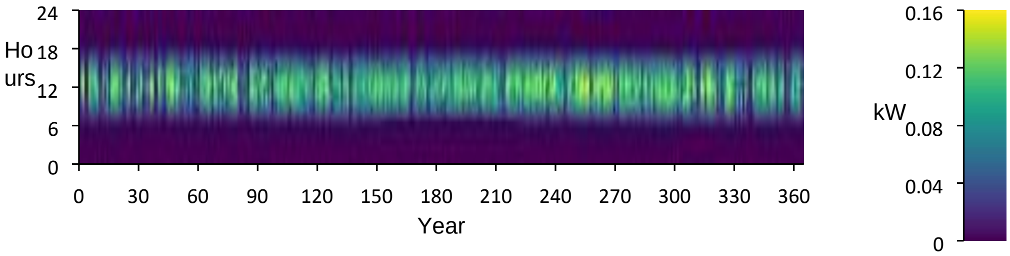
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	3.00	qty.
String Size	1.00	batteries
Strings in Parallel	3.00	strings
Bus Voltage	6.00	V

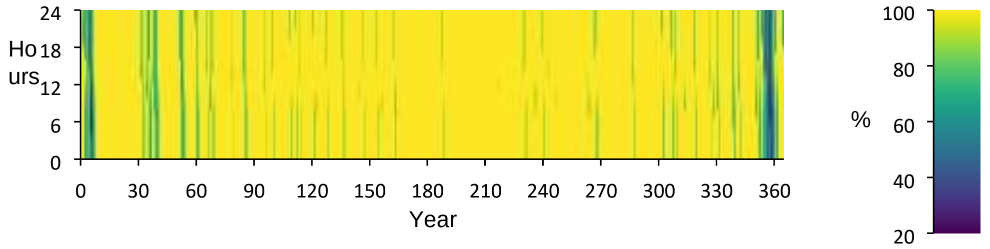
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	36.4	kWh/yr
Energy Out	33.5	kWh/yr
Storage Depletion	0.871	kWh/yr
Losses	3.68	kWh/yr
Annual Throughput	35.4	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	289	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	3.00	kWh
Usable Nominal Capacity	2.40	kWh
Lifetime Throughput	530	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

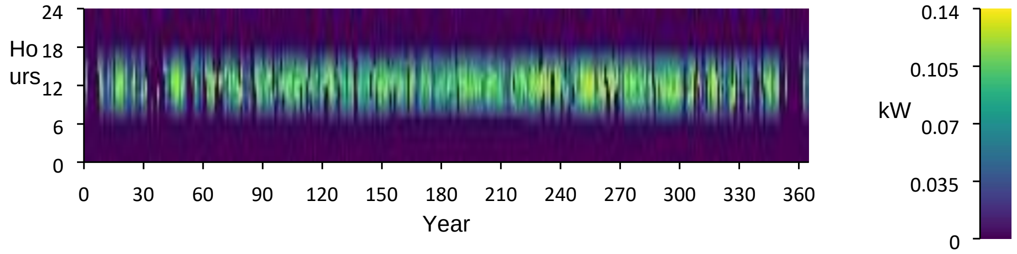
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	3,667	hrs/yr
Energy Out	215	kWh/yr
Energy In	227	kWh/yr
Losses	11.3	kWh/yr

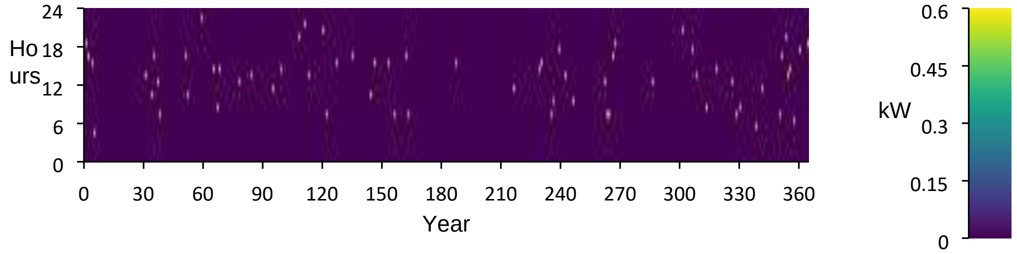
System Converter Statistics

Quantity	Value	Units
Capacity	0.556	kW
Mean Output	0.0246	kW
Minimum Output	0	kW
Maximum Output	0.130	kW
Capacity Factor	4.43	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0.585	£0.00	£0.0491
February	0	0	0	0.585	£0.00	£0.0491
March	0	0	0	0.585	£0.00	£0.0491
April	0	0	0	0.585	£0.00	£0.0491
May	0	0	0	0.585	£0.00	£0.0491
June	0	0	0	0.585	£0.00	£0.0491
July	0	0	0	0.585	£0.00	£0.0491
August	0	0	0	0.585	£0.00	£0.0491
September	0	0	0	0.585	£0.00	£0.0491
October	0	0	0	0.585	£0.00	£0.0491
November	0	0	0	0.585	£0.00	£0.0491
December	0	0	0	0.585	£0.00	£0.0491
Annual	0	0	0	0.585	£0.00	£0.589

Grid rate: Rate

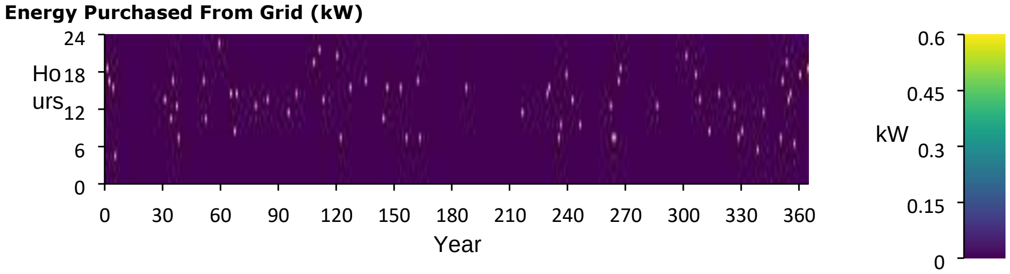
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2.34	14.2	-11.8	0	-£0.0118	£0.00
February	4.09	11.2	-7.11	0	-£0.00711	£0.00
March	3.51	16.5	-13.0	0	-£0.0130	£0.00
April	2.92	18.8	-15.8	0	-£0.0158	£0.00
May	3.51	19.5	-16.0	0	-£0.0160	£0.00
June	2.34	19.1	-16.8	0	-£0.0168	£0.00
July	0.585	22.3	-21.7	0	-£0.0217	£0.00

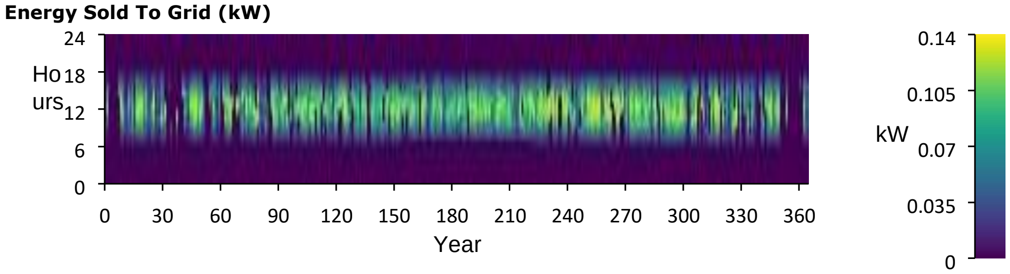
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
August	4.09	21.6	-17.5	0	-£0.0175	£0.00
September	3.51	21.5	-18.0	0	-£0.0180	£0.00
October	1.17	22.8	-21.6	0	-£0.0216	£0.00
November	4.09	16.9	-12.8	0	-£0.0128	£0.00
December	5.85	11.2	-5.34	0	-£0.00535	£0.00
Annual	38.0	215	-177	0	-£0.177	£0.00

Grid rate: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	2.34	14.2	-11.8	0.585	-£0.0118	£0.0491
February	4.09	11.2	-7.11	0.585	-£0.00711	£0.0491
March	3.51	16.5	-13.0	0.585	-£0.0130	£0.0491
April	2.92	18.8	-15.8	0.585	-£0.0158	£0.0491
May	3.51	19.5	-16.0	0.585	-£0.0160	£0.0491
June	2.34	19.1	-16.8	0.585	-£0.0168	£0.0491
July	0.585	22.3	-21.7	0.585	-£0.0217	£0.0491
August	4.09	21.6	-17.5	0.585	-£0.0175	£0.0491
September	3.51	21.5	-18.0	0.585	-£0.0180	£0.0491
October	1.17	22.8	-21.6	0.585	-£0.0216	£0.0491
November	4.09	16.9	-12.8	0.585	-£0.0128	£0.0491

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
December	5.85	11.2	-5.34	0.585	-£0.00535	£0.0491
Annual	38.0	215	-177	0.585	-£0.177	£0.589

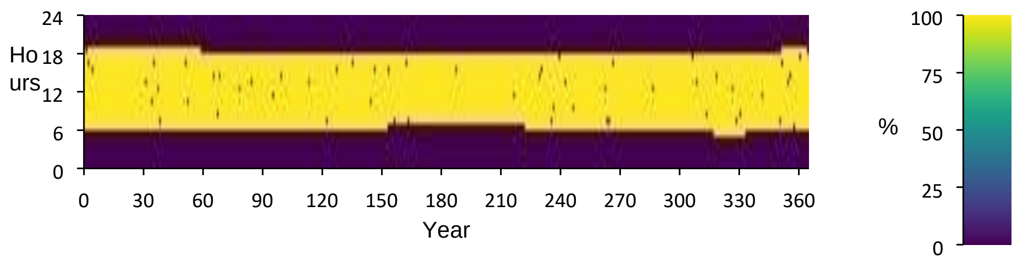




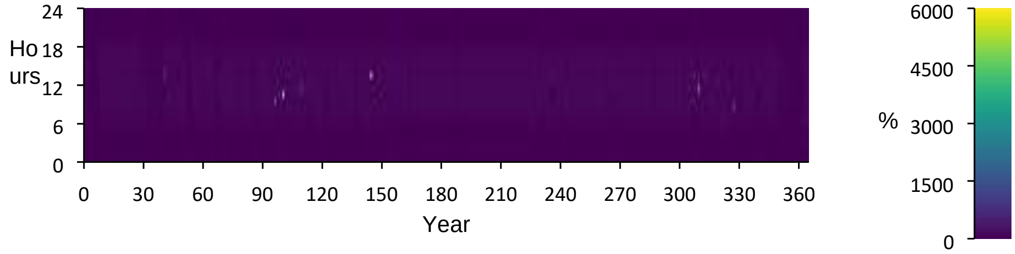
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	92.6	%
Total renewable production divided by generation	87.5	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	5,787	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

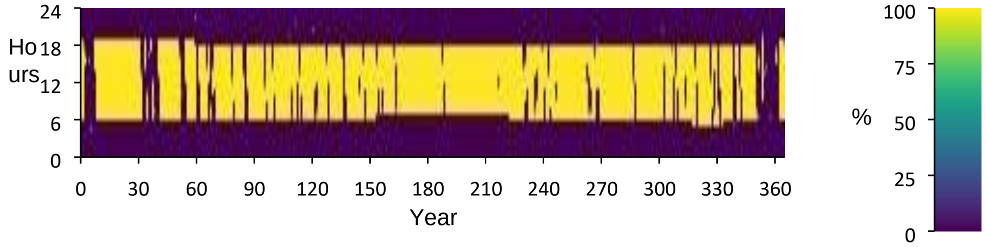
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

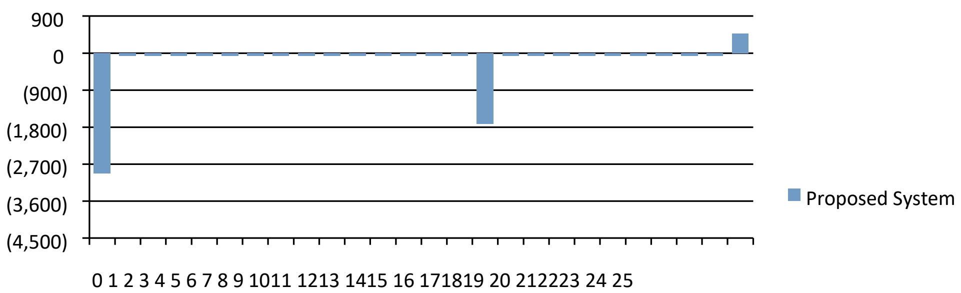
IRR (%):**N/A**

Discounted payback (yr):**N/A**

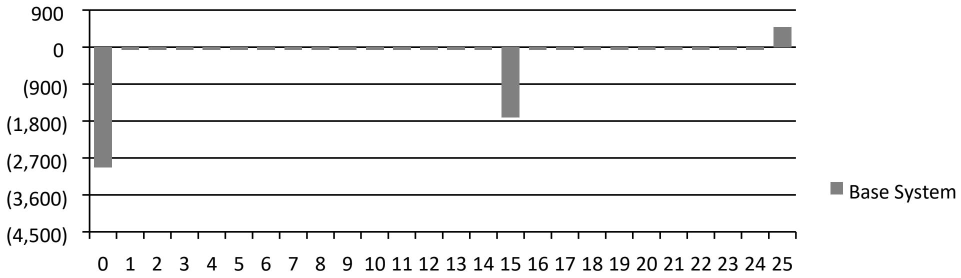
Simple payback (yr):**N/A**

	Base System	Proposed System
Net Present Cost	£4,350	£4,350
CAPEX	£2,925	£2,925
OPEX	£110.28	£110.28
LCOE (per kWh)	£1.17	£1.17
CO2 Emitted (kg/yr)	23.1	23.1
Fuel Consumption (L/yr)	0	0

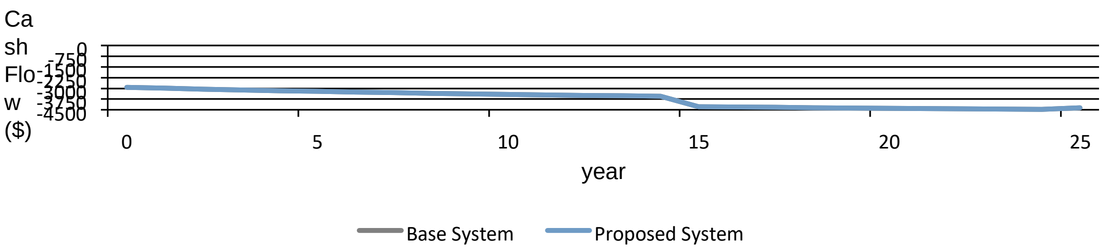
Proposed Annual Nominal Cash Flows



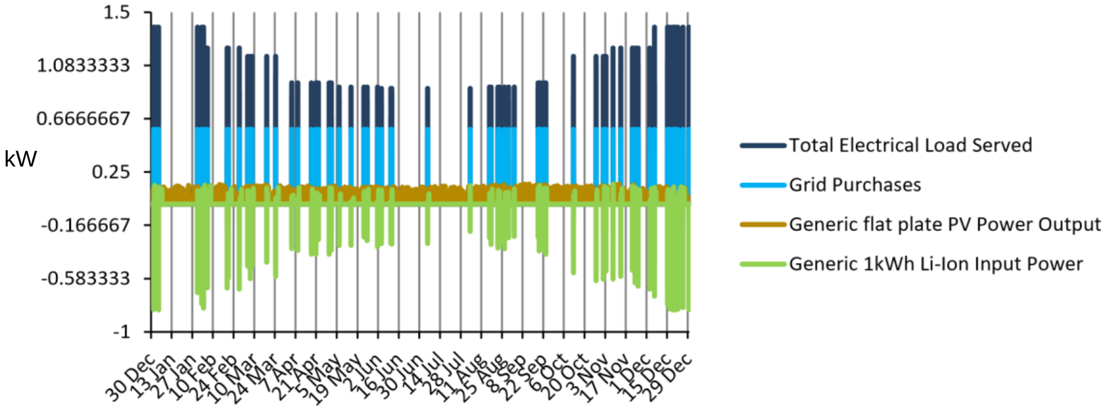
Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts:



7.6 System Simulation Report

File: Simulation 4 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £4,994.75

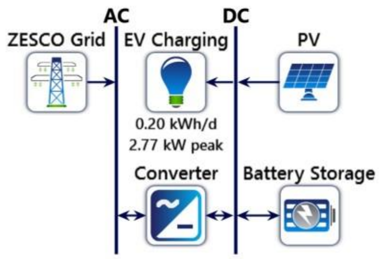
Levelized Cost of Energy (£/kWh): £1.40

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

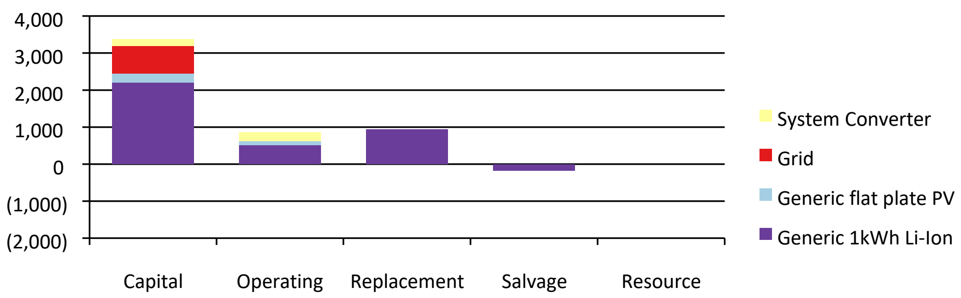
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	4	strings
System converter	System Converter	0.362	kW
Grid	Grid	0.500	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



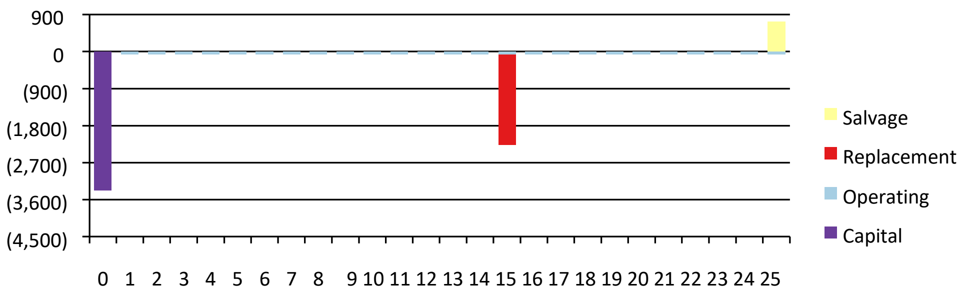
Net Present Costs

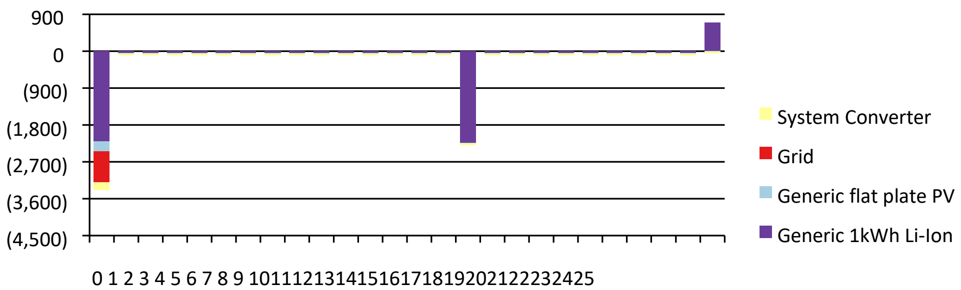
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£2,200	£517.10	£933.40	-£175.68	£0.00	£3,475
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79
Grid	£753.00	£2.68	£0.00	£0.00	£0.00	£755.68
System Converter	£181.21	£234.26	£0.00	£0.00	£0.00	£415.46
System	£3,378	£859.07	£933.40	-£175.68	£0.00	£4,995

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£170.18	£40.00	£72.20	-£13.59	£0.00	£268.79
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
Grid	£58.25	£0.207	£0.00	£0.00	£0.00	£58.45
System Converter	£14.02	£18.12	£0.00	£0.00	£0.00	£32.14
System	£261.30	£66.45	£72.20	-£13.59	£0.00	£386.37

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0.515	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0.0359	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	91.5
Grid Purchases	24.8	8.50
Total	292	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	26.5
Deferrable Load	0	0
Grid Sales	202	73.5
Total	275	100

PV: Generic flat plate PV

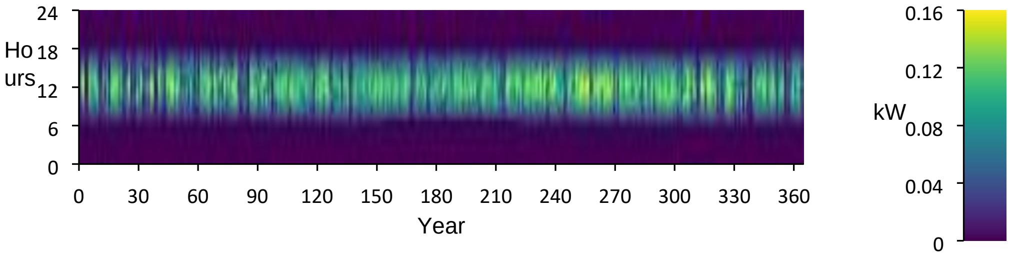
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	4.00	qty.
String Size	1.00	batteries
Strings in Parallel	4.00	strings
Bus Voltage	6.00	V

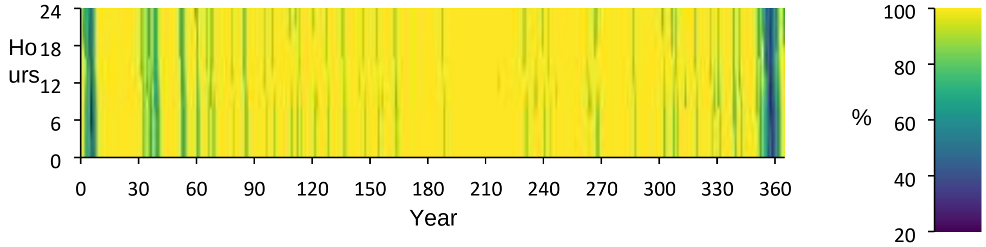
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	50.1	kWh/yr
Energy Out	46.1	kWh/yr
Storage Depletion	1.07	kWh/yr
Losses	5.06	kWh/yr
Annual Throughput	48.6	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	385	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	4.00	kWh
Usable Nominal Capacity	3.20	kWh
Lifetime Throughput	729	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

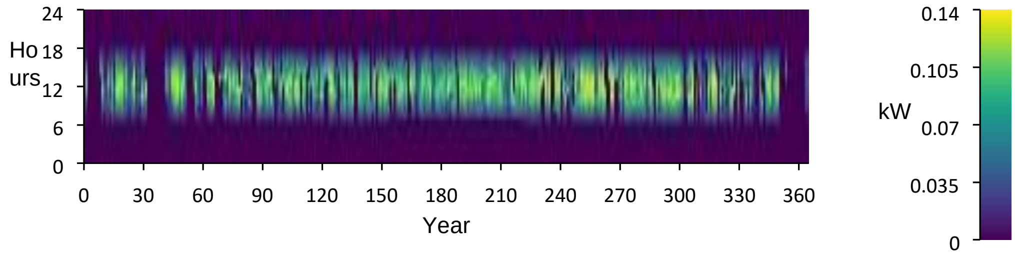
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	3,468	hrs/yr
Energy Out	202	kWh/yr
Energy In	213	kWh/yr
Losses	10.7	kWh/yr

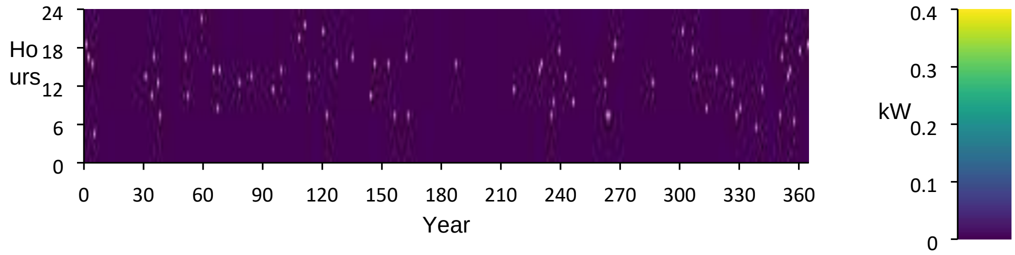
System Converter Statistics

Quantity	Value	Units
Capacity	0.362	kW
Mean Output	0.0231	kW
Minimum Output	0	kW
Maximum Output	0.130	kW
Capacity Factor	6.37	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0.381	£0.00	£0.0320
February	0	0	0	0.381	£0.00	£0.0320
March	0	0	0	0.381	£0.00	£0.0320
April	0	0	0	0.381	£0.00	£0.0320
May	0	0	0	0.381	£0.00	£0.0320
June	0	0	0	0.381	£0.00	£0.0320
July	0	0	0	0.381	£0.00	£0.0320
August	0	0	0	0.381	£0.00	£0.0320
September	0	0	0	0.381	£0.00	£0.0320
October	0	0	0	0.381	£0.00	£0.0320
November	0	0	0	0.381	£0.00	£0.0320
December	0	0	0	0.381	£0.00	£0.0320
Annual	0	0	0	0.381	£0.00	£0.385

Grid rate: Rate

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	1.53	13.3	-11.8	0	-£0.0118	£0.00
February	2.67	9.77	-7.10	0	-£0.00710	£0.00
March	2.29	15.3	-13.0	0	-£0.0130	£0.00
April	1.91	17.7	-15.8	0	-£0.0158	£0.00
May	2.29	18.3	-16.0	0	-£0.0160	£0.00
June	1.53	18.3	-16.8	0	-£0.0168	£0.00

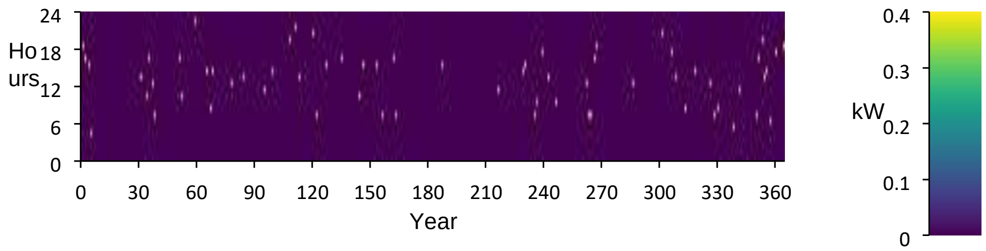
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
July	0.381	22.1	-21.7	0	-£0.0217	£0.00
August	2.67	20.4	-17.7	0	-£0.0177	£0.00
September	2.29	20.1	-17.8	0	-£0.0178	£0.00
October	0.763	22.4	-21.6	0	-£0.0216	£0.00
November	2.67	15.4	-12.8	0	-£0.0128	£0.00
December	3.81	9.36	-5.54	0	-£0.00554	£0.00
Annual	24.8	202	-178	0	-£0.178	£0.00

Grid rate: All

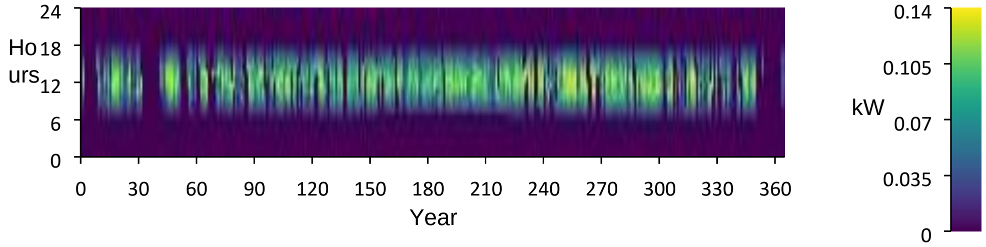
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	1.53	13.3	-11.8	0.381	-£0.0118	£0.0320
February	2.67	9.77	-7.10	0.381	-£0.00710	£0.0320
March	2.29	15.3	-13.0	0.381	-£0.0130	£0.0320
April	1.91	17.7	-15.8	0.381	-£0.0158	£0.0320
May	2.29	18.3	-16.0	0.381	-£0.0160	£0.0320
June	1.53	18.3	-16.8	0.381	-£0.0168	£0.0320
July	0.381	22.1	-21.7	0.381	-£0.0217	£0.0320
August	2.67	20.4	-17.7	0.381	-£0.0177	£0.0320
September	2.29	20.1	-17.8	0.381	-£0.0178	£0.0320
October	0.763	22.4	-21.6	0.381	-£0.0216	£0.0320

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
November	2.67	15.4	-12.8	0.381	-£0.0128	£0.0320
December	3.81	9.36	-5.54	0.381	-£0.00554	£0.0320
Annual	24.8	202	-178	0.381	-£0.178	£0.385

Energy Purchased From Grid (kW)



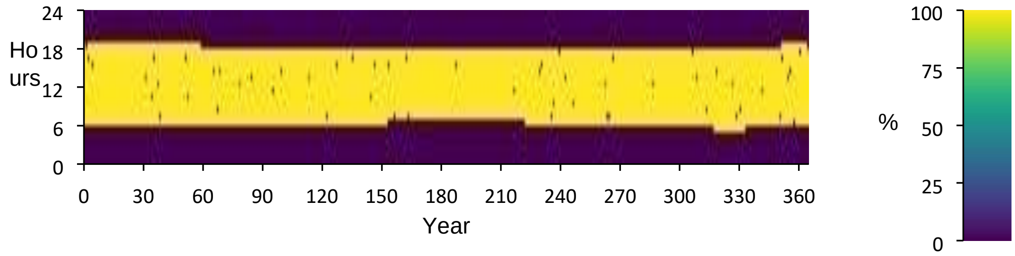
Energy Sold To Grid (kW)



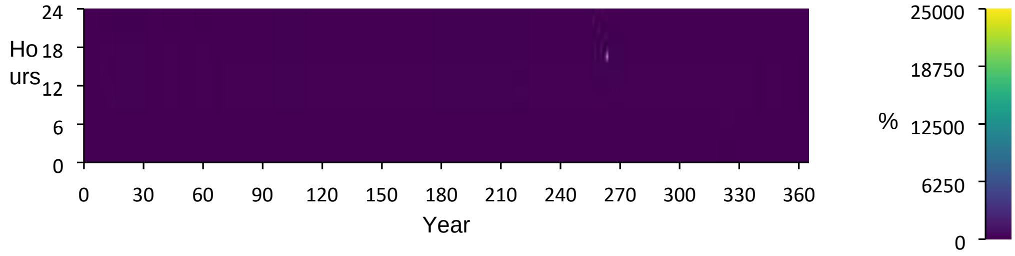
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	96.9	%
Total renewable production divided by generation	91.5	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	21,732	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

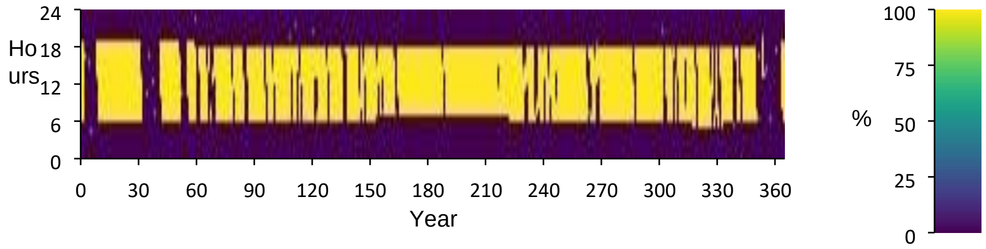
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

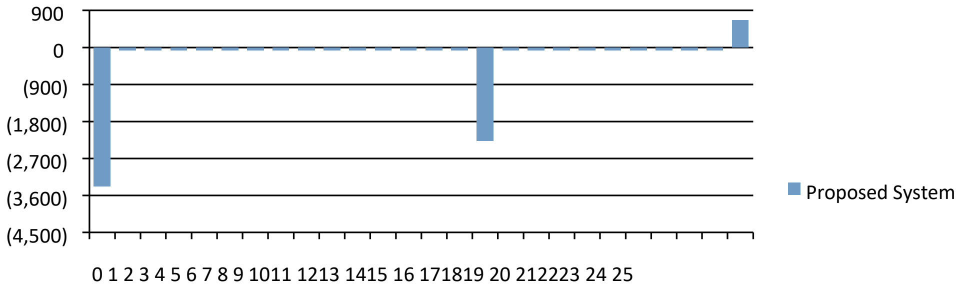
IRR (%):**N/A**

Discounted payback (yr):**N/A**

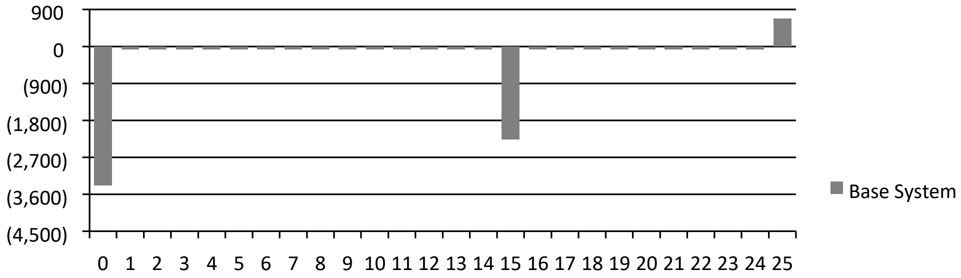
Simple payback (yr):**N/A**

	Base System	Proposed System
Net Present Cost	£4,995	£4,995
CAPEX	£3,378	£3,378
OPEX	£125.07	£125.07
LCOE (per kWh)	£1.40	£1.40
CO2 Emitted (kg/yr)	15.1	15.1
Fuel Consumption (L/yr)	0	0

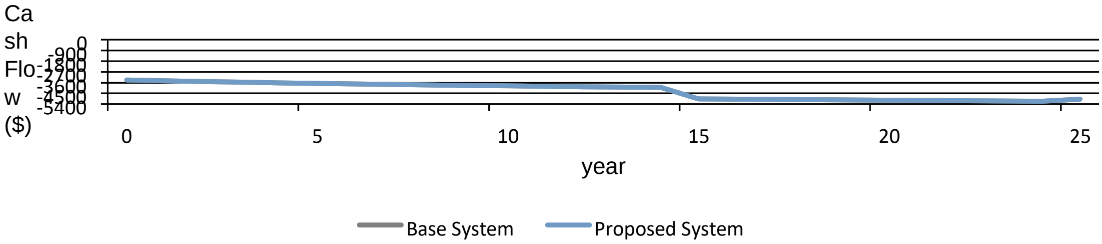
Proposed Annual Nominal Cash Flows



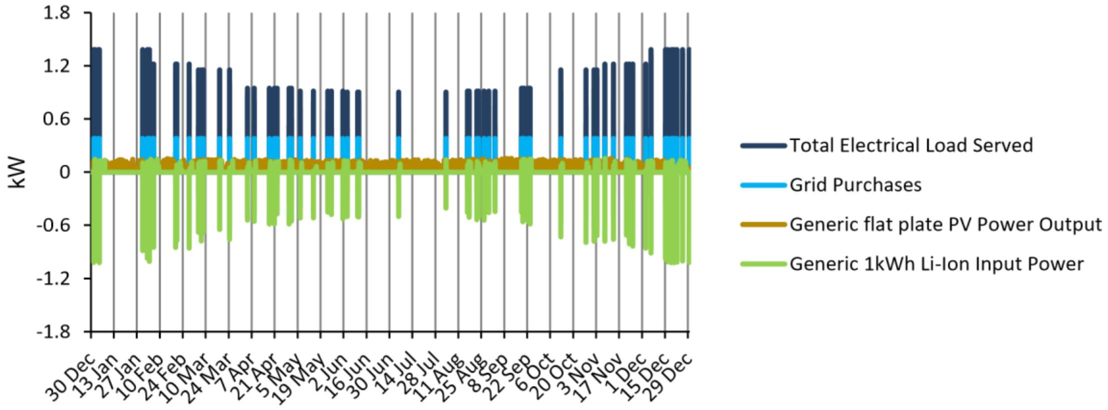
Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts:



7.7 System Simulation Report

File: Simulation 5 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £5,651.47

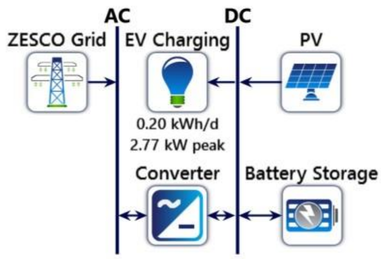
Levelized Cost of Energy (£/kWh): £1.66

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

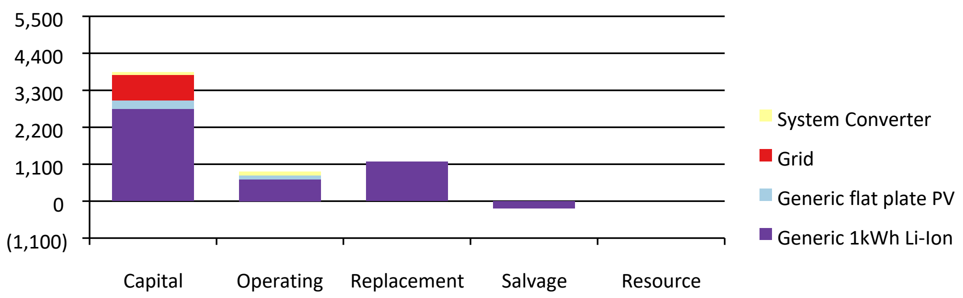
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	5	strings
System converter	System Converter	0.180	kW
Grid	Grid	0.300	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



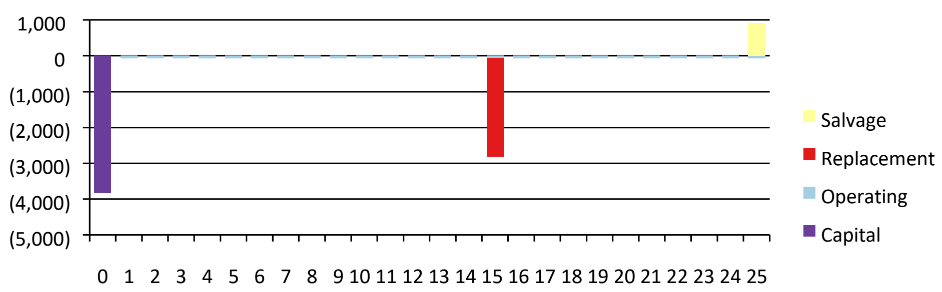
Net Present Costs

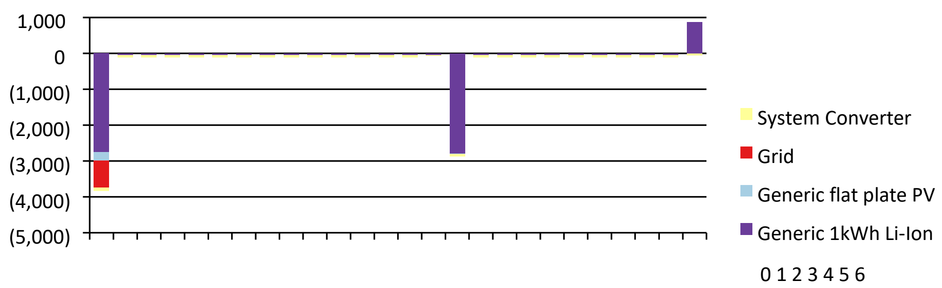
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£2,750	£646.38	£1,167	-£219.59	£0.00	£4,344
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79
Grid	£753.00	£0.161	£0.00	£0.00	£0.00	£753.16
System Converter	£89.84	£116.15	£0.00	£0.00	£0.00	£205.99
System	£3,837	£867.72	£1,167	-£219.59	£0.00	£5,651

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£212.72	£50.00	£90.25	-£16.99	£0.00	£335.99
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
Grid	£58.25	£0.0125	£0.00	£0.00	£0.00	£58.26
System Converter	£6.95	£8.98	£0.00	£0.00	£0.00	£15.93
System	£296.78	£67.12	£90.25	-£16.99	£0.00	£437.17

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	0.499	kWh/yr

Quantity	Value	Units
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0.0627	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	95.6
Grid Purchases	12.3	4.40
Total	279	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	27.7
Deferrable Load	0	0
Grid Sales	190	72.3
Total	263	100

PV: Generic flat plate PV

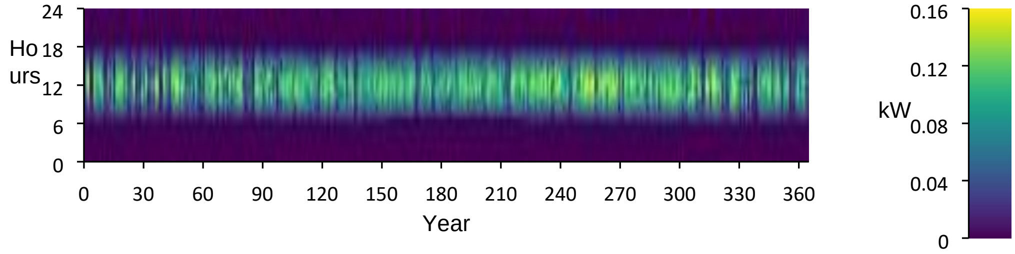
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	5.00	qty.
String Size	1.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	6.00	V

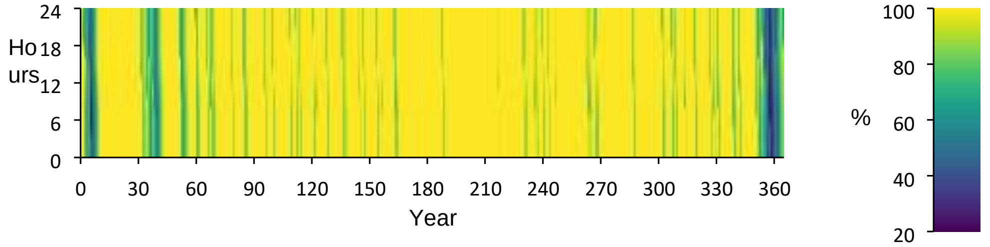
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	62.7	kWh/yr
Energy Out	58.0	kWh/yr
Storage Depletion	1.67	kWh/yr
Losses	6.35	kWh/yr
Annual Throughput	61.1	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	481	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	5.00	kWh
Usable Nominal Capacity	4.00	kWh
Lifetime Throughput	917	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

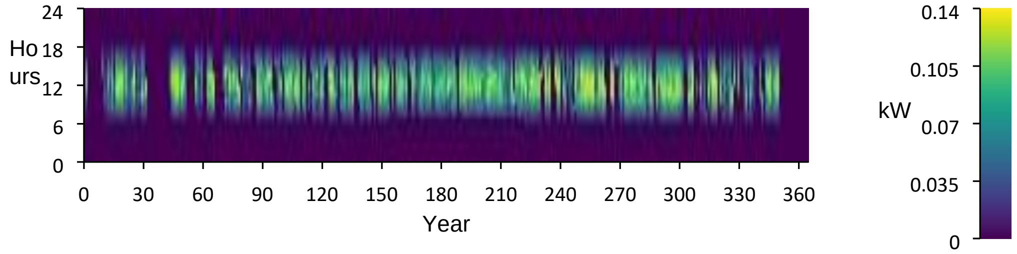
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	3,234	hrs/yr
Energy Out	190	kWh/yr
Energy In	200	kWh/yr
Losses	10.0	kWh/yr

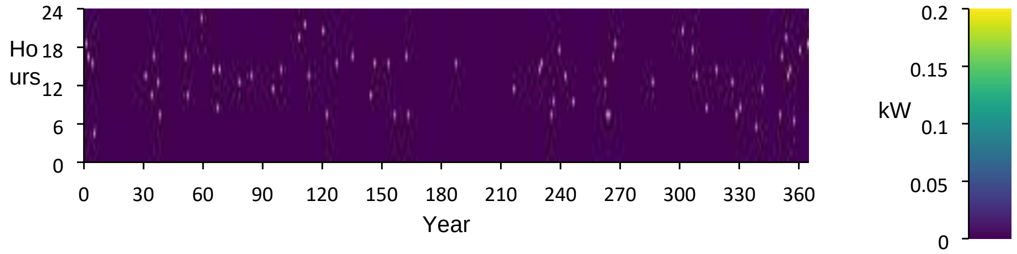
System Converter Statistics

Quantity	Value	Units
Capacity	0.180	kW
Mean Output	0.0217	kW
Minimum Output	0	kW
Maximum Output	0.130	kW
Capacity Factor	12.1	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0.189	£0.00	£0.0159
February	0	0	0	0.189	£0.00	£0.0159
March	0	0	0	0.189	£0.00	£0.0159
April	0	0	0	0.189	£0.00	£0.0159
May	0	0	0	0.189	£0.00	£0.0159
June	0	0	0	0.189	£0.00	£0.0159
July	0	0	0	0.189	£0.00	£0.0159
August	0	0	0	0.189	£0.00	£0.0159
September	0	0	0	0.189	£0.00	£0.0159
October	0	0	0	0.189	£0.00	£0.0159
November	0	0	0	0.189	£0.00	£0.0159
December	0	0	0	0.189	£0.00	£0.0159
Annual	0	0	0	0.189	£0.00	£0.191

Grid rate: Rate

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0.757	12.6	-11.8	0	-£0.0118	£0.00
February	1.32	8.42	-7.10	0	-£0.00710	£0.00
March	1.13	14.1	-13.0	0	-£0.0130	£0.00
April	0.946	16.8	-15.8	0	-£0.0158	£0.00
May	1.13	17.1	-16.0	0	-£0.0160	£0.00
June	0.757	17.6	-16.8	0	-£0.0168	£0.00

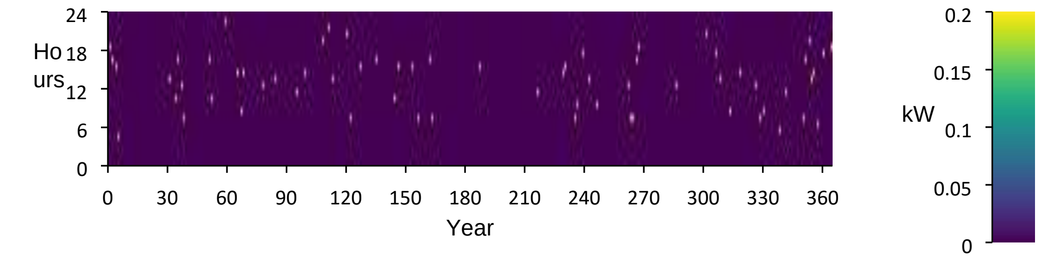
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
July	0.189	21.9	-21.7	0	-£0.0217	£0.00
August	1.32	19.2	-17.9	0	-£0.0179	£0.00
September	1.13	18.7	-17.6	0	-£0.0176	£0.00
October	0.378	22.0	-21.6	0	-£0.0216	£0.00
November	1.32	14.1	-12.8	0	-£0.0128	£0.00
December	1.89	8.03	-6.14	0	-£0.00614	£0.00
Annual	12.3	190	-178	0	-£0.178	£0.00

Grid rate: All

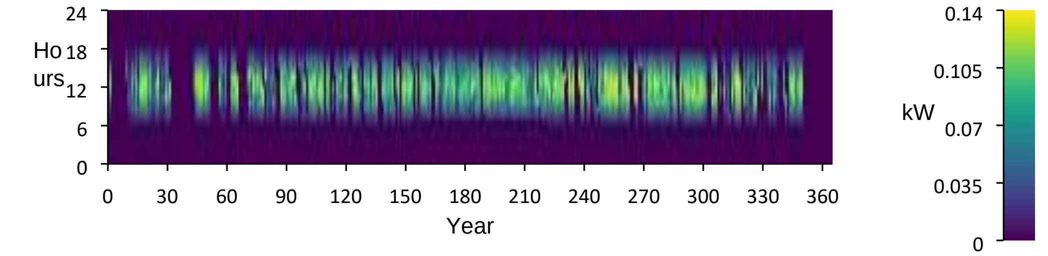
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0.757	12.6	-11.8	0.189	-£0.0118	£0.0159
February	1.32	8.42	-7.10	0.189	-£0.00710	£0.0159
March	1.13	14.1	-13.0	0.189	-£0.0130	£0.0159
April	0.946	16.8	-15.8	0.189	-£0.0158	£0.0159
May	1.13	17.1	-16.0	0.189	-£0.0160	£0.0159
June	0.757	17.6	-16.8	0.189	-£0.0168	£0.0159
July	0.189	21.9	-21.7	0.189	-£0.0217	£0.0159
August	1.32	19.2	-17.9	0.189	-£0.0179	£0.0159
September	1.13	18.7	-17.6	0.189	-£0.0176	£0.0159
October	0.378	22.0	-21.6	0.189	-£0.0216	£0.0159

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
November	1.32	14.1	-12.8	0.189	-£0.0128	£0.0159
December	1.89	8.03	-6.14	0.189	-£0.00614	£0.0159
Annual	12.3	190	-178	0.189	-£0.178	£0.191

Energy Purchased From Grid (kW)



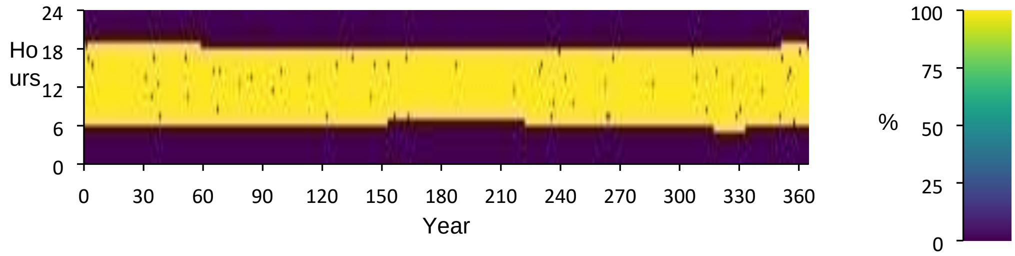
Energy Sold To Grid (kW)



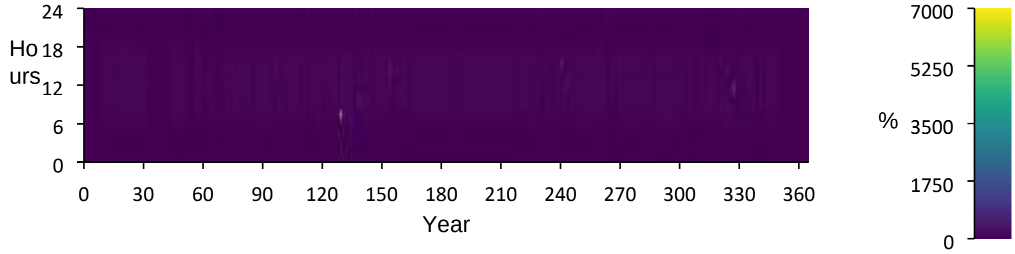
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	101	%
Total renewable production divided by generation	95.6	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	6,301	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

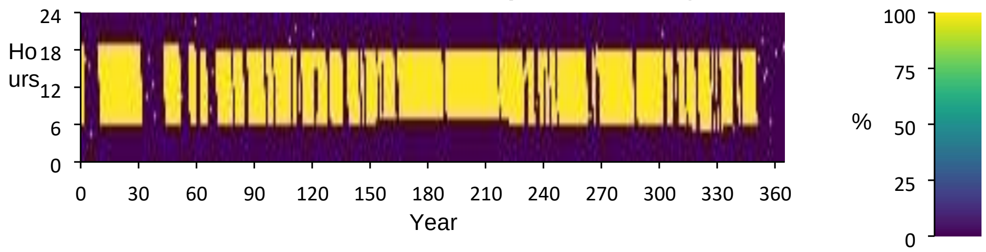
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

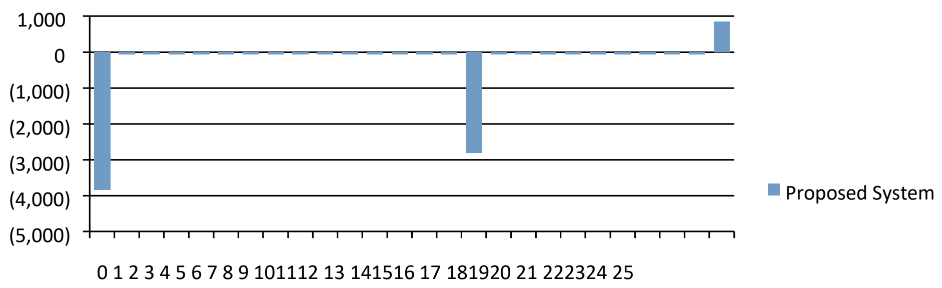
IRR (%):**N/A**

Discounted payback (yr):**N/A**

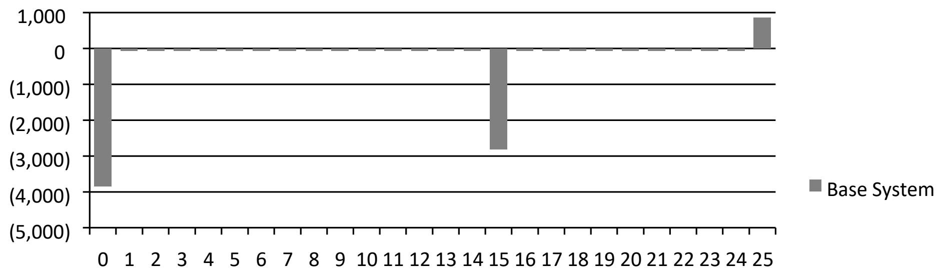
Simple payback (yr):**N/A**

	Base System	Proposed System
Net Present Cost	£5,651	£5,651
CAPEX	£3,837	£3,837
OPEX	£140.39	£140.39
LCOE (per kWh)	£1.66	£1.66
CO2 Emitted (kg/yr)	7.49	7.49
Fuel Consumption (L/yr)	0	0

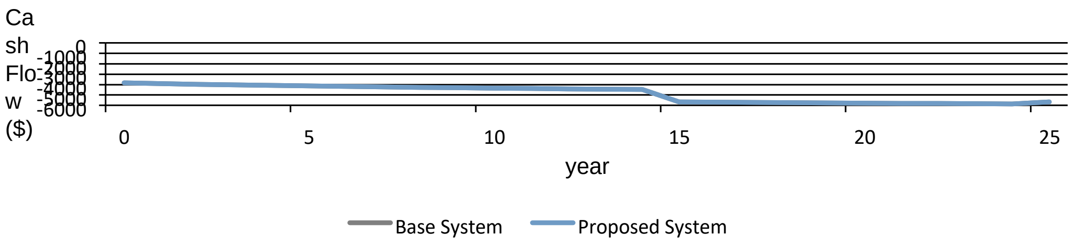
Proposed Annual Nominal Cash Flows



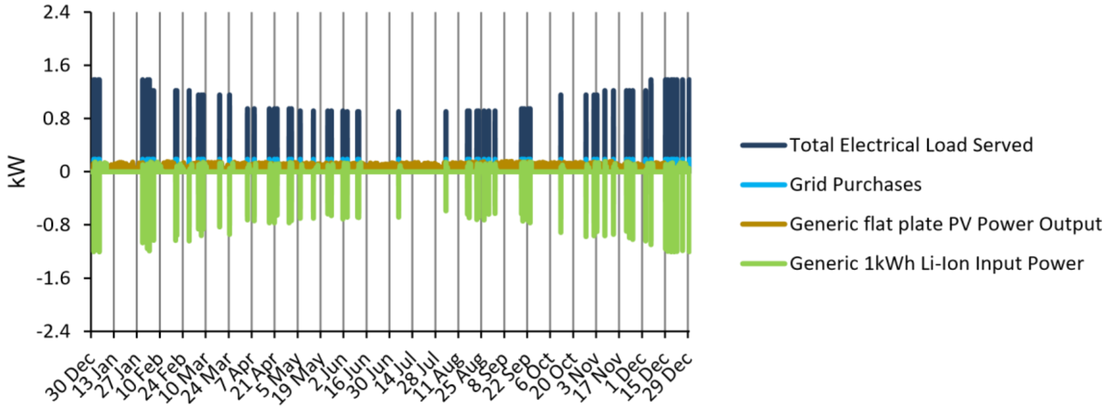
Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts:



7.8 System Simulation Report

File: Simulation 6 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £6,371.17

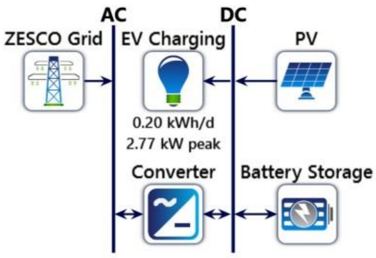
Levelized Cost of Energy (£/kWh): £2.60

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

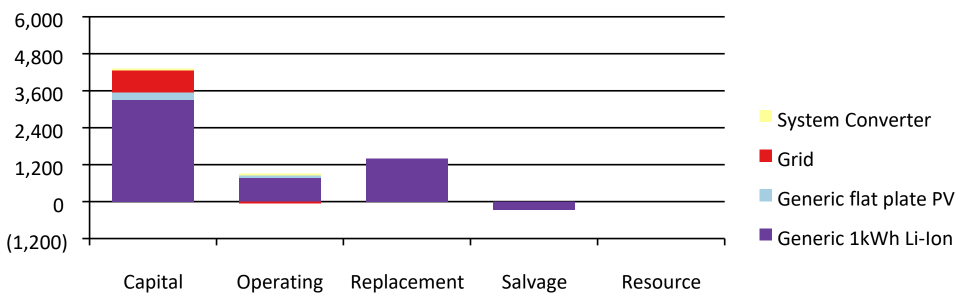
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	6	strings
System converter	System Converter	0.0505	kW
Grid	Grid	0.100	kW
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



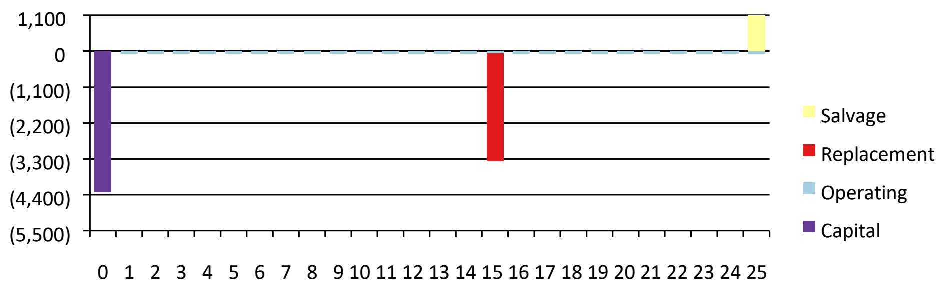
Net Present Costs

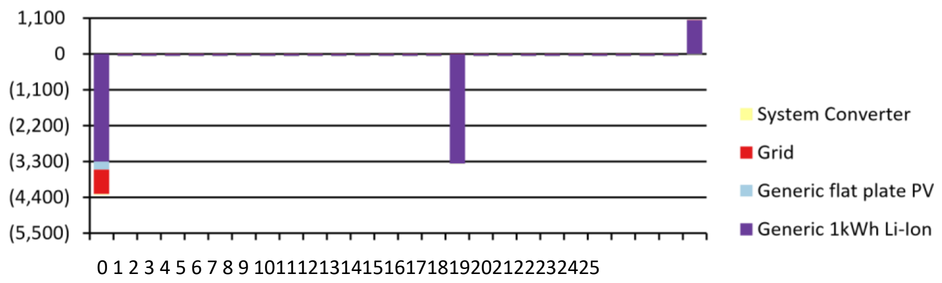
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£3,300	£775.65	£1,400	-£263.51	£0.00	£5,212
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79
Grid	£753.00	-£0.775	£0.00	£0.00	£0.00	£752.23
System Converter	£25.26	£32.66	£0.00	£0.00	£0.00	£57.92
System	£4,322	£912.57	£1,400	-£263.51	£0.00	£6,371

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£255.27	£60.00	£108.30	-£20.38	£0.00	£403.19
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
Grid	£58.25	-£0.0599	£0.00	£0.00	£0.00	£58.19
System Converter	£1.95	£2.53	£0.00	£0.00	£0.00	£4.48
System	£334.33	£70.59	£108.30	-£20.38	£0.00	£492.84

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	69.7	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0.0709	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	98.7
Grid Purchases	3.46	1.28
Total	270	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	38.4
Deferrable Load	0	0
Grid Sales	117	61.6
Total	190	100

PV: Generic flat plate PV

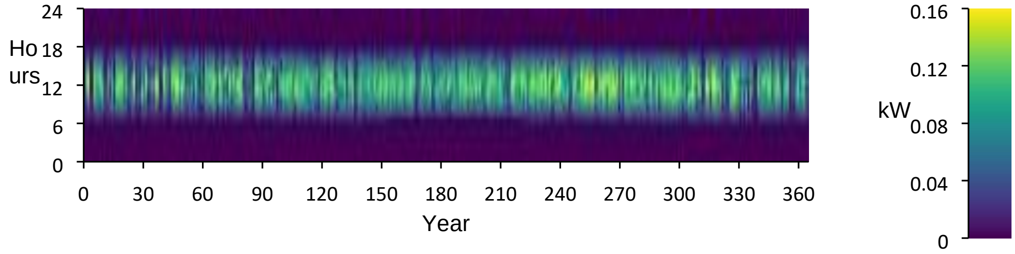
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	6.00	qty.
String Size	1.00	batteries
Strings in Parallel	6.00	strings
Bus Voltage	6.00	V

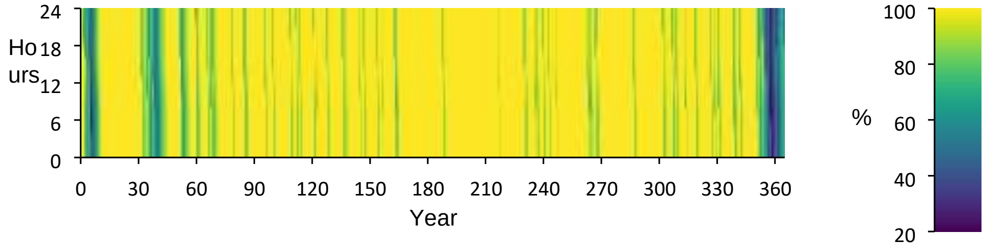
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	70.8	kWh/yr
Energy Out	66.4	kWh/yr
Storage Depletion	2.76	kWh/yr
Losses	7.23	kWh/yr
Annual Throughput	70.0	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	577	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	6.00	kWh
Usable Nominal Capacity	4.80	kWh
Lifetime Throughput	1,049	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

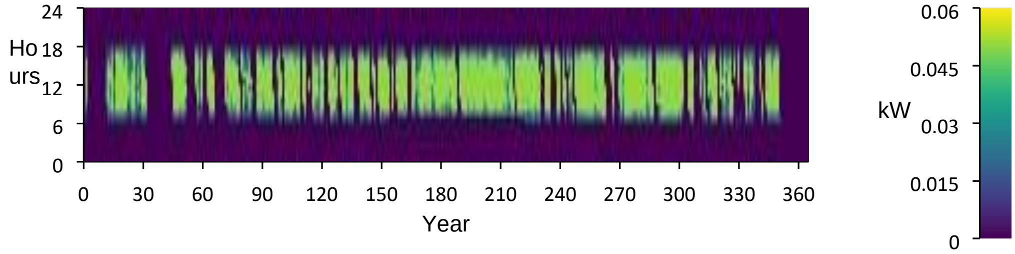
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	3,063	hrs/yr
Energy Out	117	kWh/yr
Energy In	123	kWh/yr
Losses	6.16	kWh/yr

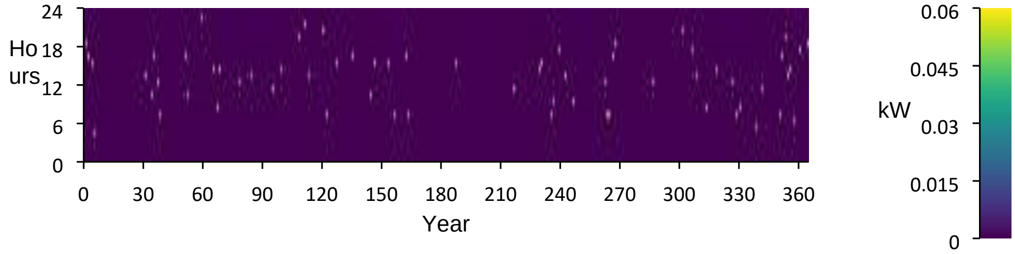
System Converter Statistics

Quantity	Value	Units
Capacity	0.0505	kW
Mean Output	0.0134	kW
Minimum Output	0	kW
Maximum Output	0.0505	kW
Capacity Factor	26.4	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Grid

Grid rate: Demand 1

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0	0	0	0.0532	£0.00	£0.00447
February	0	0	0	0.0532	£0.00	£0.00447
March	0	0	0	0.0532	£0.00	£0.00447
April	0	0	0	0.0532	£0.00	£0.00447
May	0	0	0	0.0532	£0.00	£0.00447
June	0	0	0	0.0532	£0.00	£0.00447
July	0	0	0	0.0532	£0.00	£0.00447
August	0	0	0	0.0532	£0.00	£0.00447
September	0	0	0	0.0532	£0.00	£0.00447
October	0	0	0	0.0532	£0.00	£0.00447
November	0	0	0	0.0532	£0.00	£0.00447
December	0	0	0	0.0532	£0.00	£0.00447
Annual	0	0	0	0.0532	£0.00	£0.0536

Grid rate: Rate

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0.213	8.38	-8.17	0	-£0.00817	£0.00
February	0.372	4.77	-4.40	0	-£0.00440	£0.00
March	0.319	8.69	-8.37	0	-£0.00838	£0.00
April	0.266	10.5	-10.2	0	-£0.0102	£0.00
May	0.319	10.5	-10.1	0	-£0.0101	£0.00
June	0.213	11.2	-11.0	0	-£0.0110	£0.00

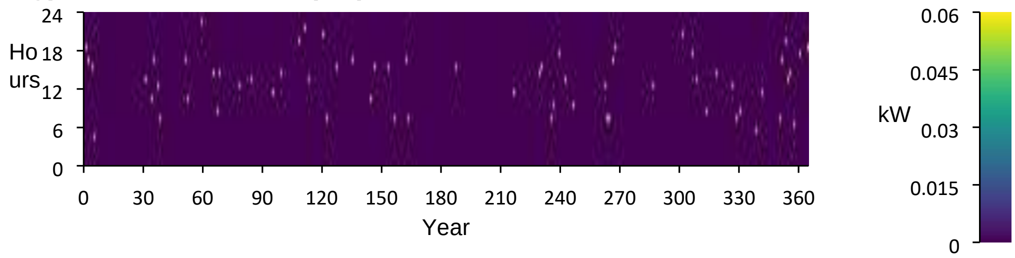
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
July	0.0532	13.7	-13.7	0	-£0.0137	£0.00
August	0.372	11.4	-11.0	0	-£0.0110	£0.00
September	0.319	10.9	-10.6	0	-£0.0106	£0.00
October	0.106	13.4	-13.3	0	-£0.0133	£0.00
November	0.372	8.45	-8.08	0	-£0.00808	£0.00
December	0.532	5.16	-4.63	0	-£0.00463	£0.00
Annual	3.46	117	-114	0	-£0.114	£0.00

Grid rate: All

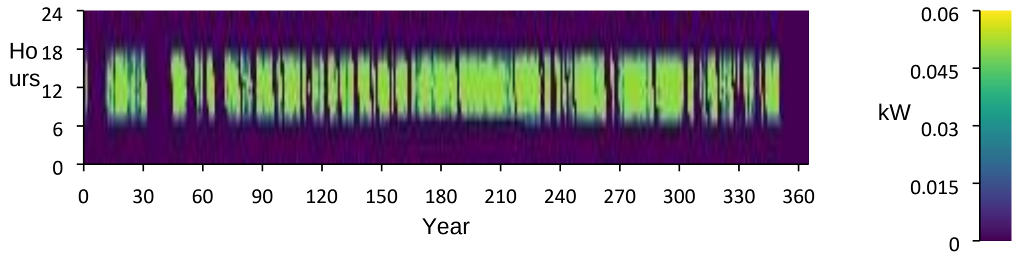
Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
January	0.213	8.38	-8.17	0.0532	-£0.00817	£0.00447
February	0.372	4.77	-4.40	0.0532	-£0.00440	£0.00447
March	0.319	8.69	-8.37	0.0532	-£0.00838	£0.00447
April	0.266	10.5	-10.2	0.0532	-£0.0102	£0.00447
May	0.319	10.5	-10.1	0.0532	-£0.0101	£0.00447
June	0.213	11.2	-11.0	0.0532	-£0.0110	£0.00447
July	0.0532	13.7	-13.7	0.0532	-£0.0137	£0.00447
August	0.372	11.4	-11.0	0.0532	-£0.0110	£0.00447
September	0.319	10.9	-10.6	0.0532	-£0.0106	£0.00447

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Demand (kW)	Energy Charge	Demand Charge
October	0.106	13.4	-13.3	0.0532	-£0.0133	£0.00447
November	0.372	8.45	-8.08	0.0532	-£0.00808	£0.00447
December	0.532	5.16	-4.63	0.0532	-£0.00463	£0.00447
Annual	3.46	117	-114	0.0532	-£0.114	£0.0536

Energy Purchased From Grid (kW)



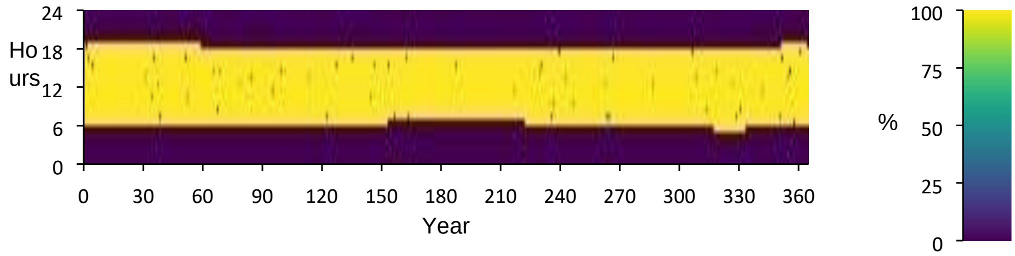
Energy Sold To Grid (kW)



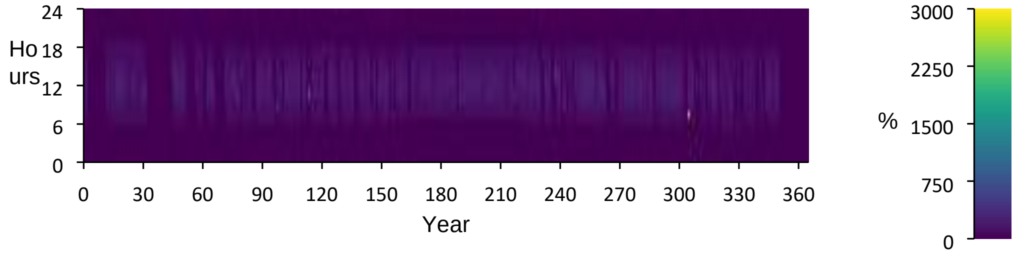
Renewable Summary

Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit
Total renewable production divided by load	141	%
Total renewable production divided by generation	98.7	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	2,889	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

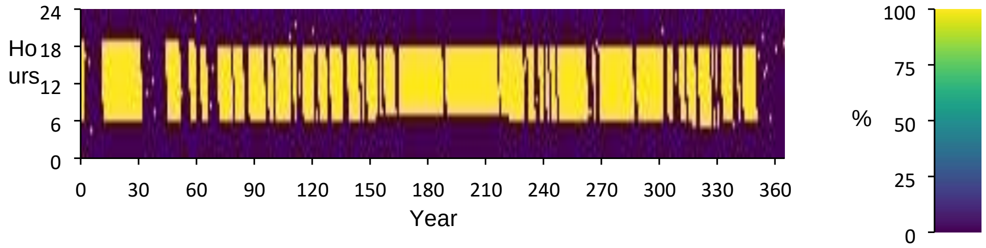
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

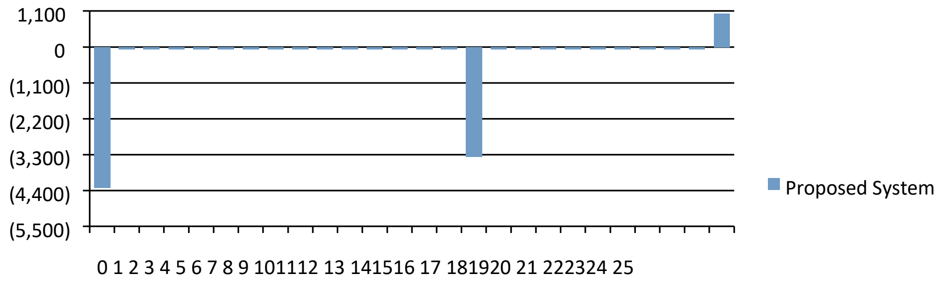
IRR (%):7.95

Discounted payback (yr):**14.7**

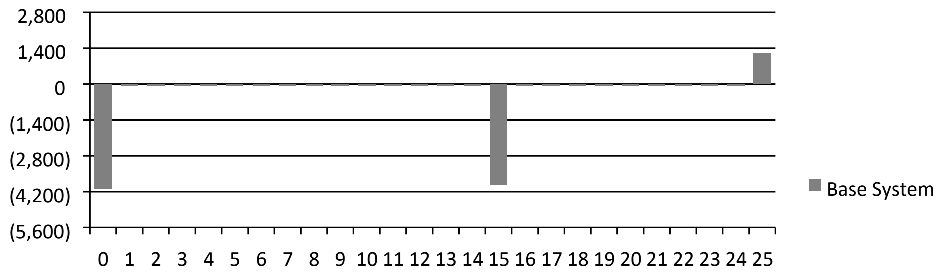
Simple payback (yr):**14.2**

	Base System	Proposed System
Net Present Cost	£6,430	£6,371
CAPEX	£4,094	£4,322
OPEX	£180.70	£158.51
LCOE (per kWh)	£6.83	£2.60
CO2 Emitted (kg/yr)	0	2.11
Fuel Consumption (L/yr)	0	0

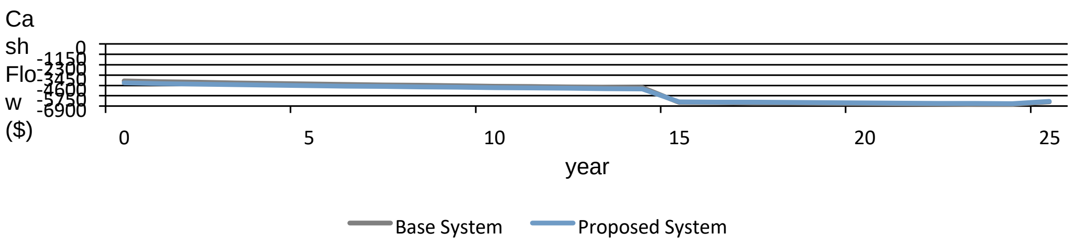
Proposed Annual Nominal Cash Flows



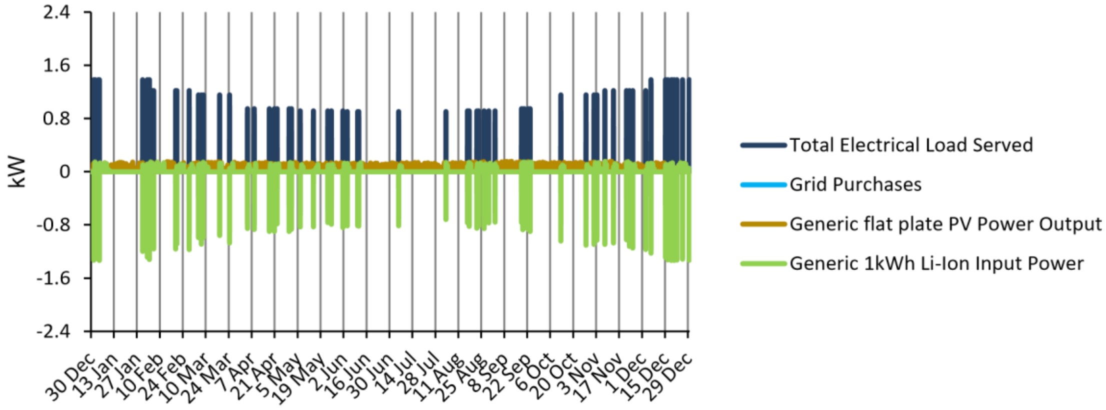
Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts:



7.9 System Simulation Report

File: Simulation 7 REV1.homer

Author: Felix Katiki Kusaloka

Location: J86F+X4V, Lusaka, Zambia (15°23.3'S, 28°19.4'E)

Total Net Present Cost: £6,429.73

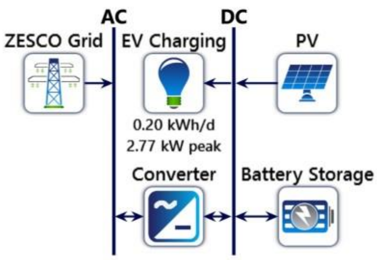
Levelized Cost of Energy (£/kWh): £6.83

Notes: Mobility Charging Hubs using Photovoltaic Arrays and Battery Storage – A Case Study of Zambia

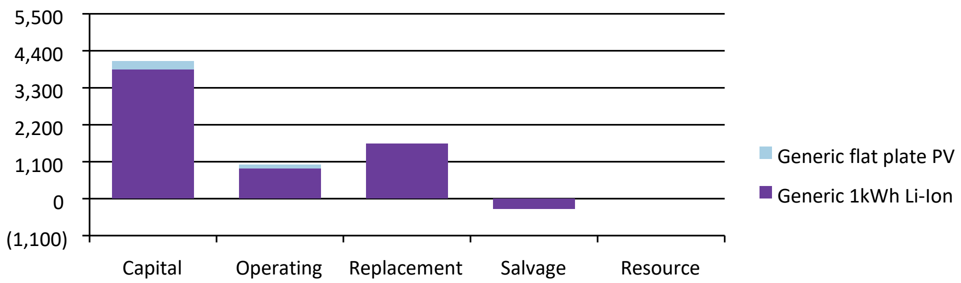
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	0.163	kW
Storage	Generic 1kWh Li-Ion	7	strings
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



Net Present Costs

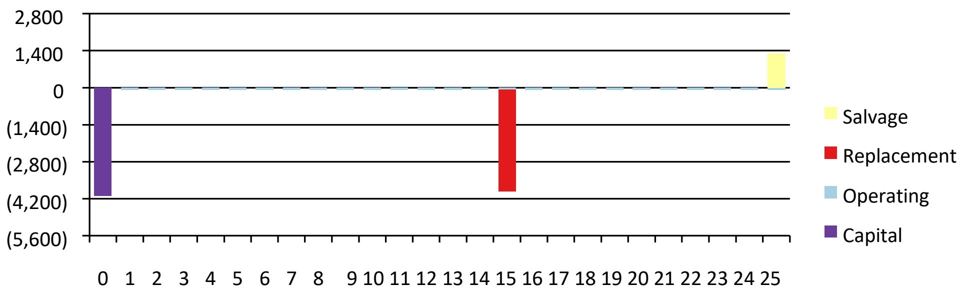
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£3,850	£904.93	£1,633	-£307.43	£0.00	£6,081
Generic flat plate PV	£243.75	£105.04	£0.00	£0.00	£0.00	£348.79

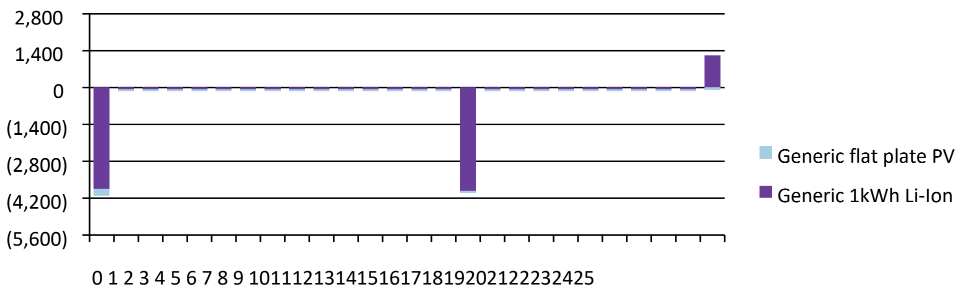
Name	Capital	Operating	Replacement	Salvage	Resource	Total
System	£4,094	£1,010	£1,633	-£307.43	£0.00	£6,430

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	£297.81	£70.00	£126.35	-£23.78	£0.00	£470.39
Generic flat plate PV	£18.86	£8.13	£0.00	£0.00	£0.00	£26.98
System	£316.67	£78.13	£126.35	-£23.78	£0.00	£497.37

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	190	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	267	100
Total	267	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	72.9	100
Deferrable Load	0	0
Total	72.9	100

PV: Generic flat plate PV

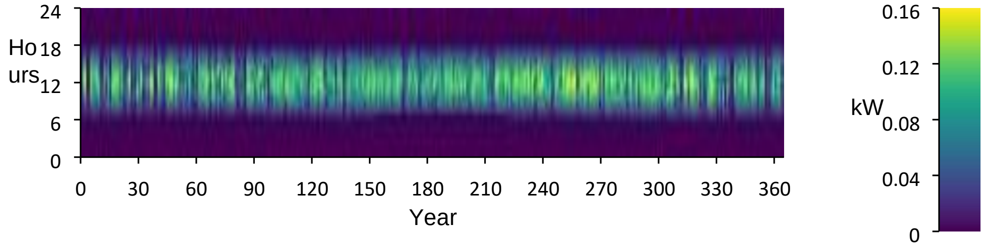
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.156	kW
PV Penetration	366	%
Hours of Operation	4,400	hrs/yr
Levelized Cost	0.101	£/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	0.163	kW
Mean Output	0.0305	kW
Mean Output	0.731	kWh/d
Capacity Factor	18.7	%
Total Production	267	kWh/yr

Generic flat plate PV Output (kW)



Storage: Generic 1kWh Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	7.00	qty.
String Size	1.00	batteries
Strings in Parallel	7.00	strings
Bus Voltage	6.00	V

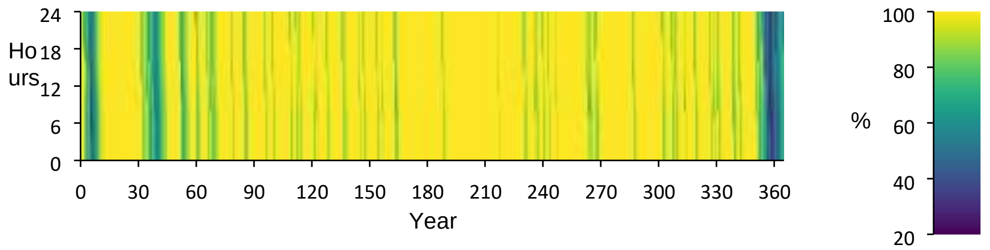
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	74.0	kWh/yr
Energy Out	69.7	kWh/yr
Storage Depletion	3.19	kWh/yr
Losses	7.57	kWh/yr
Annual Throughput	73.4	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	673	hr
Storage Wear Cost	0.193	£/kWh
Nominal Capacity	7.00	kWh
Usable Nominal Capacity	5.60	kWh
Lifetime Throughput	1,101	kWh
Expected Life	15.0	yr

Generic 1kWh Li-Ion State of Charge (%)

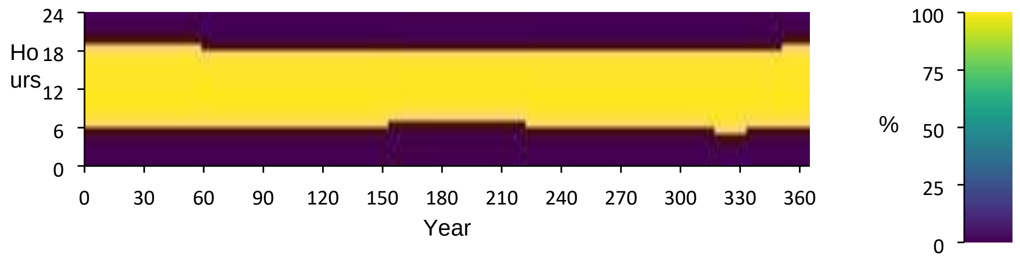


Renewable Summary

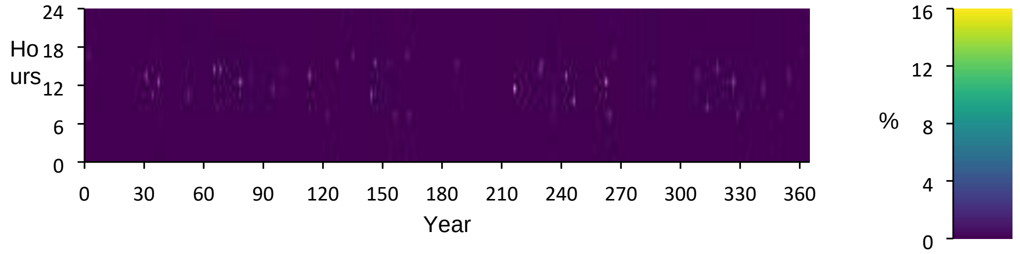
Capacity-based metrics	Value	Unit
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%
Energy-based metrics	Value	Unit

Capacity-based metrics	Value	Unit
Total renewable production divided by load	366	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	100	%
Peak values	Value	Unit
Renewable output divided by load (HOMER standard)	15.1	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

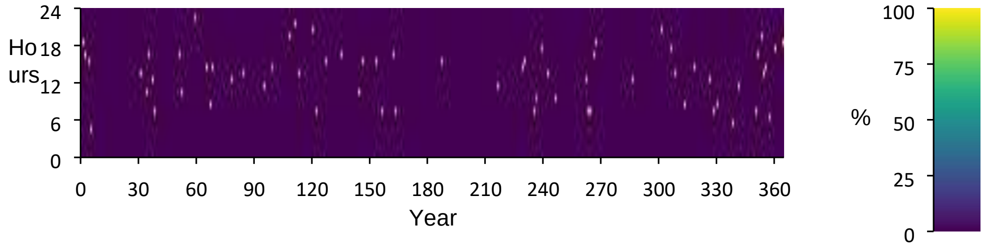
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

IRR (%):**N/A**

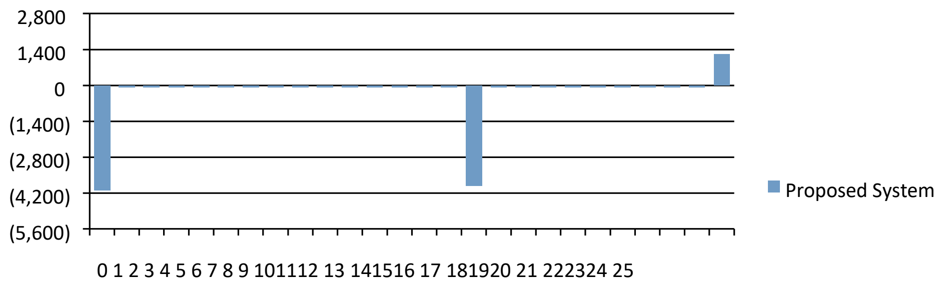
Discounted payback (yr):**N/A**

Simple payback (yr):**N/A**

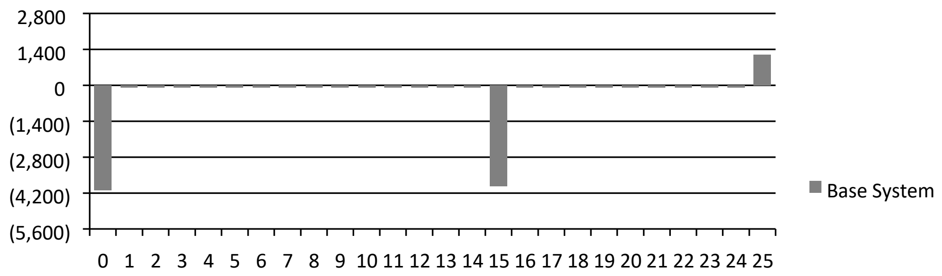
	Base System	Proposed System
Net Present Cost	£6,430	£6,430
CAPEX	£4,094	£4,094
OPEX	£180.70	£180.70

	Base System	Proposed System
LCOE (per kWh)	£6.83	£6.83
CO2 Emitted (kg/yr)	0	0
Fuel Consumption (L/yr)	0	0

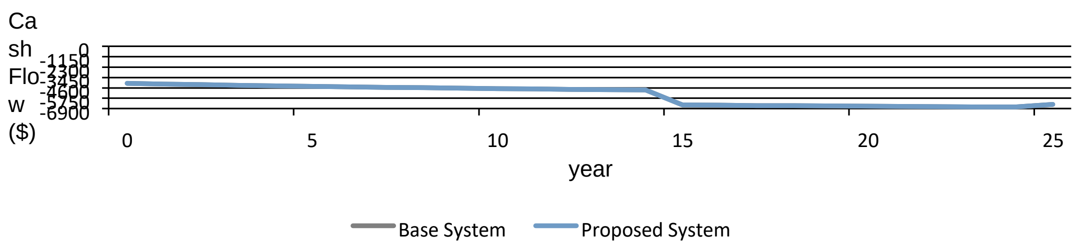
Proposed Annual Nominal Cash Flows



Base System Annual Nominal Cash Flows



Cumulative Discounted Cash Flows



Time series charts: