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MASTER THESIS

Master Level Thesis

European Solar Engineering School

No. 274 December 2020

Energy-Water-Agriculture Nexus Mini-grids to Power Rural Productive Hubs in Sub-Saharan Africa

A case study of Walta Jalala village in Bedeno Woreda of Ethiopia

Master thesis 30 credits, 2020
Solar Energy Engineering

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Course Code: EG3011

Examination date: 2020-12-18

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Abstract

The thrive to achieve Sustainable Development Goal 7 is never been easy, and numbers are still showing that Sub-Saharan Africa is lagging in access to electricity index. Most of the energy poor communities residing in the rural part of the region, this by itself is a conundrum with multifaceted implications. The high capital expenditure for renewable energy technologies, the low paying ability of the society in Sub-Saharan Africa, the unavailability of anchor customer's and so on needs new means of approaching the access problem. This study aims to enlighten policy makers on promoting energy as input to production than merely focusing on the access issue. In the report, a renewable mini-grid powering a local economic activity of a remote agrarian village in Ethiopia is discussed. Through a simulation study using PVsyst and Homer Pro tools, a yearly optimized PV diesel hybrid system with rounded up lowest LCOE of $0.17/kWh is obtained for the village in the case study. The LCOE of the mini-grid with lead acid battery and Li-ion battery is also studied at a yearly average operating temperature range of 10 to 40 ℃. The simulation-based study demonstrated that mini-grid systems with lead acid and Li-ion battery have fairly comparable LCOE between 10 to 20 ℃, however the Li-ion battery results in a lower LCOE for operating temperature beyond 25 ℃. The study has shown that mini-grids with productive energy can be cost effective option for powering areas where the grid-connection is cost and time intensive to address the energy poverty issue by 2030 or after.

Keywords: Sub-Saharan Africa, Ethiopia, Rural, Agriculture, Mini-grid, Productive use of energy, Lead acid battery, Li-ion battery

Acknowledgement

In the beginning, I would like to thank my rock, life, exemplar, present, help and medal Jesus. I thank also my dearest wife Tsicho, my brother Yifru and everyone who inspired me in deeds and deep conversations. My sincerest gratitude to very courteous Desiree and my kindest supervisor Manos. I thank Michel Battikh and Yacob Mulugeta (PhD)for offering me an opportunity to learn from their expertise. My big credit and gratitude to Swedish Institute which sponsored my master's program. In the end, I will close by saying Thank you Jesus.

Content

Abbreviations

Abbreviations	Description
Capex	Capital expense
DEG	Diesel generator
DSM	Demand side management
EE	Energy efficiency
ESMAP	Energy Sector Management Assistance Program
EW	East-west
GDP	Growth domestic product
GHG	Greenhouse gas
GIS	Geographic information system
GOE	Government of Ethiopia
GTP	Growth and Transformation plan
LCC	Life cycle cost
LCOE	Levelized Least Cost of Electricity
MoWIE	Ministry of Water Irrigation and Electricity
MTF	Multi-tier framework
NDC	Nationally determined contribution
NEP 2.0	National Energy Policy 2.0
NREL	National Renewable Energy Laboratory
Opex	Operating expense
PUE	Productive use of energy
PV	Photovoltaics
RE	Renewable energy
SDGs	Sustainable development goals
SHS	Solar home systems
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Development Organization
USAID	United States Agency for International Development
VRLA	Valve regulated lead Acid

1 Introduction

Sustainable development goals (SDG) 7 aims in delivering access to electricity for all in 2030. Energy being a key matrix in overall economic development, the lack of access to electricity has also an implication on the rest of SDGs too. According to Nerini et al., action on SDG-7 is a prerequisite for achieving 113 of 169 UN 2030 SDGs targets. The endeavor towards SDG7 also synergizes with 143 targets spanning over the 17 SDGs, in fact with trade-off relation with 65 of targets [1]. Though there is a huge increase in access to electricity worldwide, there are still almost 0.9 billion people without access to electricity [2]. More than 75 % of the population without access to electricity reside in Sub-Saharan Africa (SSA) [3] . Despite a huge progress towards access to electricity in the region, a lot is expected to address the 0.6 billion leftovers and to outpace the expected population growth by 2030. If the energy policies drafted before COVID-19 crisis is applicable, 85 % of the total estimated 650 million people without access to electricity in the world reside in SSA [2]. This necessitates using a variety of technology options, innovative business models, and multidisciplinary approaches.

In the past decade, the larger portion of progress in access to electricity in SSA is due to grid connection but there is also a large bump in deployment of Solar Home System (SHS) especially in Kenya, Tanzania, and Ethiopia [3]. There is also a growing disposition of mini-grids in many countries in SSA. Especially the number of photovoltaics (PV) based mini-grid is increasing due to its advantage in terms of resource availability, ease of implementation, cheaper lifetime cost, easier operation, and maintenance and so on [4]. The emergence of sophisticated electronic technologies is also making the hybridization of PV with other energy resources efficient.

One way to offset the unavailability of solar source is hybridizing it with wind energy. This might be more interesting for coastal areas, but the introduction of low-speed wind turbines is making wind energy competitive in inland regions too [5]. Since both wind and solar energy are clean energy sources, they contribute a lot to decreasing deforestation and the use of unsustainable energy sources. However, the conundrum with both wind and solar is availability of the source in demand. There might be not enough sunshine and wind when needed but in places where wind and solar are complimentary, the PV-wind hybrid with small back up system and/or storage can be cost efficient. In the paradox, the higher maintenance cost due to moving parts of wind turbine sometimes can set it in a back burner depending on the location, application, and availability of technical staff in a remote location where the electrification is sought for.

In SSA where the grid is fed with large diesel generators and rural villages without access to electricity, PV-diesel mini-grids can be implemented to save fuel costs [6]. In fact, energy-storage systems can also be part of such system for storing the excess solar radiation for later use, and can set itself as load, when the genset has an electricity production more than the load demand. Due to the decreasing cost of battery storage technologies especially Li-ion batteries, a high Renewable Energy (RE) penetration mini-grids are also becoming more and more competitive [4]. However, there is still a long way to go in making the mini-grid systems financially feasible. Though the technology options to address the access to electricity issue in SSA is available, the complex nature of the livelihood has made the problem more intricate. The high capital expenditure (Capex) for RE technologies [7], the low paying ability of the society, considerable replacement cost for storage technologies, and so on needs innovative and diverse means of approach encompassing technical, financial, business model and policy instigated thrives.

One of the approaches for making rural Africa mini-grids work is designing localized techno-economically optimal systems. This also includes promoting agriculture led productive use of energy (PUE) for powering agrarian economy of the rural population. This study takes a case study of an agrarian village in Ethiopia which can be a general example of rural villages in SSA. In the context of Ethiopia, this will reinforce the plan of Government of Ethiopia (GOE) to reach 100 % electrification by 2025 and attain middle income country in the same year [8]. GOE energy policy Nep 2.0 states the least cost option to this is through connecting 65 % of the population through the grid and the rest by off-grid solutions, mini-grids and SHS [8].

As mentioned above, in this report, a techno-economic study of a high renewable PV mini-grid design to stimulate the income generating activities of a rural village in Bedeno Woreda which is located in Oromia region of Ethiopia is discussed. More the study includes a case study on choosing the cost optimal battery technology from lead acid and Li-ion battery based on the mini-grid system´s level Levelized Least Cost of Electricity (LCOE). The mini-grid design is also done in conjunction with the different policies the GOE has set to implement throughout the country. The high renewable energy penetration of the mini-grids is related with GOE´s policy towards a zero-carbon economic growth [9]. And it will also be additional contribution in the top of massive tree plantation plans of GOE in combating climate change and fulfill the Nationally Determined Contributions (NDCs) submitted to United Nations Framework Convention to Climate Change (UNFCC) [10].

1.1 Problem Statement

According to a World Bank data analysis, around 59 % of SSA population reside in the rural parts of the region; from which less than 32 % of people living in a rural place have access to electricity which is less compared to 78 % for urban areas [2, 11].Using only a traditional connection to national grid being time consuming and expensive, decentralized systems are regarded as the least-cost way for supplying energy by 2030 to many remote areas in SSA [3].

In Ethiopia 79 % of the population live in rural area, and the gap between rural and urban electricity rate is very high; 33 % for rural population and 92 % of urban population has access to electricity [11, 12]. Access to energy and energy consumption trends in the world show a direct relation with the living standard and poverty [13]. More than three fourth of the world’s poor live in rural areas and the poverty rate in rural areas is estimated to be 3 times or more compared to urban areas [14]. In Sub-Saharan Africa, studies show that a higher proportion of poor population live in rural areas [15]. This might have also a correlation with low energy consumption index in rural population compared with urban areas.

In Ethiopia, the Growth Domestic product (GDP) per capital of the country has been developing on average of 8 % from 2011 to 2016 and poverty reduced by 20 %, the numbers from World Bank study show that the poverty level on rural areas increased in the same time period [16, 17]. The continual of this situation will further induce social division and creates economic inequality. This necessitates a customized rural electrification solution with focus on backing rural economic activities including agriculture, small industries and other income generating activities. With more than 60 million people without access to electricity, the latest energy policy by GOE considered this situation, and has introduced a systematic National Energy Policy (NEP 2.0) [8]. NEP 2.0 stated different electrification means based on the proximity of the location to the national grid, population density of the area, cost and multi-tier framework (MTF).

Mini-grids are one of the energy solutions stated under NEP 2.0 strategy document. Depending on energy tier level, least cost alternative solutions and population density, mini-grids could be deployed for places far from the grid and can also reinforce existing weak grid. The GOE already floated a bid for 36 solar mini-grids with PV-DEG and Li-ion battery packs, and the first 12 pilot projects are already in commissioning phase [18]. With the help from Power Africa program, GOE also selected 285 mini-grid sites [19]. Though RE mini-grids can be a good solution for rural electrification, associated cost with mini-grid deployment and running is a challenge due to low utilization factor and expensive components mainly battery storage. According to phone interview the author had with professionals working in Ethiopia Ministry of Water Irrigation and Electricity (MOWIE), the previously advertised 12 mini-grid projects, presently in commissioning phase have not rigorously studied the availability of anchor customers beyond the residential households. The cost of electricity in Ethiopia being less, and the residential electricity demand being low, the probability where such mini-grids will be economically competitive is questionable.

Though there are many different risk factors associated with the failure of mini-grid projects, low paying ability of customers, low utilization factor of mini-grid energy supply, and risk associated with battery lifetime are the main challenges faced by operating mini-grids [20 - 22].Planning rural mini-grids in such a way to stimulate productive use of the mini-grids energy could help for economic viability of mini-grid projects [23]. Innovative business model and financing to stimulate demand can also compensate for expensive unused capacity of the mini-grids. One good example for this can be the village of Bisanti in India. In the village of Bisanti, the utilization factor of the mini-grid is increased to 74 % by providing loans for soft-start electric motors [24].

In the context of rural Ethiopia and SSA, mini-grids which will power agricultural value chains can have a double advantage in leaping the community through making their work more efficient which in turn enhances the user's willingness to pay, and mini-grid viability. More the cost competitiveness of mini-grids can be enhanced through an educated decision on battery type choice for the specific application and climate [22]. Battery storage being the expensive part of mini-grid projects with high-risk implication, studies on properties of different batteries under various operation conditions could help. So, this study focuses on how to be localized mini-grid design for powering rural residential household and their income generating activities can makes rural mini-grids cost optimal.

1.2 Ethiopia Energy Situation

Ethiopia is a country with a total estimated population of 110 million in 2018 [25]. The country is one of the fastest growing economies in SSA with average GDP growth of 10 % in the past decade [26]. According to GOE´s Growth and Transformation plan II (GTP II), the country is aiming to reach a middle country status by 2025 and a net zero carbon state in the same time frame [27]. Energy being a driver for economic development and industrialization, the low access to electricity is hampering its ambitious plan to reduce poverty. The World Bank defined multi-tier framework approach is used to assess the state of energy access. Table 1 and Table 2 show an excerpt from MTF categorization of electricity service, capacity, and consumption [28].

Table 1 Multi-tier framework to household electricity services [28]

Tier level	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Tier criteria	NA	Task lighting, Phone charging	General lighting, Television, Fan (if needed)	Tier 2 and Any medium-power appliances	Tier 3 and Any high-power appliances	Tier 4 and Any very high-power appliances

Table 2 Multi-tier framework for household electricity supply and consumption [28]

Tier level	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Power (W)	NA	≥ 3	≥ 50	≥ 200	≥ 800	≥ 2000
Daily consumption levels (Wh)	NA	≥ 12	≥ 200	≥ 1,000	≥ 3,425	≥ 8,219

According to Energy Sector Management Assistance Program (ESMAP) report, only around 44 % of Ethiopian households (hh) have access to basic electricity supply which greater or equal to tier 1 level in relative to multi-tier framework benchmark [29]. This means the large share of the population lack reliable access to electricity. Figure 1 shows the energy access rate in Ethiopia.

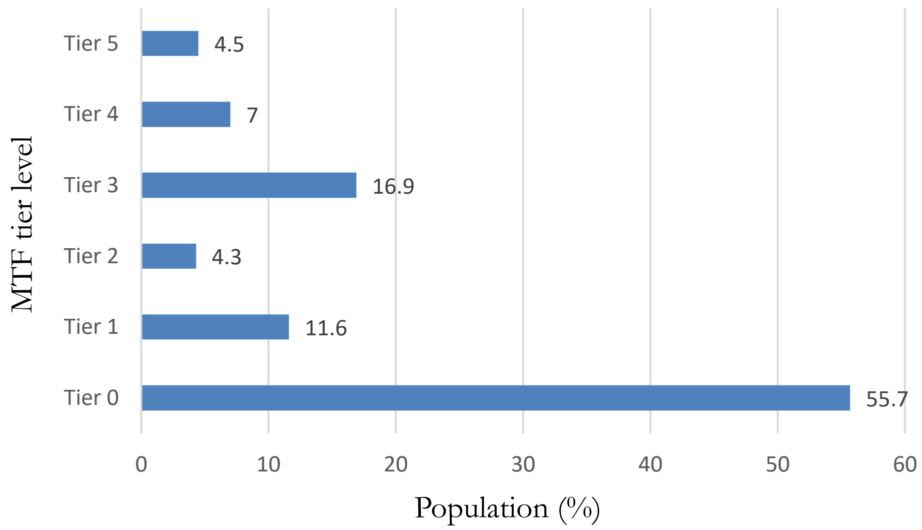

Figure 1. Energy access rate in Ethiopia [29]

For changing this scenario, GOE´s latest energy policy, NEP 2.0, aims to reach 100 % electrification in 2025 with addressing 65 % of the population with the grid, and the rest with mini-grid and SHS [8]. GOE plans to connect 96 % of population with the national grid by 2030. These strategies are enacted based on the geospatial analysis study result for identifying least cost solutions based on location and time of reach. Based on the Geographical Interface System (GIS) study, it is found that more than 90 percent of hhs lives within 10 km from the national grid and this share increase to 96 % within 25 km distance. Merging GIS analysis result on least cost solution, reaching time and location with MTF approach for including the energy service matrix of capacity and service; the strategy stated that tiers 1 and 2 approximately correspond to off-grid solar solutions, and tiers 3 to 5 to mini-grids and grid connectivity [8]. Figure 2 shows potential electricity access solutions for Ethiopia.

The main components of NEP 2.0 policy document are summarized below for using them as a bases for this study [8].

- On grid access by 2025 (15 million hhs): Beneficiaries are 65 % of the population which are within 2.5 km from the grid. This number also includes already grid connected hhs which represent 31 % of total population.
- Off-grid short term pre-electrification (3.3 million hhs): These are hhs to be connected to the grid to later years of 2025 but SHS will complement till the grid roll out happens.
- Off-grid long term deep rural: These are hhs beyond 25 km from the grid, and they are not expected to be connected to the grid by 2030. SHS and mini-grids will be means of energy access.

- Mid-term pre-electrification (5 million hhs): These are beneficiaries located between 2.5-25 km from the national grid and are expected to be connected to the grid between 2025 and 2030. These beneficiaries will be served by off-grid solar and mini-grids.

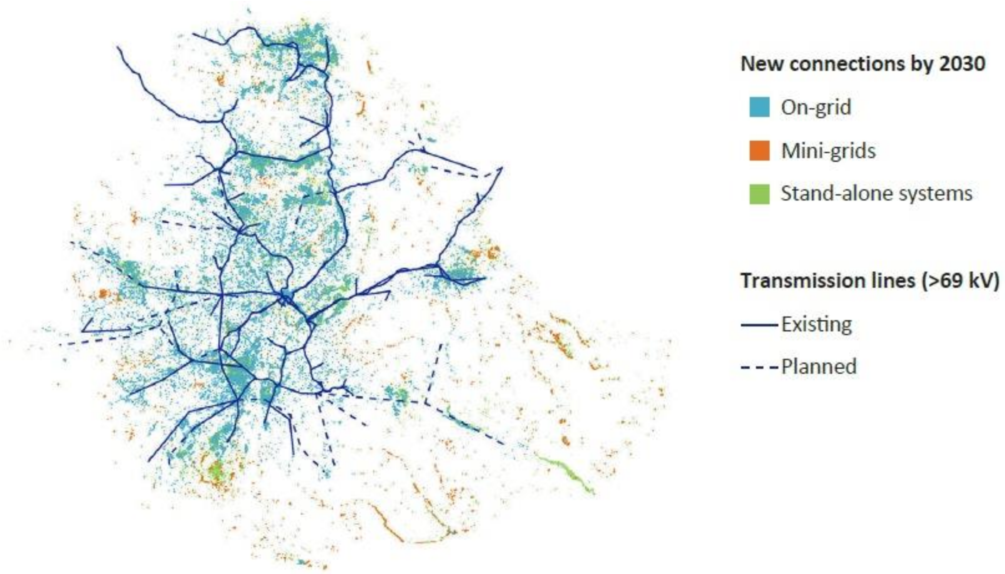

Figure 2. Ethiopia electricity access solutions by type [30]

1.3 Energy Resource Assessment in Ethiopia

The world climate change and the continuous cost competitiveness of RE system is pushing the deployment of sustainable power generation worldwide. In Ethiopia, building a climate resilient economy being the main part of the overlaid development and energy policies, renewable based power generation is a key part of national energy policy, and industrial development targets. Though the country is endowed with RE potential, the exploitation is still in a primitive stage. Table 3 shows the renewable energy potential of Ethiopia [31].

Table 3 RE resource potential in Ethiopia [31]

Resource	Unit	Exploitable Reserve	Exploited Percent
Hydropower	MW	45 000	< 5 %
Solar/day	kWh/m^2	4 - 6	< 1 %
Wind: Power	GW	100	< 1 %
Speed	m/s	> 7	
Geothermal	MW	< 10 000	<1 %
Wood	Million tons	1120	50 %
Agricultural waste	Million tons	15 - 20	30 %
Natural Gas	Billion m^3	113	0 %
Coal	Million tons	300	0 %
Oil shale	Million tons	253	0 %

Solar energy being evenly distributed all over the country, it has a huge potential in addressing the huge energy access problem in rural and remote areas of the country where the grid is not expected to reach by 2025. The average global solar insolation in Ethiopia is estimated 5 kWh/m^2 which implies the huge solar energy resource of the country like the rest of SSA. Figure 3 from Solargis tool shows the solar energy resource in Ethiopia.

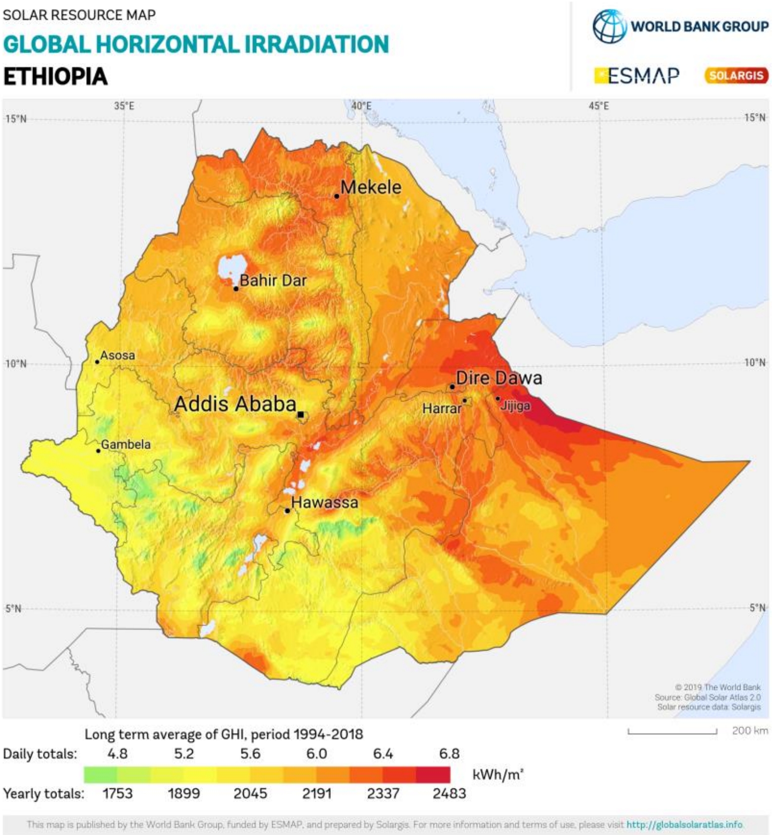

Figure 3. Solar energy potential in Ethiopia [32]

Though it is not evenly distributed as solar energy, there are also a potential for a small-scale wind energy and hydropower. There is more than 3 GW small scale hydropower potential concentrated in western half of the country and there are possibilities for wind-based off-grid projects, especially in Somali region [33]. Depending on the local economy, agricultural waste such as cotton stalk, coffee hull, animal dung are a few sources of biomass energy. These resources can be hybridized to build cost optimal energy systems for rural electrification.

1.4 Aims

The aim of this study is to show the potential of stimulating agriculture led productive use of energy (PUE) for mini-grid based rural energy systems in SSA. A case study site from a rural village in Ethiopia will be studied in consideration of agricultural sector such as water pumping for supplemental irrigation as one of the anchor or main loads. The proposed site is situated in Walta Jalala Village in Bedeno Woreda of Ethiopia where there is no access to electricity. The village is more than 10 km away from the national grid and it is assumed as site which is sat within GOE´s mid-term pre-electrification plan. For the case study village, a mini-grid will be sized in consideration of energy efficient (EE) appliances for better Demand Side Management (DSM), and inclusion of income generating activities for improved utilization factor of energy generated.

Apart from agriculture based productive use of energy (PUE) study, the economic competitiveness of the mini-grid with Li-ion battery technology, and lead acid battery will also be evaluated in consideration of representative commercial brands from the industry. This is included in the study due to high-cost implication of battery technologies for mini-grid based energy systems. The output from the study is aimed to stir a high-level thinking on the inclusion of productive use of the energy on mini-grids design, and consideration of techno-economic optimization for considering a preliminary financial assessment. More, cost effective battery technology will be suggested based on the battery's financial implication in overall mini-grids net present value (NPV).

The goals of the project can be summarized as:

- Design a RE mini-grid system for suggested load with 100 % availability
- Optimize the system for lowest LCOE
- Compare mini-grid system with lead acid battery vs Li-ion batteries based on LCOE
- Recommend battery technologies based on financial inference
- Recommend policy directive based on the result

1.5 Method

As a first step to design the mini-grid system, a sensible daily load profile is estimated based on proxy data approach. An excel based tool developed by National Renewable Energy Laboratory (NREL) for estimating a micro-grid electrical load profile for rural Africa [34]. Microgrid Load profile explorer tool is mainly aimed to inform high level design thinking around household and commercial load profiles common in rural SSA, not to be a modular source of estimating load profiles. The load profile from the tool is also enhanced by literature, village specific census and local economic activities of the community. The estimated hourly load profile is fed to another tool orginally developed by NREL, Homer Pro. Homer Pro is a commonly used techno-economic optimization tool widely used for hybrid energy systems sizing and simulation study. Homer Pro tool introduces stochasticity and random variability to our load profile.

Homer Pro will also take different renewable energy sources cost figure and recommend a cost optimal system based on least net present value. For this study, PV, wind power, bi-directional inverter, battery and DEG cost figure will be given in to Homer Pro as an input, and Homer Pro will suggest the least cost system based on the defined boundaries. For increasing the quality of the simulation study, the PV input to Homer Pro were an hourly PV production data from PVsyst. Since PVsyst is one of the reliable tools for PV systems simulation study, this will help to use the strongest feature of both tools for optimizing the system in a more realistic approach. For PVsyst simulation a 25 kW PV size is simulated. The reason why 25 kW system is chosen is due to a previous mini-grid tenders floated by

Ethiopian Electric Utility stated that the maximum amount of PV allowed per string is 25 kW. More if smaller systems such as 1 kW PV system with grid inverter is simulated in PVsyst, the low efficiency of small grid inverters will increase the uncertainty of the result however with considering a higher PV size, it is possible to include PV inverter which are practically used in real mini-grids.

For comparing a mini-grid design with Li-ion and lead acid battery, a simulation study has been done by simulating two representative commercial lead acid and Li-ion battery technologies in the market. As an input to battery characteristics at different condition, the data sheet of the battery technologies is referred. The properties such as cycle life of the batteries, depth of discharge, operating temperature, temperature, and cycle charging degradation as stated in the batteries is then feed in to Homer Pro simulation. For techno-economic study, an economic figure from most recent literatures more specifically from World Bank reports will be used. Then the optimized mini-grid is chosen using the Homer Pro tool which simulates all the possible options and recommends a system with the lowest LCOE. A parametric study is to be done using Homer Pro´s sensitivity analysis features. The result will then be compared with previous research and literature review.

The method can be summarized as:

- Estimate the water need for supplemental irrigation of different crops
- Use proxy data method integrating Microgrid Load Profile Explorer tool, census, and literature to generate load profile
- Simulate PV system in PVsyst and import the AC electricity production in to Homer Pro
- Feed load profile and other techno-economic data to Homer Pro
- Feed the data from the Battery manufacturers data sheet, and literature to Modified Kinetic Model of batteries in Homer Pro
- Compare the result from Homer Pro and suggest a system with least LCOE

2 Literature Study

There are more than half a billion people without access to electricity in SSA[3].In Ethiopia, more than 55 % of the population lacks access to electricity [8]. For past years, the GOE has made substantial investment in the national grid aiming to change this energy narrative. Regardless of its significant financing on grid system, the energy access issue is still a big challenge. This incites a need for additional means of approaching the energy access issue which in turn can be cost and time optimal option for some areas. NEP2.0 stated mini-grid as one means of the solutions, and there is a plan to deploy more than 285 mini-grids before 2025 through public and private investment [8]. Though the economic competitiveness of mini-grids is not proven yet in the context of Ethiopia, literatures on previous mini-grid deployment schemes in other areas show both success and failure rates [4, 35, 36, 37].

Some of the key barriers' relation to mini-grids deployment in SSA are high capital cost, financing unavailability, low paying ability of the society, a small load factor due to underutilization of electricity from the mini-grids, mismatch between the demand and supply, intricate rules, and regulations etc. [4, 24]. Measures like DSM especially those flexible loads to fit with renewable generation, promoting PUE, remote monitoring of operation can contribute for better economics of the mini-grids [4, 24]. The emerging of smart grids and digitalization enabled new business models and mobile money are also driving the mini-grid sector and rural electrification [24].There are a number of studies made on the feasibility, market assessment and techno-economic optimization of mini-grid projects in Ethiopia and the region. Some of the literature reviewed are discussed briefly in the following section. Since this case study report spans from mini-grids feasibility study to PUE and localized battery selection (lead vs Li-ion), literatures reviewed will be wider in content to cover these issues.

The study by Gebrehiwot.k et al. [38] discusses about the potential of hybrid mini-grids for electrifying remote villages in Ethiopia and concludes that wind-PV-battery-diesel generator combination as economically least option to address access issue in remote areas. The sensitivity analysis done to show how changes in solar radiation, wind speed and diesel price affect the optimal system configurations and cost is the strength of the paper. On the other side, the paper has not discussed on the competitiveness of the electricity from the mini-grid (LCOE: $0.207/kWh) with cost of electricity from the national grid.

The study by Nigussie.T et al. [39] discussed about the feasibility of micro-hydro-PV-diesel generator for rural electrification of Melkey Hera village in Ethiopia. The system also includes batteries as part of optimal system configuration. The energy consumption estimation took in consideration of domestic, commercial and community loads, and the authors also considered consumption projection for three years which is calculated based on estimated population growth. Though sensitivity analysis was done with respect to fuel price and solar radiation availability, the sensitivity analysis for hydropower (covers 80 % share) seasonal variation not made. The whole hybrid system has a LCOE of $0.133/kWh which is higher than selling price of electricity from the grid $0.06/kWh in the year of the publication. However, the renewable energy penetration is stated as 99 % which makes the system more environmentally friendly.

The study made by Getachew.B et al. [40]. also discusses about the possibility of supplying electricity from solar-wind hybrid system to a remote location in Ethiopia. Though this article is published in 2009, it is mentioned here due to its interesting finding that diesel-battery-bi-directional inverter-based system which is running on cycle charging strategy is a least cost option with LCOE of $0.322/kWh, PV-wind-DEG-battery being the next one with $0.353/kWh. In fact, the mini-grid for PV and wind has reduced in the past decade, and the cost for fuel has gone up from the study period which is 2009. Though this literature is a bit dated, it could show how renewable based mini-grids have become cost competitive with conventional system in the past decade.

The study by NREL [21] on techno-economic comparison of the Li-ion and lead acid battery in mini-grid application in Sub-Saharan Africa contrasts them based on life-cycle cost (LCC). It also examines different types of operational practices in terms of their contribution for reducing LCC of battery technologies which are 20 to 30 % of total cost of solar mini-grids. Container based battery storage being common in the mini-grid setting in Africa, the study compares this with batteries housed in brick structure, concrete structure, and wooden structure. It merges the thermal modelling, battery degradation and techno-economic analysis together for drawing vented type lead acid battery with NMC (lithium nickel manganese cobalt oxide) based Li-ion battery technology operational behavior under different 5 different climate condition in SSA, different housing construction materials, five heating, ventilating and air-conditioning (HVAC) configurations and two load profiles. Some of the conclusion from the NREL study include wood is better construction material in terms of keeping the battery in cooler temperature while shipping containers being the worst, the system with Li-ion resulted in lower LCC for every case, and systems with no-HVAC are most cost optimal for most of the cases. The study by NREL is detailed and compares the LCC of lead and Li-ion battery technologies for PV-battery mini-grids.

The article by Keshan.H et al. [41] on comparison of lead caid and Li-ion for stationary application in off-grid systems reviews prior work on various characteristic of the two batteries on charging efficiency, charging and discharging characteristic, life cycle and costs. In the study lead acid batteries are represented by valve regulated type (VRLA) and Li-ion batteries are represented by lithium iron phosphate (LFP) type. The paper infers that Li-ion batteries are the cost optimal option for off-grids systems in developing countries except for lower temperature regions.

The study by Anuphappharadorn.S et al. [42] studies economic competitiveness of Li-ion and lead acid battery technologies for 140 W solar home systems in Thailand. The authors used excel based model to compare the representative two battery technologies based on levelized cost of electricity (LCOE), benefit cost ratio (BCR), and simple net present value (SNPV). The study concluded that PV standalone system with lead acid batteries have lower LCOE and SNPV than with Li-ion battery. However, the size of the battery on this study is for a smaller solar home system.

Though there are several studies made in techno economic feasibility of mini-grids in Ethiopia and SSA context, the studies focused on mere coverage of the household load profile, a few public centers mainly schools and health posts and churches and did not take in consideration of how to increase the utilization factor of energy from the mini-grids through designing systems in consideration to the local income generating activities. More the load profile estimation on this study adopts a more realistic load profile consideration of households through estimating the consumption based on empirical literature data from previously introduced mini-grids and localized study of the site.

There is no costal optimal comparison of the two common battery technologies deployed in mini-grid sector at least in the context of Ethiopia. This study could be a positive addition to the current literature by illustrating the potential of productive use of mini-grids for making the energy from such systems cost optimal and improving the livelihoods of rural low-income villages in rural Ethiopia and beyond. More it gives a brief analysis on the cost implication of the two most common battery technologies in off-grid sector which is expected to inform high level decision of policy makers, utilities, and mini-grid developers.

3 Load Profile Estimation

3.1 Background

The National electrification program in Ethiopia has started with $375 million financial source from World Bank [43]. Mini-grid sector is one of the pillars of the electrification program. De-risking the financial viability of the mini-grid sector especially in the context of the rural community requires new and localized approaches. Though access to energy can drive economic development, pre-planning electrification schemes in nexus with agriculture and water access can have manifold effect [44]. This can stimulate the holistic development of the community while energy systems such as mini-grids, power the local economy and could be financially sustainable.

Energy need assessment study is one of important factors for planning such mini-grids powering agriculture and other local economies. In fact, energy assessment is one of the main risk factors for energy system development for communities connecting for the first time [45]. Good energy assessment studies mean a better possibility of developing a financially feasible project. It cuts unnecessary investment, making such public initiatives productive and cost efficient. It also relates with a potential of recovering the project costs with a minimal time.

Estimating energy demand for communities which are connecting to electricity for the first time needs caution since it has a strong implication both on the technical and financial feasibility of renewable energy projects. On this regard, the load profile prediction for rural mini-grid is a key and often unaccentuated part of its financial feasibility. The uncertainty associated with different methods of pre-energy demand estimation is adding a financial risk for spread of mini-grids in Africa [45].

There are different ways of executing energy need assessment in the industry. Energy use surveys and measured consumption are the common ones. Energy use surveys are basically done through estimating the present and aspirational energy consumption through structured survey. Measurement based assessment is seldom used for communities which are connecting for the first time, unless it has been connected to other means of energy resources. Though it is not common, data-driven proxy approaches are also emerging due to more data availability from ground operational systems [46]. The load profile estimation in literatures show a diverse method of estimating load profile.

The article by Mandeli et al. on Novel procedure to formulate load profiles for off-grid rural areas mentions some of the common approaches in literature on load profile estimation in mini-grid design [46]. Few studies defined profiles without much explanation about their origin [47 - 49], derived from other load profiles with similar contexts [50 - 54], by assuming on electric appliance rating and running periods without any defined procedures [55 - 57].

A study by Blodgett et al. in rural mini-grids compared survey-predicted energy use to actual measured consumption after the proliferation of 8 rural mini-grids in Kenya [45]. The result from the case study site shows more than 300 % difference between energy use survey made before mini-grid deployment and energy audit made after the installation of the mini-grids. Some of the reasons for the error are related with energy survey, and realized system difference in inventory, power rating, and hours of use and so on. The authors also used data-driven proxy village approach to comparing the accuracy of such approaches with survey-predicted energy consumption, and the mean absolute error has been reduced massively with data-driven load profile estimation approach.

Though the data-driven method is still debatable and needs more investigation, the method of data-driven proxy village load profile estimation will be used for predicting the load profile of the village for this specific case study, literature and census-based data from available sources will also be integrated for the purpose of improving the accuracy of load-profile and execute the study based on a realistic potential consumption pattern for a representative village in rural Africa. In fact, the pattern of electric consumption in rural mini-grid also being a significant factor for the conclusion of this study, the data driven approach could be a realistic approach to estimating the load profile.

Multi-tier framework defined in Table 1 and Table 2 is used as baseline for estimating the household energy consumption for this study. The figures for the electricity consumption level can differ depending on the use of super-efficient energy appliances or standard equipment. Since consumption data considering uncertainty of load profiles through stochastic model being more realistic, Homer Pro energy will be used to introduce uncertainty in the daily load profile through instituting a random noise on the formulated profile.

3.2 Site Description

The village in the case study is in Easter part of Ethiopia, in Oromia Regional state, East Hararghe Zone, Bedeno Woreda. The village level name for the area is called Walta Jalala, and it is a rural neighborhood which with agrarian economy. The area is known for its high population density and farming of maize, sorghum, potato, and cash crops such as coffee and khat [58]. The geographical coordinate for the area where the mini-grids system supplied for is in latitude and longitude of 9°10'31.0"N and 41°31'44.8"E. Figure 4 shows the picture of the village.

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Figure 4. Part of Walta Jalala village picture taken from Google Earth

3.3 Load Profile Estimation for Walta Jalala Village

The load profile estimation will be made using Rural Africa Load Profile Explorer tool in conjunction with literature. The tool is developed by Power Africa program based on consumption pattern from mini-grids in operation in Africa [59]. Household consumption, community load and PUE service load will be estimated based on the localized context and localized economic activities.

NEP 2.0 considers mini-grid and grid-based energy system for reaching tier 3-5 access, level according to MTF framework [8]. Few studies assumed homogenous consumption level for all households [38 - 40] but the consumption amongst individual households might vary. Speaking in terms of tier level, different households within in a community might have consumption which might fall in different tier level. Some of the main reasons for this are:

- Difference among individual's income and paying ability for appliance's and electricity
- Different appliance ownership
- Difference on the awareness of the benefit of electricity

To introduce the presence of multi-tier consumption within the community, the households are categorized into three groups based on their income level, high income household, middle income household and low-income household. The excel based load profile generation tool also uses the same kind of categorization. The result from GIS based study for estimating household income level for Bedeno Woreda, which is a wider area where the village in the case study belong to will used as a baseline [19]. For some of the information not available for lower administrative level, available data for higher administrative hierarchy level will be used.

3.3.1. **Household Profile Estimation**

The village in the study is a rural farming village. In consideration of 0.5-hectare land per household, the load profile estimation is made for 300 household residing in 1.5 km^2 area. For the village considered in this study, potential appliance ownership has not been assessed, instead an ownership summary from Rural African Load Profile tool which is basically formulated based on a study made on rural Kenya household appliance ownership is adopted. To increase the adaptability of the result in the context of a case study village, appliance ownership and other inputs from Ethiopia off-grid market assessment study report by USAID Power Africa project is introduced to the excel tool. The data from Power Africa projects are mainly based on geospatial analysis on the income level and demographics categorization [19].

The assumptions made for the village under study is given in a table below. The average number of households in East Hararghe Zone where the village in the case study is situated reported 5 in 2014 [60], and the average household number for higher hierarchical administration level Oromia Region is reported 5.2 in 2019 [61]. For this study 5.2 is taken as the average number of people in households. Table 4 shows the proposed demographic and income level data for the village.

Table 4 Case study village data

Average Household size	5.2
Total number of households	300
High consumer households	50
Medium consumer households	100
Low consumer households	150

The type of appliances considered for the different type of household based on the income level is also given in Table 5. Lighting is considered for all households.

Table 5 Appliance wattage count

Appliances	Wattage (W)	High income household appliance count	Medium income household appliance count	Low income household appliance count
Lights	9	3	2	1
Mobile Phone/Charger	8	3	2	1
Radio	15	1	1	1
Television (Not LCD)	40	1	1	1
DVD Player/ parabolic satellite	35	1	1	1
Refrigerator [1]	50	1	1	1

1 Assumed to be average watt accounting for compressor cycle on and off

Ownership data for mobile phone and radio is considered based on country level quantitative figure from USAID report [19]. The usage of off-grid household high wattage appliance in the context of Ethiopia is poor. Table 6 represents assumed appliance ownership for the households.

Table 6 Appliance ownership summary

Appliances	High income household ownership (%)	Medium income household ownership (%)	Low income household ownership (%)
Lights	100	100	100
Mobile Phone charger	78	62	37
Radio	36	34	23
Television	82	45	16
DVD Player	38	2	3
Refrigerator	17	4	1

In the Table 7, assumed hourly usage of the different appliances adopted from the load profile estimation spread sheet from Power Africa program is shown [34].

Table 7 Proposed hourly appliance usage (%)

Hours of	Lights	Phone charger	Radio	Television	DVD Player	Refrigerator
0:00	0	0	0	0	0	1
1:00	0	0	0	0	0	1
2:00	0	0	0	0	0	1
3:00	0	0	0	0	0	1
4:00	0	0	0	0	0	1
5:00	0	0	0	0	0	1
6:00	0	0.1	0	0	0	1
7:00	0	0.1	0	0	0	1
8:00	0	0.1	0.25	0	0	1
9:00	0	0.1	0.25	0	0	1
10:00	0	0.1	0.25	0	0	1
11:00	0	0.25	0.25	0	0	1
12:00	0	0.25	0.5	0	0	1
13:00	0	0.25	0.5	0	0	1
14:00	0	0.25	0.5	0	0	1
15:00	0	0	0.25	0	0	1
16:00	0	0	0.25	0	0	1
17:00	0	0.5	0	0.1	0	1
18:00	0.25	0.5	0	0.15	0.1	1
19:00	0.75	0.5	0	0.3	0.2	1
20:00	0.75	0.5	0	0.6	0.2	1
21:00	0.5	0.5	0	0.6	0.3	1
22:00	0.5	0	0	0.25	0.2	1
23:00	0.25	0	0	0	0	1
Total (hours/day)	3.0	4.0	3.0	2.0	1.0	24.0

3.3.2. **Community, and Productive Use of Electricity Load**

As the focus of this study being on promoting the PUE in mini-grid development in rural Africa, the community load is a major component of the load profile estimation. The community load for the village is assumed to include school, health center and a few streetlights. In addition to this, the productive use of energy services is estimated based on consideration of the resources in the village which includes irrigation-based agriculture. There is also potential to provide other agricultural outputs such as egg for nearby cities such as Diredawa and Harrar.

The village being agrarian rural village, one of the main PUE application thought of is mini-grid-based irrigation. This is assumed to increase the productivity of the area which is considered as one of the major food insecure regions in Ethiopia [58]. In the past years, the region also experienced rainfall shortage which is claimed to relate to climate change. The community mainly dependent on subsistence based rainfed agriculture, the energy from the mini-grid can supplement the food security through improving the agricultural sector productivity. In the following sub section, the irrigation water need for main crops in the area is estimated as preliminary parameter to estimate the energy need for water pumps.

3.3.3. **Water Consumption Estimation for Irrigation**

The irrigation requirement of crops differs depending on climate, soil type, crop genetics and so on. For the village understudy, since there is seasonal availability of rainfall, the proposed framing scheme is supplemental irrigation. This means the irrigation only covers whenever there is deficit of water from the seasonal rain fall. The seasonal perception data for the site is shown in the Figure 5.

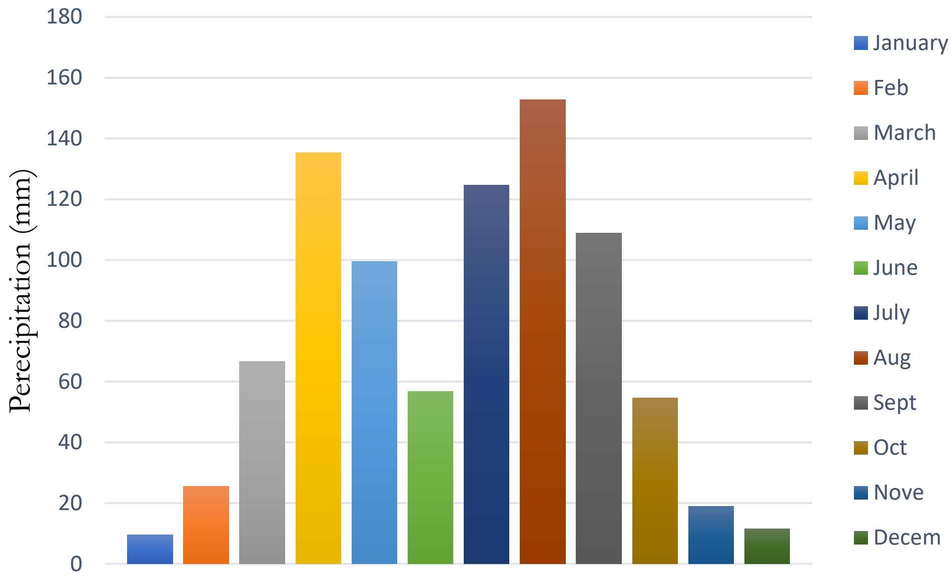

Figure 5. Monthly average rainfall for 30 years [62]

The whole rainfall which falls in the soil might not mean that it will be used by the plant. Some portion of the rainfall will be effectively used by the plant, and the rest run-off away from the soil surfaces and percolates below the root zone of the plants. For this analysis, a simple way of effective rainfall calculation will be used with assuming the slope of the farming land is less than 5 %. Equation 3.1, Equation 3.2 and Equation 3.3 are retrieved from Food Aid Organization (FAO) guideline for determination of the effective rainfall for areas with a maximum slope of 4 to 5 % [63]. Table 8 contains the rainfall and effective precipitation data for the case study village.

$$P_e = 0.8\,P - 25 \quad \text{if } P > 75 \text{ mm/month} \qquad \text{Equation 3.1}$$

$$P_e = 0.6\,P - 10 \quad \text{if } P < 75 \text{ mm/month} \qquad \text{Equation 3.2}$$

Where: P: rainfall or precipitation (mm/month)

P_e: effective rainfall or effective precipitation (mm/month)

P_e is always equal to or larger than zero; never negative

Table 8 Rainfall and effective rainfall (mm/month)

Month	Rainfall (mm/month)	P_e (mm/month)
January	9.61	0.00
February	25.48	5.29
March	66.65	29.99
April	135.30	83.24
May	99.51	54.61
June	56.70	24.02
July	124.62	74.70
August	152.83	97.26
September	108.90	62.12
October	54.56	22.74
November	18.90	1.34
December	11.47	0.00

The crop water requirement (ET_{crop}) to compensate the loss through evapotranspiration for coffee, sorghum, maize, and potato is estimated to find how much share the rainfall and irrigation will have. The relationship between the reference grass crop (ET_o) and the crop factor (K_c) is used to estimate the crop water requirement (ET_{crop}).

$$ET_{crop} = ET_o \times K_c \qquad \textit{Equation 3.3}$$

Where: ET_{crop}: crop evapotranspiration or crop water need (mm/day)
K_c: crop factor
ET_o: reference evapotranspiration (mm/day)

The ET_o (mm/day) for reference grass at specific area can be estimated using the Hargreaves temperature method, which can be used for preliminary determining ET_o (mm) in many developing countries since temperature data could be easily available [64]. The Hargreaves temperature method of estimating ET_o (mm) is given in Equation 3.4 [64 - 65]. Table 9 contains the reference evapotranspiration calculation.

$$ETo = .0023\ Ra\ Tr^{0.5}\ (T_{avg}+17.8) \qquad \textit{Equation 3.4}$$

Where: Ra: extraterrestrial solar radiation (mm per day), function of latitude and time of year.
T_{avg}: average temperature in °C for the period, i.e., $T_{avg}=(T_{max}+T_{min})/2$
T_r: difference in average daily maximum and minimum temperatures for the period in °C.

Table 9 Reference evapotranspiration (mm/day) calculation

Month	Ra	T_{max}	T_{min}	T_{avg}	$T_r^{1/2}$	ET_o (mm/day)
January	13.20	28.19	13.31	14.88	3.86	4.50
February	14.20	29.75	14.34	15.41	3.93	5.10
March	15.30	29.84	15.78	14.06	3.75	5.40
April	15.70	28.25	16.57	11.68	3.42	5.00
May	15.50	28.48	16.54	11.94	3.46	5.00
June	15.30	28.29	15.94	12.35	3.51	4.90
July	15.30	26.49	15.17	11.32	3.36	4.60
August	15.50	26.03	14.96	11.07	3.33	4.50
September	15.30	26.38	15.35	11.03	3.32	4.50
October	14.70	27.10	14.70	12.40	3.52	4.60
November	13.60	27.25	13.47	13.78	3.71	4.40
December	12.90	27.35	12.88	14.47	3.80	4.30

Table 10 contains the length of crop development stage and crop factor for coffee.

Table 10 Coffee lengths of crop development stages [63]

Coffee: Crop water need (mm/total growing period), 1500 - 2500 mm				
Lengths of crop development stages (305)	Initial	Development	Mid	Late
	50	65	100	90
Kc	1.1	1.1	1.1	1.1
Mon.	Mar. - Apr.	May - Jun.	Jul. - Sep.	Sep - Nov.

Table 11 contains the length of crop development stage and crop factor for maize.

Table 11 Maize lengths of crop development stages [63]

Maize: Crop water need (mm/total growing period), 500 - 800 mm				
Lengths of crop development stages (180)	Initial	Development	Mid	Late
	30	50	60	40
Kc	0.4	0.8	1.15	0.7
Mon.	Mar.	Apr. - May	Jun. – Jul.	Aug.

Table 12 contains the length of crop development stage and crop factor for sorghum.

Table 12 Sorghum lengths of crop development stages [63]

Sorghum: Crop water need (mm/total growing period), 450 - 650 mm				
Lengths of crop development stages (120)	Initial	Development	Mid	Late
	20	30	40	30
Kc	0.45	0.83	1.18	0.78
Mon.	Mar.	Apr.	May	Jun.

Table 13 contains the length of crop development stage and crop factor for potato.

Table 13 Potato lengths of crop development stages [63]

Potato: Crop water need (mm/total growing period), 500 - 700 mm				
Lengths of crop development stages (115)	Initial	Development	Mid	Late
	25	30	30	30
Kc	0.45	0.75	1.15	0.85
Mon.	Dec.	Jan.	Feb.	Mar.

Using the formula for crop requirement, Equation 3.3 and the data in the tables defined above, it is possible to calculate the crop water requirement (ET_{crop}) for each month. The irrigation water requirement for each of the months can also be calculated using Equation 3.5 [63].

$$IWR = ET_{crop} - P_e \qquad \textit{Equation 3.5}$$

Where ET_{crop}: crop water requirement
P_e: effective rainfall

Table 14 contains the irrigation water requirement for the assumed irrigated crop types.

Table 14 Irrigation water requirement for the assumed crops

Month	Coffee		Maize		Sorghum		Potato		TIWR (mm/day)
	ET crop	IWR	ET crop	IWR	ET crop	IWR	ET crop	IWR	
Jan.	0.00	0.00	0.00	0.00	0.00	0.00	3.39	3.39	3.39
Feb.	5.62	5.43	0.00	0.00	0.00	0.00	5.87	5.69	11.12
Mar.	5.89	4.93	2.14	1.18	2.41	1.44	4.55	3.59	11.13
Apr.	5.46	2.68	3.97	1.20	4.12	1.34	0.00	0.00	5.22
May	5.46	3.70	3.97	2.21	5.86	4.10	0.00	0.00	10.01
Jun.	5.43	4.63	5.68	4.88	3.85	3.05	0.00	0.00	12.55
Jul.	5.03	2.62	5.26	2.85	0.00	0.00	0.00	0.00	5.47
Aug.	5.00	1.86	3.18	0.04	0.00	0.00	0.00	0.00	1.90
Sep.	4.97	2.90	0.00	0.00	0.00	0.00	0.00	0.00	2.90
Oct.	5.07	4.33	0.00	0.00	0.00	0.00	0.00	0.00	4.33
Nov.	4.87	4.83	0.00	0.00	0.00	0.00	0.00	0.00	4.83
Dec.	0.00	0.00	0.00	0.00	0.00	0.00	1.93	1.93	1.93

Assuming five hectares of each of the crops (coffee, maize, sorghum, and potato) is irrigated, and with the assumption that there is no extra storage tank for irrigated water, the irrigation water requirement and average daily kWh requirement for each of the months is calculated. The kWh energy of the pump is estimated with assuming 10 pumps with nominal capacity of 0.75 kW are working. The technical specification of the pump considered is shown in Table 15.

Table 15 Pump specification considered for water pumping

Manufacturer: DAB
Model: Model K 35/40 T
Depth: 15 m
Flow: 5.5 m^3/h
Nominal power: 0.75 kW
Number: 10 pumps

Based on the requirement of the irrigation water need from Table 14 and the pump specification above, the volume water requirement and its equivalent energy need for each month is given in the Table 16.

Table 16 Daily water requirement and consumption for 5-hectare irrigation

Mon.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
V(m^3)	169.3	555.8	556.7	261.2	500.5	627.7	273.6	95.1	145.0	216.7	241.5	96.3
Load (kWh)	23.09	75.79	75.91	35.61	68.25	85.60	37.31	12.96	19.77	29.56	32.93	13.13

3.3.4. **Estimating Other PUE Loads**

Water supply system: One of PUE loads in consideration is clean water supply system. Due to the ease of operation and maintenance, possibility to run with PV systems, Yamaha water cleaning system is considered on this study. Though Yamaha clean water supply system has some limitations, it is assumed that the system is compatible for the village. The water supply system consumes 5 kWh/day for purifying 8000 l of clean water [66]. The system comes with 3000 l storage capacity but in this study, additional 5000 l storage capacity is considered for considering a possibility of the mini-grid to purify the water when there is excess output from the PV.

Coffee pulpers: Coffee pulper machine with a rating of 750 W and a capacity to pulp 1200 kg/hour is considered [67]. Based on reaping period of the village, the coffee pulpers are proposed to be used from November to February. This is because the community starts to reap the beans from Novembers and finishes most of the reaping at the end of February. So, the coffee pulpers are considered to operate only for this time frame. It is assumed the operation of the Coffee pulpers is from 9:00 to 16:00.

Other Loads: 985W milling machine, 2 shops, 1 school, 20 streetlights, 10 small egg incubators and 2 diary chillers are considered. 1 small health center, which is called health post in the context of Ethiopia is also assumed. Each rural kebele (ward) in Ethiopia has health post with a capacity to give first aid service for each village.

Table 17 contains the community owned appliances rating.

Table 17 Community owned appliance rating

Commercial entity type	Per unit wattage (W)	Count
Milling	985	1
Small Shop (refrigerators, freezers, TV, lighting)	388	2
School (lighting, fans, computers)	940	1
Clinic (lighting, refrigerator, TV, misc.)	320	1
Number of streetlights	20	5
Egg incubators	50	10
Coffee pulper	750	1
Diary chiller	200 (225 l)	2

Table 18 shows the assumed community loads hourly usage. The hourly usage estimation figures are estimated based on the excel sheet-based tool for preliminary rural Africa load profile generation tool and practical operation of the equipment.

Table 18 Assumed hourly commercial usage (%)

Hour	Milling	Egg incubator and Diary chiller	Small Shop	School	Clinic	Street lighting	Coffee pulper
0:00	0.00	1	0.30	0.10	0.10	1.00	0.00
1:00	0.00	1	0.30	0.10	0.10	1.00	0.00
2:00	0.00	1	0.30	0.10	0.10	1.00	0.00
3:00	0.00	1	0.30	0.10	0.10	1.00	0.00
4:00	0.00	1	0.30	0.10	0.10	1.00	0.00
5:00	0.00	1	0.30	0.10	0.10	0.50	0.00
6:00	0.00	1	0.30	0.30	0.30	0.00	0.00
7:00	0.00	1	0.35	0.60	0.60	0.00	0.00
8:00	0:00	1	0.50	0.60	0.60	0.00	0:00
9:00	0:00	1	0.60	0.65	0.65	0.00	0:00
10:00	1.00	1	0.60	0.65	0.65	0.00	1.00
11:00	1.00	1	0.60	0.65	0.65	0.00	1.00
12:00	1.00	1	0.60	0.65	0.65	0.00	1.00
13:00	0.00	1	0.60	0.65	0.65	0.00	1.00
14:00	1.00	1	0.60	0.65	0.65	0.00	1.00
15:00	1.00	1	0.60	0.65	0.65	0.00	1.00
16:00	1:00	1	0.65	0.55	0.55	0.00	1:00
17:00	0.00	1	0.65	0.20	0.20	0.00	0.00
18:00	0.00	1	0.65	0.10	0.10	0.00	0.00
19:00	0.00	1	0.70	0.10	0.10	0.50	0.00
20:00	0.00	1	0.70	0.10	0.10	1.00	0.00
21:00	0.00	1	0.70	0.10	0.10	1.00	0.00
22:00	0.00	1	0.50	0.10	0.10	1.00	0.00
23:00	0.00	1	0.30	0.10	0.10	1.00	0.00
Total hrs/day	6	24	12	8	8	10	6

3.3.5. **Total Estimated Load for the Village**

The load for the community is proposed to be treated as primary load and deferable load. The load for water pumping and clean water supply unity will be considered as deferable load, but the rest will be considered as primary load. This is supposed to increase demand side flexibility and economics. Though the daily primary load considered is the same for the whole year, the weekdays and weekend primary load is differentiated since schools will be closed in the weekends. More seasonality of the cropping period is considered when the load profile data is imported in to Homer Pro tool. The total primary load profile for the whole village which includes both the household and commercial profile is given in Table 19. However, the primary load profile in Table 19 represents only the load profile for weekdays from November to February which is the season where coffee pulpers is assumed to run. For weekend, only the primary load for the school is subtracted. For the months from March to October the coffee pulpers are assumed not to operate. For July and August, the schools are assumed to be closed. The primary load profile estimated through proxy data approach has no random variability instead stochastic random variability is introduced into the daily profile for weekdays, weekends, and seasons by Homer Pro tool (10 % day to day variability and 20 % step to step).

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Table 19 Hourly Load profile of the village

	Primary load profile output table (kWh)		
	Total household load	Primary commercial load	Total primary load
0:00	1.38	2.39	3.77
1:00	1.01	2.39	3.40
2:00	0.84	2.39	3.23
3:00	0.75	3.38	4.13
4:00	0.74	4.41	5.15
5:00	0.78	5.45	6.23
6:00	0.91	6.83	7.74
7:00	1.01	8.33	9.34
8:00	1.19	9.53	10.72
9:00	1.28	9.77	11.05
10:00	1.36	10.34	11.70
11:00	1.58	9.35	10.93
12:00	1.78	8.17	9.95
13:00	1.84	7.80	9.64
14:00	1.8	9.35	11.15
15:00	1.53	9.25	10.78
16:00	1.76	10.05	11.81
17:00	2.73	9.14	11.87
18:00	4.04	6.95	10.99
19:00	5.83	5.85	11.68
20:00	6.66	3.74	10.40
21:00	5.98	2.75	8.73
22:00	4.17	2.55	6.72
23:00	2.43	2.39	4.82
Total kWh/day	53.38	152.56	205.94
Total kWh/year	19.484	55685.13	75168.83
Max kW/day	6.66	10.34	11.87
Min kW/day	0.74	2.39	3.23

Figure 6 shows the primary load profile tabulated in Table 19. As the figure shows the primary load for the households is steep in the evening time. However, the primary load profile proposed for the community is almost constant during daytime.

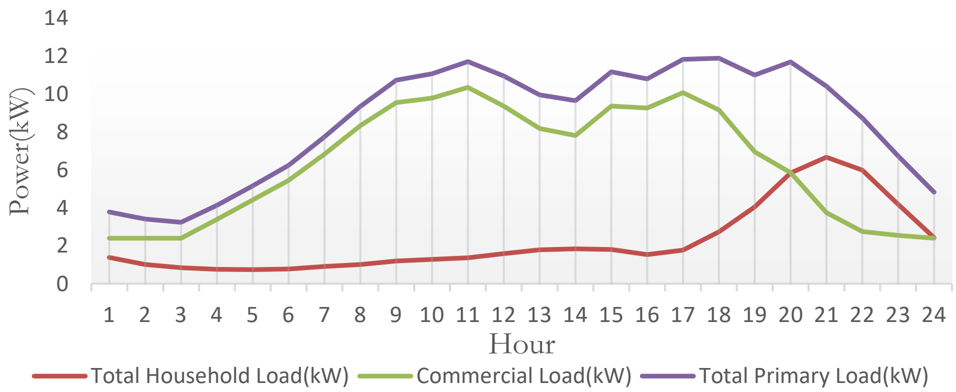


Figure 6. Households, commercial and total primary load profile for the village

The deferrable load is considered to include the water requirement for irrigation purpose and Yamaha clean water supply water for drinking purpose (5 kWh/day) [66]. Figure 7 shows the proposed deferable load estimated based on the consumption of water irrigation pump and the Yamaha clean water supply system.

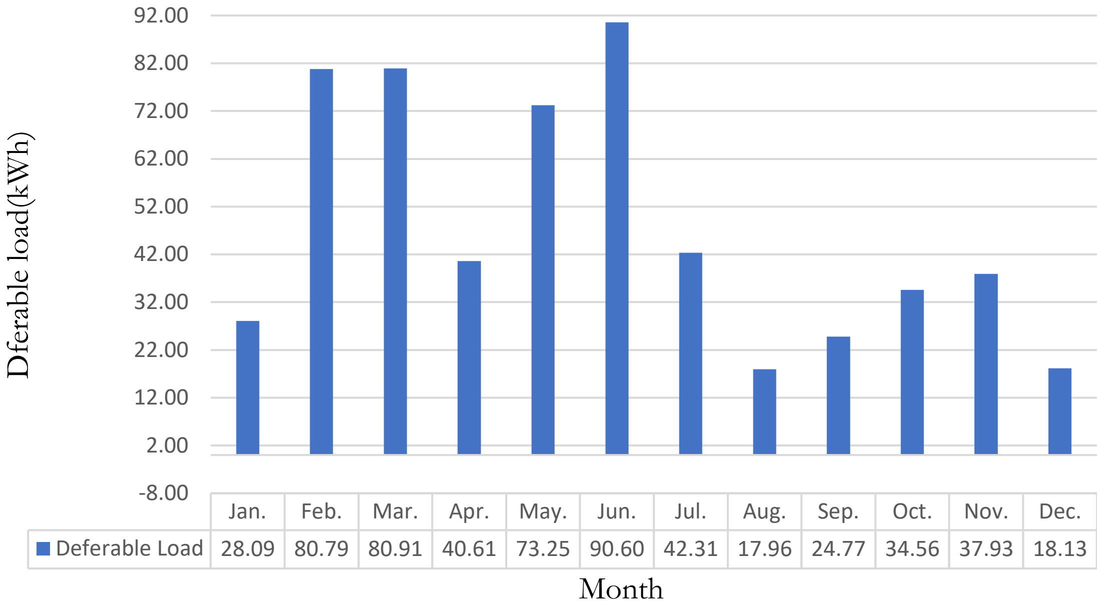


Figure 7. Average daily deferable load estimation for each month

4 System Description

4.1 System Design

The proliferation of mini-grids is increasing in SSA, but the financial sustainability of mini-grids is still an issue in African mini-grids [24]. The introduction of PUE in rural mini-grid context can have an impact on making investment in mini-grids more attractive [4]. As mentioned in the aim, the main scope of this study is to introduce cost factor in the mini-grid deployment initiative undergoing in Ethiopia which is assumed can be a model for such initiatives in other SSA countries. Based on a load profile assessment made in chapter 3, the mini-grid will be designed in consideration of the current energy policy, and plans set by the GOE. For suggesting a financially interesting investment for the specific site, a techno-economic simulation study will be made for a PV hybrid mini-grid system which include battery storage component.

The NEP 2.0 energy policy document states that Ethiopia will reach 100 % access to electricity by 2025 by mixing 65 % grid and 35 % off-grid solution. The communities between 2.5 km to 25 km far from the grid will be connected to the national grid between 2025 and 2030, and those far by more than 25 km will be connected after 2030. The mini-grid site selected being below 25 km far from the grid, it is expected to be connected with the grid between 2025 and 2030. The simulation study will be made for two scenarios, for a mini-grid energy system with lead acid battery and for mini-grids with Li-ion battery.

Based on these two scenarios, a mini-grid for Walta Jalala village in Oromia region of Ethiopia will be modelled using PVsyst and Homer Pro. The battery lifecycle cost will be analyzed based on a simulation study which includes temperature sensitivity of the different battery technologies in the climatic condition of the case study village. For making the analysis simpler, the batteries will be assumed to operate at an outside ambient temperature. Since GOE has a plan to connect the mini-grids with the national grid, AC based three phase systems are considered for the system design. AC configurations are also preferable since there will be more appliance and equipment option for the customers. The system design in consideration is AC coupled system, and the PV modules will be directly connected with grid-inverter. Figure 8 shows the system design for the proposed mini-grid system.

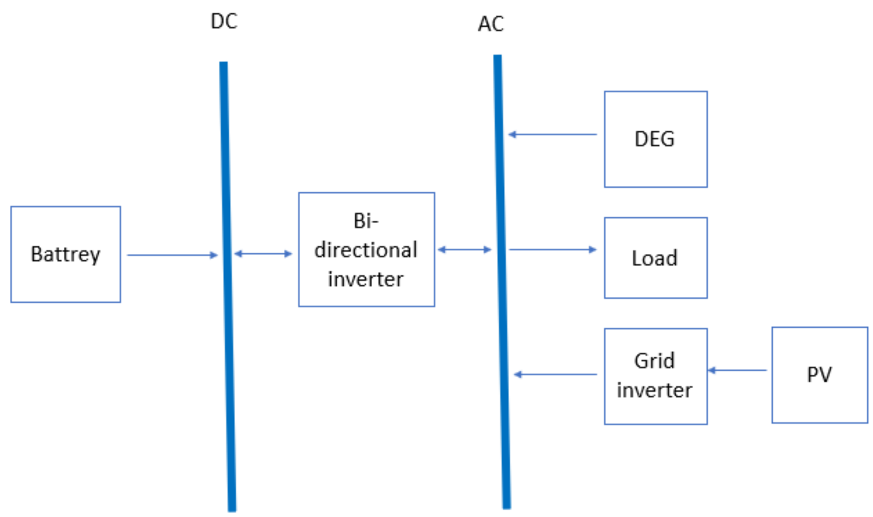


Figure 8. System design for AC coupled standalone system

4.2 Computer Tools Used for the Study

The three main tools used for this specific study are described briefly in section 4.2. As mentioned in section 1.5 , the Micro-grid Load Profile Explorer tool, PVsyst and Homer Pro tools are used as part of the methodology of this report.

4.2.1. **Micro-grid Load Profile Explorer**

The Micro-grid Load Profile Explorer tool for rural SSA is developed by National Renewable Energy Laboratory (NREL) with support from Power Africa partners, an initiative established by United States Agency for International Development (USAID) to electrify people living without electricity [34]. It is designed to provide hourly electrical load profiles for rural household types (i.e., high income, medium income, and low-income households) and for different community service centers (i.e., grain milling, small shops, schools, clinics) which are common in SSA. The weakness of the tool is that there is no variation in the load profiles from weekday/weekend and from season to season. This tool allows the user to input the number of households, types of households, and number of commercial entities in order to see how the hourly electrical load profile changes and to see how the maximum and minimum electrical load changes. In addition to the load profile estimation from the load explorer tool, a literature study has made for estimating the load profile for the mini-grid site in the case study report.

4.2.2. **PVsyst**

PVsyst is a prominent PV system study, data analysis and sizing tool. It aids to assess the solar electricity from a specific site through modelling a complete PV system, and different losses in the system. PVsyst has a feature to deal with simulation study of grid-connected, stand-alone, solar pumping systems. The tool also models grid connected systems, and battery storage for optional self-consumption, peak shaving or weak islanding. Some of the features of PVsyst include meteorological input, batch simulations and optimizations, shadings calculation, carbon balance (CO_2) evaluation etc.

4.2.3. **Homer Pro**

Homer Pro (Hybrid Optimization of Multiple Energy Resources) software is commonly used mini-grid design and analysis tool. It is originally developed at the US Department of Energy's National Renewable Energy Laboratory (NREL) and was licensed to Homer Pro Energy LLC in 2009. Homer Pro is the latest product released by Homer Pro Energy for optimization and decision analysis for hybrid renewable mini-grids. Homer Pro helps in designing in mini-grids by helping to answer a range of design questions and It has a strong future for executing sensitivity analysis and parametric studies. Some of the questions Homer Pro will answer include:

- Which technologies are most cost-effective?
- What size should components be?
- Which factors have bigger impact on the cost and operation of the mini-grids?
- Which is an economically preferable system?
- Is the renewable resource adequate?
- How much GHG emission is reduced/avoided through the system?

HOMER Pro's optimization and sensitivity analysis capabilities help answering these questions.

4.3 Energy Resource Assessment

The location where the mini-grid will be designed for is in latitude and longitude of 9°10'31.0"N and 41°31'44.8"E. The metrological data of the location is a key input to the design and sizing of the energy system. The size of the mini-grid is decided based on the available energy resource such as solar irradiation, wind velocity, biomass etc. The intermittency of the renewable energy sources and seasonal variation, temperature also has an implication on the choice of technology. The preliminary energy resource assessment is made using a satellite data from National Aeronautics and Space Administration (NASA) database. The average daily solar insolation is estimated around 6 kWh/m^2. Figure 9 shows the daily average Global Horizontal Irradiance (GHI) value for 12 months on the site.

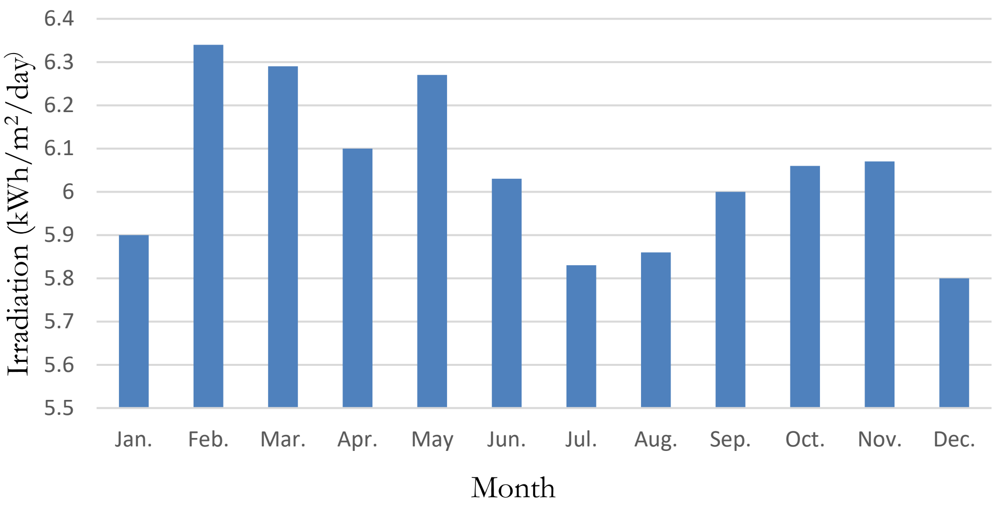


Figure 9. Daily average GHI output for the site (kWh/m^2) [68]

Since the NEP 2.0 policy document clearly states that solar based mini-grids are preferred means of rural electrification, the wind energy resource assessment is not extensively done for the village. But the first prefeasibility studies based on Global Wind Atlas shows the wind energy potential for Bedeno area is not much. The time it takes for wind resource mapping and need for experience technical for maintenance of wind turbines are also a bottleneck for such small-scale systems. There is biomass energy resource which is mainly from agricultural waste. The challenge with biomass is, the agricultural byproducts are the main source of food for the livestock and this restrains the use of biomass energy for powering the village.

From the Global Wind Atlas which is a web-based tool devised by World Bank and Denmark Technical university (DTU), at a height of 10 m, data for 10 % of windiest areas is estimated an average speed of 3.46 m/s and power density of 110 W/m^2, and an average speed of 3.94 m/s and power density of 133 W/m^2 at 50 m height for 10 % of windiest areas. The monthly average temperature for the site is also adopted from Meteonorm database and given in the Figure 10 [69].

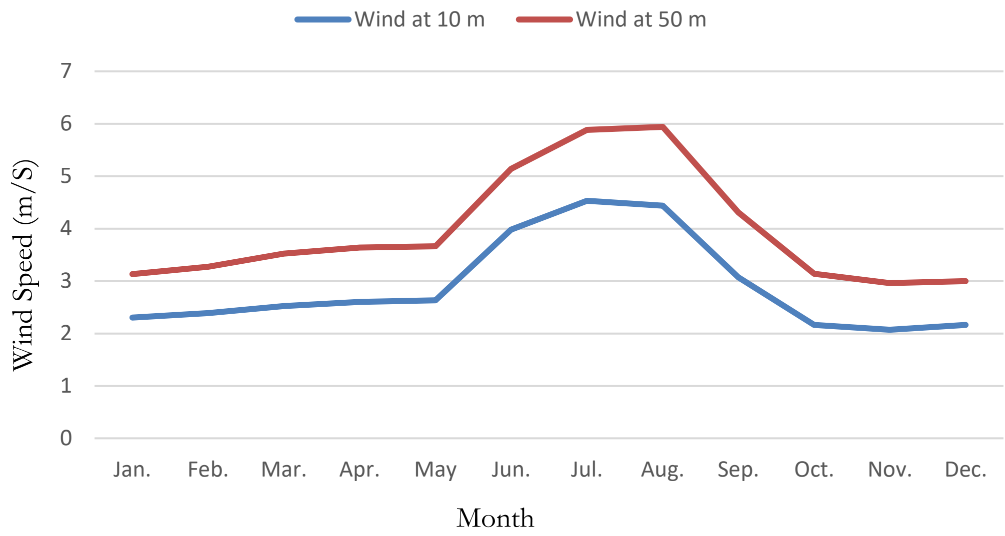


Figure 10. Wind speed at Walta Jalala village [62]

The ambient temperature for the site is also an important climatic input for the techno-economic optimization of the energy system and choice of suitable technologies. For example, ambient temperature of a site can impact on the lifetime of the battery bank and operation of the PV modules. Figure 11 shows the ambient temperature of the case study site.

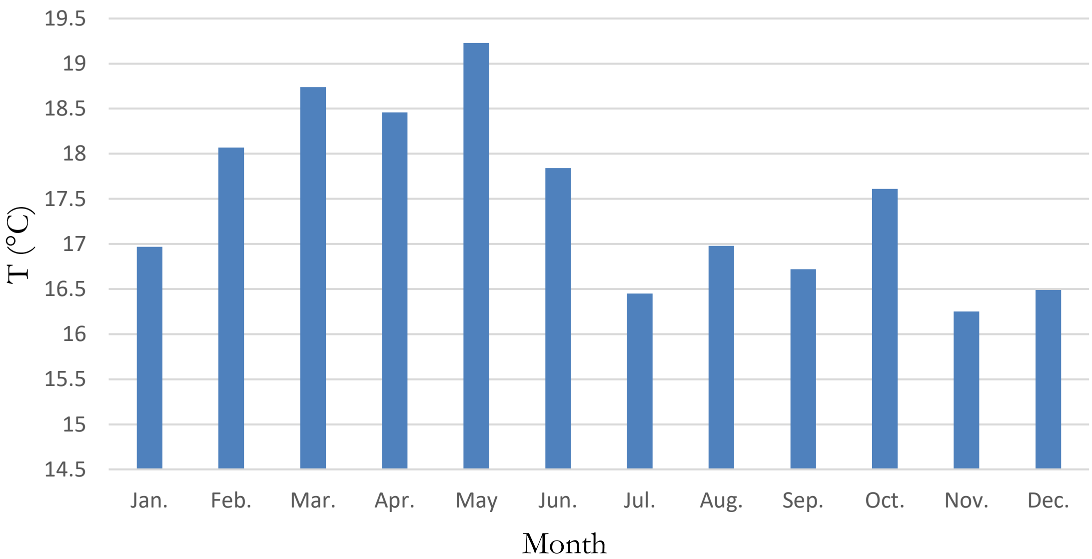


Figure 11. Monthly average ambient temperature of Walta Jalala village [68]

4.4 System Components and Sizing

The mixture of the energy source type in the proposed energy systems depends on the local availability of the resource, suitability, and cost. Solar PV, wind energy resource, DEG and storage technology (lead acid or Li-ion battery technology for this specific report) will be assessed for supplying the village in the study. These energy resource types are common in the state of art of mini-grids in SSA in addition to hydropower and biomass based mini-grids [70]. Due to unavailability of hydropower and enough biomass resource in the vicinity to Walta Jalala village, PV, wind power, DEG and battery technologies will only be studied. The inclusion of solar on the energy system increases the interoperability of the result since solar resource is almost uniformly available throughout Ethiopia and SSA.

4.4.1. **Simulation Technical Input**

Based on the availability of different renewable energy resources on the site, the optimal size of different energy types in the proposed energy system is decided with aid of Homer Pro Microgrid Analysis Tool. The Homer Pro analysis tool calculates the output from different energy resource types and equates it with cost figures input from the user for suggesting the techno-optimized system. Homer Pro uses the metrological data input from NASA and NREL database for energy resource assessment. However, in this specific study, the metrological data from Homer Pro default databases will only be used for wind resource assessment. For the PV part, the solar radiation resource from Meteonorm database will be used. Since PVsyst has a more detailed analysis of PV systems, the PV part will be analyzed using PVsyst tool, and the production data will be imported to Homer Pro through its PVsyst data importing wizard. This helps to use the strength of PVsyst on PV systems simulation, and Homer Pro on hybrid system sizing simultaneously.

The PV modules of 25 kW is sized with 25 kW SMA grid inverter in PVsyst, and the hourly production data is exported from PVsyst and imported to Homer Pro. This procedure is followed for south oriented PV system with a fixed orientation, and for another system with east-west (EW) orientation, for verifying whether EW orientation can facilitate the absorption of the direct PV energy substantially or not. The reason why 25 kW system is chosen is due to a previous mini-grid tenders floated by Ethiopian Electric Utility stated that the maximum amount of PV allowed per sting is 25 kW. In addition to the PV, wind turbine manufactured by Ennera Energy Windera, with rating of 3.2 kW is and associated cost figures are feed as input to Homer Pro.

More, the technical specification of two commercial products of lead acid battery and Li-ion battery technology are fed into Homer Pro from the manufactures data sheet. The hourly temperature of the site is also imported to Homer Pro so that the tool can suggest a techno-optimized system based on the cost of the battery technologies and their modelled behavior at different climatic and operating condition. Bi-directional inverters and DEG are the other system components considered in Homer Pro simulation study. Table 20 and Table 21 show the technical parameters and components considered during PVsyst and Homer Pro simulation study. In the PVsyst simulation shading scene is not defined assuming that there will be plenty of space in the site without near shading obstacle in the PV modules.

Table 20 PVsyst system simulation inputs

PVsyst simulation components, parameters and assumed losses	
Inputs	Description
PV module	Model: CS6V - 250MS, 250 W, manufactured by Canadian Solar
Grid-inverter with two MPPT inputs	Model: Sunny Tripower 25000TL-30, 25 kW, manufactured by SMA
Orientation and tilt	15° and 0° for fixed orientation system (south oriented)
	15° and -90/90° for EW orientated system
Albedo	20 %
Soiling loss	3 %
PV module Degradation	0.4 %/year
Light induced Degradation	2 %
Other loses	3.9 %

In the PVsyst input in Table 20, the assumed losses are estimated 9.3 % without including PV loss due to temperature, and the impact of spectral correction which will be added by PVsyst during simulation. The PV production output will then be an input to Homer Pro. The technical components and parameters which are an input to Homer Pro are also given in Table 21.

Table 21 Homer Pro simulation component inputs

Homer Pro inputs	Description
PV	PVsyst electricity output
Wind turbine	Ennera Windera S, 3.2 kW
Lead Acid battery	Hoppecke OPzS 2-520, C100/520 Ah, manufactured by Hoppecke
Li-ion battery	B-Box PRO 2.5, C10/50 Ah, manufactured by Byd
Battery inverter	Generic with 96 % DC/AC to AC/DC efficiency
DEG	Generic auto size option
Hourly ambient temperature	From Meteonorm database
Wind speed and power density	From Global Wind Atlas, and NASA database
Load profile	Estimated primary and deferable load

The computer simulation-based study of lead acid and Li-ion battery technologies in mini-grid setting being one of the aims of this study, the properties of the two representative commercial products were also sourced from their data sheet and modeled in Homer Pro tool. In the section 4.4.1.1 and section 4.4.1.2, these properties are discussed in brief.

4.4.1.1. Lead Acid Battery (Hoppecke OPzS 2-520)

The lead acid battery type modeled is vented type vented lead acid battery type manufactured by Hoppecke. It has a nominal voltage of 2 V and a C-100 rating of 520 Ah [71]. Table 22 shows the technical parameters of the lead acid battery type modelled.

Table 22 Technical parameters of the battery modelled

Parameters	Quantity
Nominal voltage (V)	2
Round trip losses (%)	14
Minimum SOC (%)	50
Maximum charging current (A)	104
Minimum charging current (A)	104
Internal resistance (mΩ)	1
Content shelf life (years)	20
Operating temperature (℃)	-20 to 55
Mass (kg)	28.10
Conductance to ambient (W/K)	10
Specific heat capacity (J/(kgK)	800

The internal resistance of the battery stated in the table above is considered in the simulation study of lead acid behavior to amount the loss due to the resistance in the battery. This effect will be considered by Homer Pro Advanced Storage Model. The operating temperature versus capacity, depth of discharge versus cycle life, temperature versus lifetime years of the battery is also exported to Homer Pro for studying the battery behavior. Figure 12 shows how the capacity of lead acid battery changes with respect to operating temperature. The nominal capacity of lead acid battery is given for 20 °C.

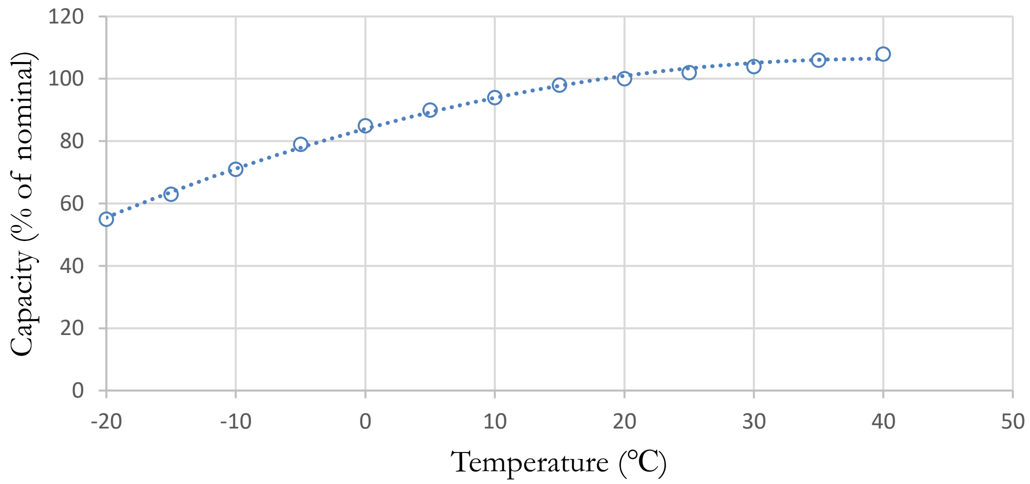


Figure 12. Temperature versus capacity graph for Hoppecke batteries

In additional to the nominal capacity of the battery, the lifetime in years of batteries is related with operating temperature. Figure 13 shows the estimated lifetime of the modelled battery with respect to operating temperature.

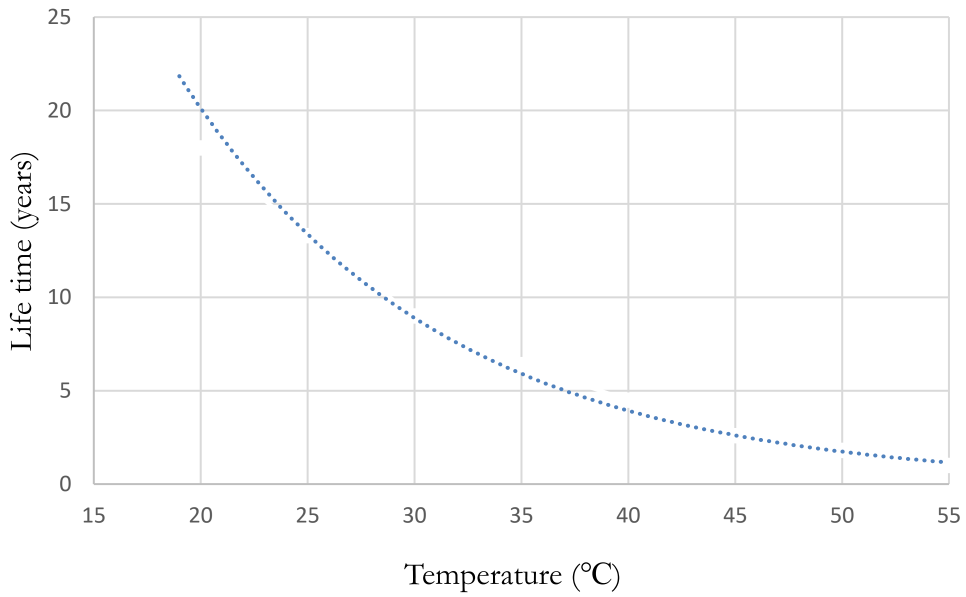


Figure 13. Temperature versus lifetime graph for Hoppecke battery

The cycle life of the lead acid battery also depends on the depth of discharge of the battery. Figure 14 shows the relation between depth of discharge and cycle life of the battery.

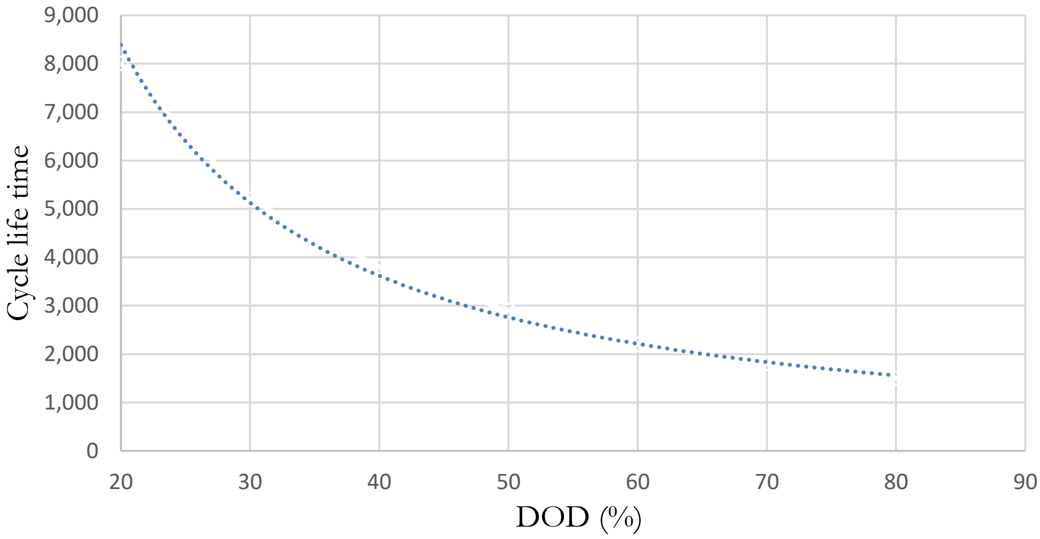


Figure 14. DOD versus cycle lifetime graph for Hoppecke battery

4.4.1.2. Li-ion Battery (B-Box PRO 2.5)

The representative Li-ion battery technology considered is lithium iron phosphate (LFP) based battery type manufactured by Byd [72]. The battery has a nominal voltage of 51.2 V and a capacity of 2.5 kWh. For Li-ion battery the discharging hour does not have an impact on the discharge capacity [73]. Table 23 shows the modeled Li-ion battery´s simulation parameters.

Table 23 Li-ion simulation parameters

Parameters	Quantity
Nominal voltage (V)	51.2
Round trip losses (%)	4.7
Minimum SOC (%)	20
Maximum charging current (A)	50
Minimum charging current (A)	100
Internal resistance (mΩ)	21
Constant shelf life (years)	15
Mass (kg)	79
Operating temperature (°C)	-10 to 50
Conductance to ambient (W/K)	10
Specific heat capacity (J/(kgK))	1100

The characteristic of proposed Li-ion battery type as coined from the manufacturer data sheet are collected as an input to Homer Pro [72]. The discharge capacity of Li-ion batteries in relation with operation battery, in Figure 15 shows that Li-ion battery has elevated discharge capacity at higher temperature.

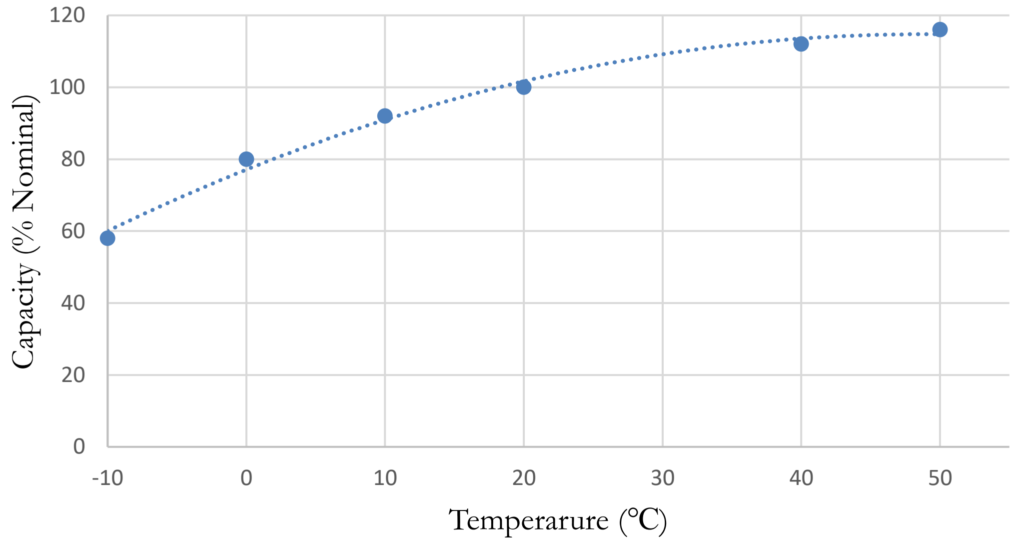


Figure 15. Temperature versus capacity relation chart

In the Figure 16, the cycle life of the representative Li-ion battery in comparison with the operating temperature is given. From the figure, it can be seeing that the proposed Li-ion battery technology have around 6000 cycles of life at 80 % DOD.

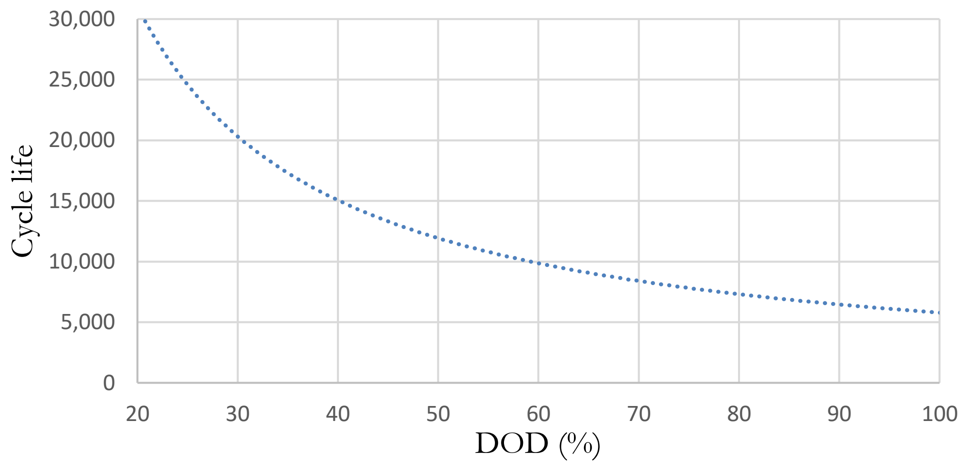


Figure 16. Temperature versus cycle lifetime chart

The temperature versus the lifetime in year of the representative Li-ion battery technology is not given in the manufactures data sheet. Instead, cyclic degradation properties defined in Figure 16 will be used to introduce maximum lifetime operation. In addition to this, a constant shelf life of 15 years is put as an input to Homer Pro model to limit the maximum lifetime of the battery to 15 years. In the section 4.5 the cost figures assumed in the Homer Pro simulation study will be discussed.

4.5 Homer Pro Simulation Study Economic Input Parameters

As mentioned in the method section, Homer Pro tool is used for techno-economic optimization of the mini-grid components. For taking advantage of the strength in PVsyst tool, the PV part of the mini-grid is simulated in PVsyst algorithm, and the output from PVsyst is imported to Homer Pro tool. The cost figures considered for different components of the mini-grid during the Homer Pro simulation study are shown in Table 24. The cost figures are taken form World bank report on mini-grids [4]. The cost figures in the report are available for two countries from SSA, Kenya and Ghana. Due to the geographical proximity of Kenya to Ethiopia, the cost figures in Kenya are opted for use as an input to

Homer Pro. Table 24 shows the economic figures considered for Homer Pro simulation study.

Table 24 Economic inputs for Homer Pro simulation study

Simulation study inputs	Cost and other simulation parameters
Project lifetime	25 years
Inflation rate	7 %
Discount rate	10 %
Annual capacity shortage	0 %
DEG:	Capex: $773/kW Oil price: $0.5/l O&M: $0.030/op hour
PV (including PV rack and grid inverter)	Capex: $1542/kW O&M: $10/kW/year
Wind turbine, Ennera Windera S, 3.2 kW	Capex: $3750/kW O&M: $20/kW/year
Lead acid battery: Hoppecke OPzS 2-520	Capex: $167/kWh Replacement: $167/kWh O&M: $15/kWh/year
Li-ion battery: BYD battery 2.5 kW	Capex: $598/kWh Replacement: $598/kWh O&M: $5/kWh
Bi-directional Inverter:	Capex: $503/kW Lifetime: 15 years. Efficiency: 96 % DC/AC to AC/DC
Distribution grid for 310 connections	$48 800 ($160 / connection)
Grid extension	$20 000/km [74]
O&M cost for grid	$1000/yr/km [74]
Unsubsidized grid power price	$0.09/kWh

5 Result

The simulation study result of PVsyst tool and Homer Pro tool will be discussed in chapter 5. Since the Homer Pro simulation result will take the PV production output from PVsyst as its input, the PVsyst simulation study will be executed priorly. The result from the PVsyst simulation study in addition to the technical and economic parameters described in chapter 4 will then be an input to Homer Pro simulation tool. The summary of the method used for this study is shown in Figure 17.

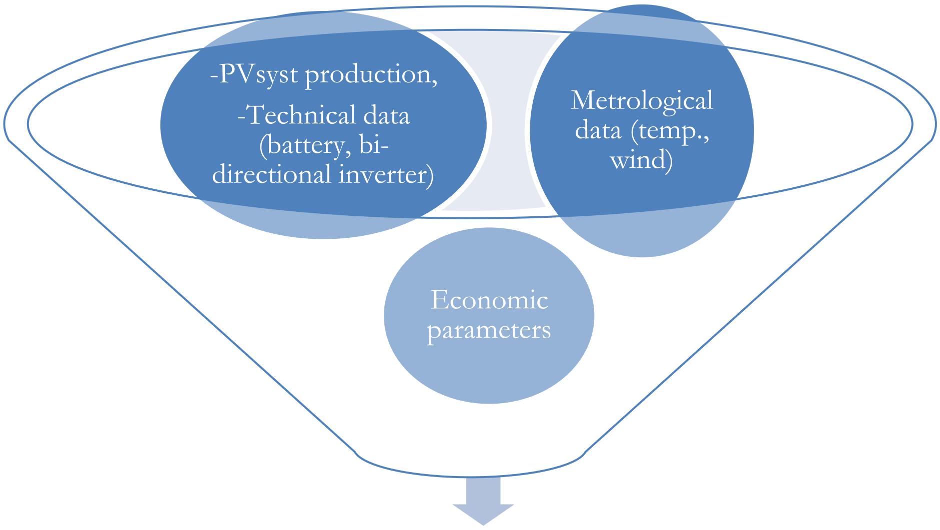


Figure 17. Summary of the method used for this study

5.1 PVsyst Simulation Result

The PVsyst simulation study is made for a modular size of 25 kW system in considering two ways of installing the system i.e., south oriented and EW orientation system. The AC output from the PV system after the grid inverter is shown in Table 25.

Table 25 PVsyst Simulation Result

Month	South oriented-PV (kWh) Tilt: 15°, Azimuth: 0°	EW-PV (kWh) Tilt:15°, Azimuth: -90°/90°
January	4268	3706
February	3645	3323
March	3915	3765
April	3377	3423
May	3325	3551
June	3170	3451
July	2989	3185
August	3138	3228
September	3435	3388
October	3901	3628
November	4140	3645
December	4303	3677
Year	43607	41970

The yearly average PV electricity for each hour of the day from the two systems is also shown in Figure 18. As the figure depicts, the PV output from the south oriented system has a bit higher production than EW system in the noon time. The EW system also looks to have marginally higher production than the south oriented system in the early morning and late afternoon.

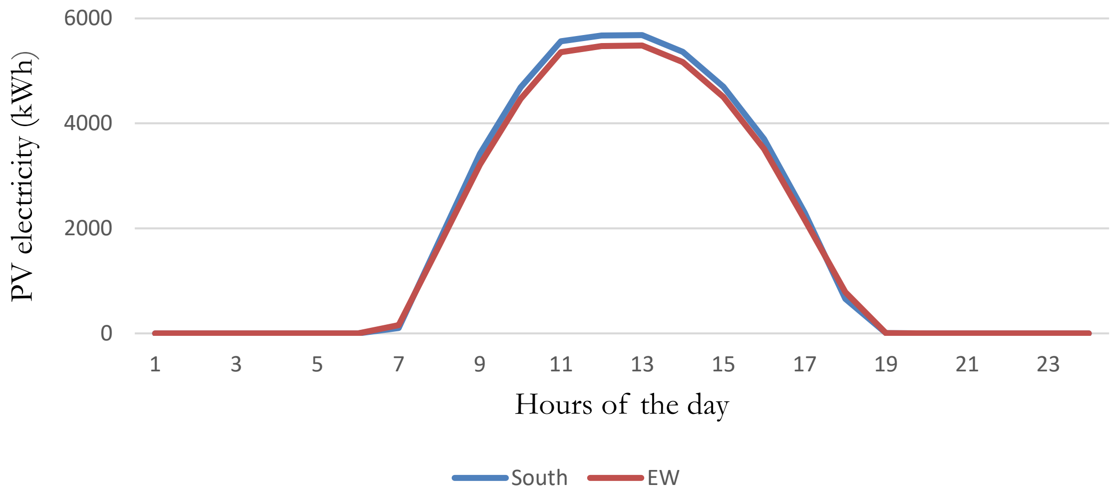


Figure 18. Hourly average electricity produced from south and EW oriented PV system

Figure 19 shows the normalized production and loss factor of PVsyst simulated result. As it is seen in the figure, the loss factor due to PV array losses (for example temperature loss, light induced degradation, aging, soiling) and system loss (such as invertor loss) can reach 16.4 %.

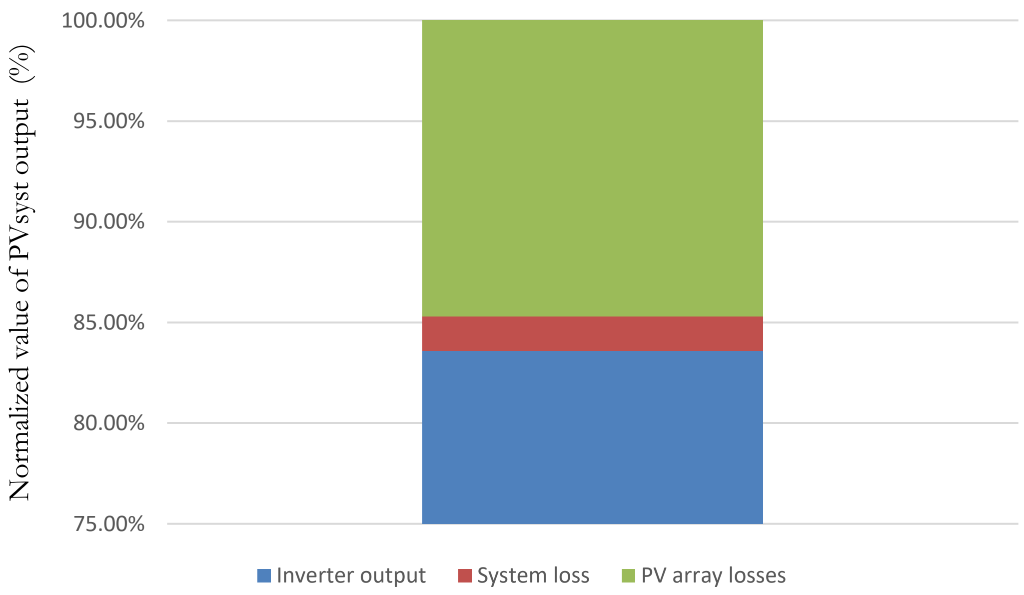


Figure 19. Normalized PV electricity and loss factor of PVsyst simulated system output

5.2 Homer Pro Simulation Result

The Homer Pro techno-economic optimization tool suggests a cost optimal system component based on design boundary and least Net Present Value (NPV). The tool takes the inputs from PVsyst result, other technical inputs, economic parameters, and metrological information for proposing component sizing. In the section 5.2.1 and section 5.2.2 the Homer Pro simulation result is described.

5.2.1. **System with Lead Acid Battery**

The techno-economic optimization study with lead caid battery system obtained the hybridization of PV, DEG and battery as techno-optimal system for the specific site. The simulation study is made for two scenarios, for south oriented PV system and for PV installation in EW orientation. The goal behind including EW system is to test out if EW system can produce in the morning and evening time where household peak can happen, and to find out whether it has a significant effect on the NPV or not. The cost optimal system and economic result for the two scenarios is discuss in the following section.

Scenario 1: South oriented PV system
Tilt: 15°, Azimuth/Orientation: 0 °/ South

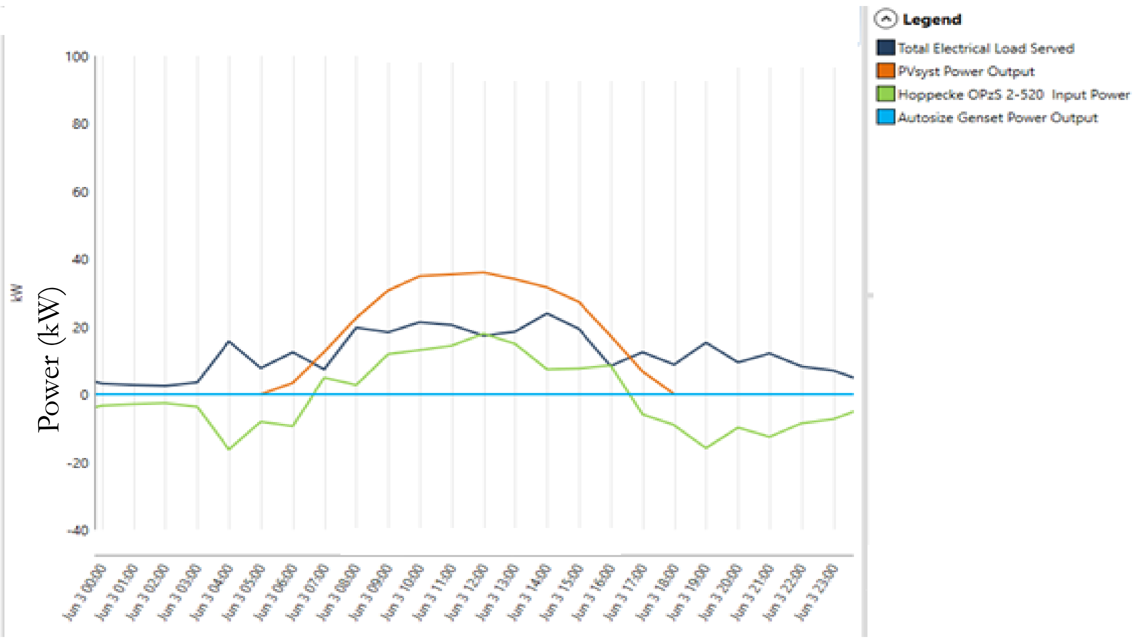
Under this scenario, the PVsyst PV AC output for south oriented system is feed into Homer Pro with other components, and economic figures mentioned in chapter 4. The optimal system size as proposed by the tool, and its related cost figures are shown in

Table 26. The load profiles will be covered fully with PV size of 35.5 kW, 245 kWh battery size and a backup generator of 35 kW.

Table 26 South oriented PV system results with lead acid battery

Component	DEG (kW)	PV (kW)	Bi-directional inverter (kW)	Battery (kWh)	LCOE ($/kWh)	RE fraction (%)
Size	35	35.5	20	245	0.169	94

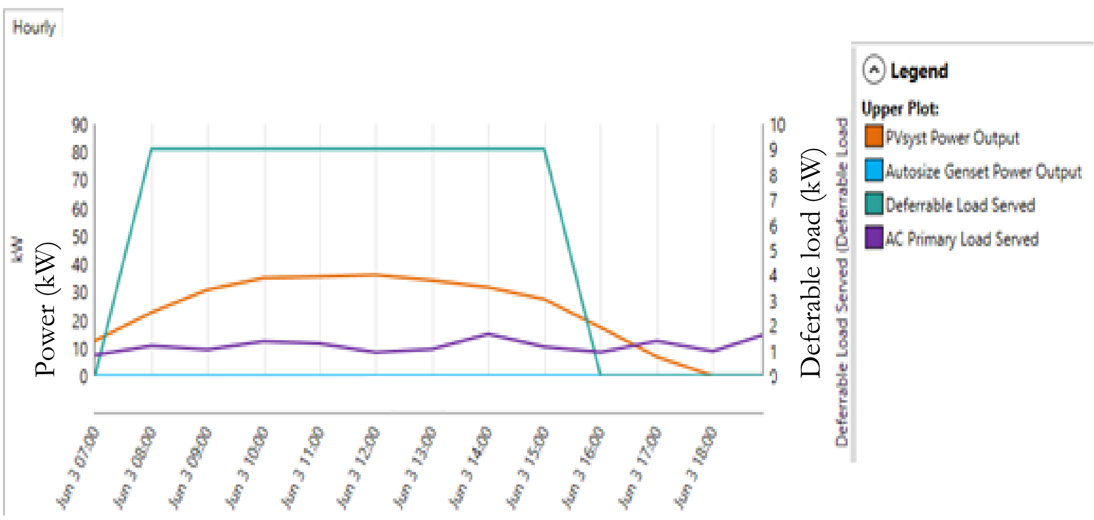
The electricity demand is majorly covered by the renewable energy sources (PV and battery), and the rest 6 % through the DEG. In the Figure 20, hourly power output and consumption pattern is shown for a single day of the year. It shows that for June 3 in the Figure 20, the daily energy consumption is covered by PV and battery output. From 0:00 hour to 05:00, the battery is discharged to cover the load over non-sunshine hours, and the PV full covers the load from 06:45 till 16:45. In the middle of 05:00 and 06:45, both the battery and PV contribute to cover the AC load. From 06:45 till 16:30, the excess PV is also charging the battery.



Hours of day for June 3

Figure 20. Mini-grid hourly power output and consumption pattern for Jan 3

Figure 21 shows the hourly deferable load, primary load, and the PV (represented as PVsyst in the graph) power output graph. The PV electricity output primarily serves the primary load, and when there is excess electricity it will serve the deferable load. The deferable load is shown in the right side-Y-axis. As it is seen in Figure 21 , the deferable load is following the PV excess during the sunshine hours and it is served from 07:00 to 16:00, when there is excess PV electricity production than the primary load requirement.



Hours of day for June 3

Figure 21. Deferable load, Primary load, and PV output

Figure 22 shows the hourly power generation from PV (represented as PVsyst in the graph), DEGS, battery, and the total electric load served. The DEG started when there is power shortage from PV and battery to serve the load. As the Figure 22 shows the DEG is charging the battery and covering the load when the PV output could not cover the load.

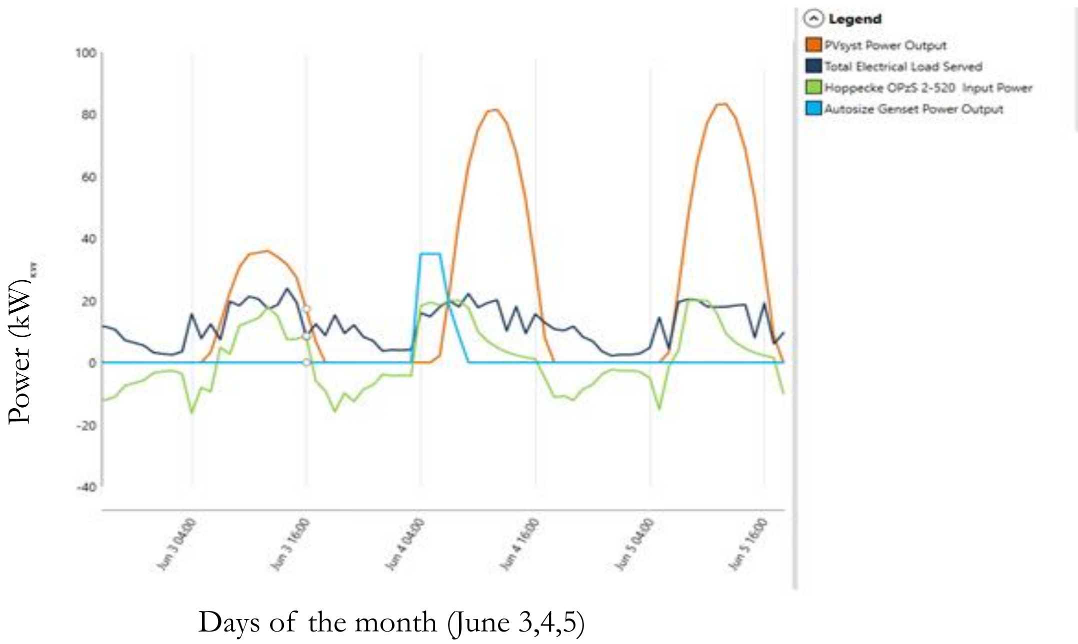
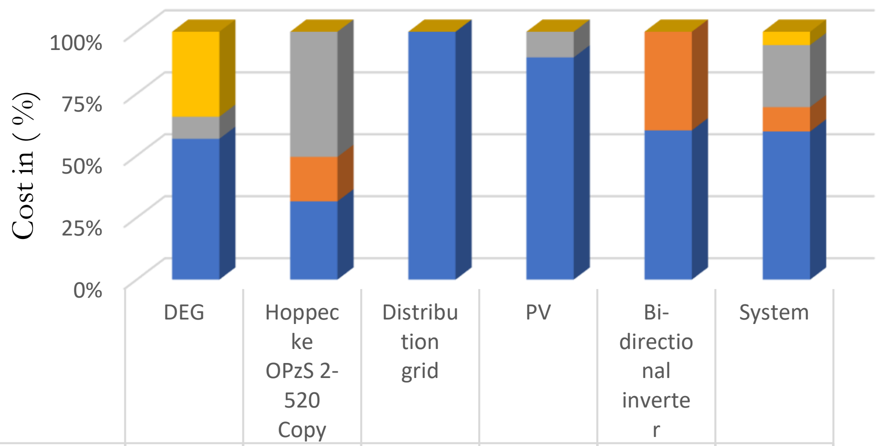


Figure 22. PV, battery, electric load and DEG´s pattern

The financial figures for different components of the system, including their capital cost, O&M, and the replacement cost is given in the Figure 23. From the Figure 23, it can be seen that the capital cost takes the higher share of the total expense for PV, distribution grid, bi-directional inverter, DEG and the total system cost. The reason why the capital cost of the DEG being higher than its operating expenses (Opex) has a relation with the generator being seldom used since the PV and battery are covering more than 90 % of the time. The battery component instead has a higher operation and maintenance cost since vented lead acid battery types need regular maintenance. With the regular maintenance, the manufacturer data sheet shows that it can have 18 years life, depending on its operational DOD.



	DEG	Hoppecke OPzS 2-520 Copy	Distribution grid	PV	Bi-directional inverter	System
Fuel	16327	0	0	0	0	16327
Operating	4243	65416	0	6304	0	75962
Replacement	0	23213	0	0	6645	29858
Capital	27055	40915	48800	54613	10060	181443

Capital Replacement Operating Fuel

Figure 23. Cost figures for south oriented system with lead acid battery

Scenario 2: PV modules with EW orientation
Tilt: 15°, Azimuth/Orientation: -90°/90°

On this scenario, the EW faced PV system production output is feed into Homer Pro. The aim behind this is to check if facing the modules in EW orientation can distribute the PV electricity output in the morning and afternoon in equal way. This could help in better use of the PV supply by offsetting the peak in the noon time before and after noon. The PV, DEG, battery and other components size and cost proposed by the Homer Pro tool is shown in Table 27. It contains a result for both the EW oriented and south oriented system.

Table 27 Optimal system components for mini-grid with lead acid battery

Description	South oriented	EW oriented
PV (kW)	35.5	35.5
DEG (kW)	35	35
Lead-battery (kWh)	245	242
Bi-directional inverter (kW)	20	20
NPV ($)	277 492	274 148
LCOE ($/kWh)	0.169	0.167
Renewable fraction (%)	94	94

From Table 27, it is shown that the optimal PV array size for the system with EW orientation and south oriented system is equal to, 35.5 kW. More the DEG size and bi-directional inverter size for each system is similar. The distribution grid component contains only a capital cost due to the O&M cost are assumed to be included in it. There is a marginal difference in battery size and LCOE for the two systems. The marginal reduction in LCOE in EW oriented system is might be related with the system with EW orientation is lower from the system with fixed orientation, and this might relate with the higher PV production from EW system in the morning and afternoon in comparison with the system with fixed orientation. Otherwise, the economic parameters for system with EW PV installation share the same property with the system in scenario 1 except a little lower cost for a system in scenario 2.
Figure 24 shows the cost of different components for system in Scenario 2.

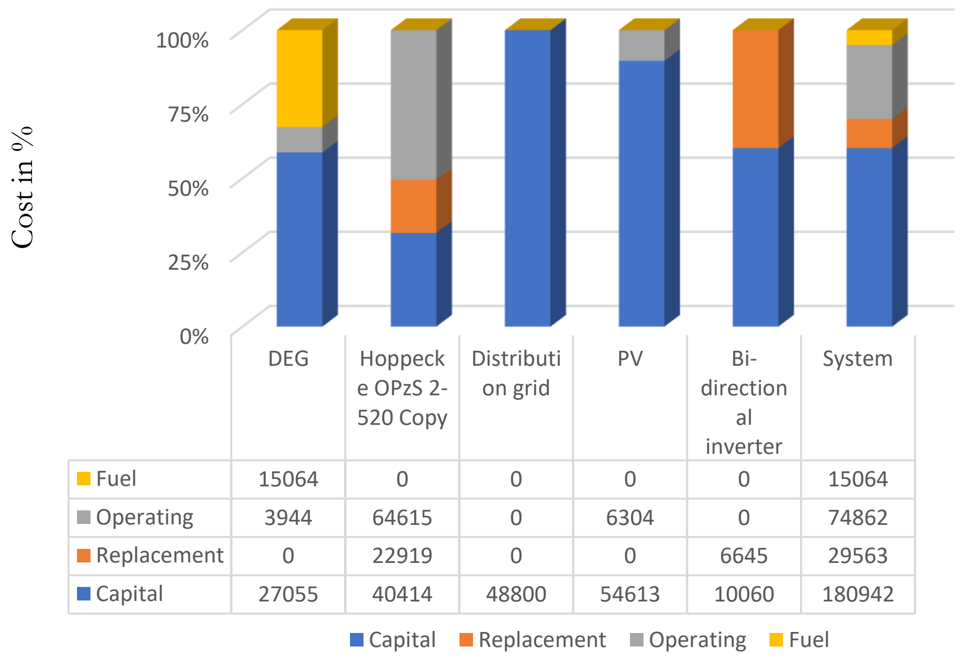


Figure 24. Cost figures for EW oriented system with lead acid battery

5.2.2. **System with Li-ion Battery**

The procedure for Homer Pro simulation study of systems with Li-ion batteries is the same as the system with lead acid batteries. The result from the techno-economical optimizing exercise for the two scenarios of PV system installation is discussed in this section.

Scenario 1: South oriented PV modules
Tilt: 15°, Azimuth/orientation: 0 °/ South

The Homer Pro tool optimal system size and associated cost figures for system with Li-ion batteries in scenario 1 is shown in Table 28. The community load profile can be fully covered with 35.5 kW of PV, 120 kWh of battery and a backup generator which has contribution of less than 6 % to the total energy delivered to the load. One of the interesting results in this analysis is the PV size and LCOE of the system with Li-ion battery has almost similar figure to the systems with lead acid battery.

Table 28 Homer Pro result for south oriented system with Li-ion battery

Component	PV (kW)	DEG (kW)	Bi-directional inverter (kW)	Battery (kWh)	LCOE ($/kWh)	RE fraction (%)
Size	35.5	35	20	120	0.167	94

The cost of different components of the south oriented system with Li-ion battery under scenario 1 is also shown in Figure 25. As the Figure 25 shows, the capital cost takes the lion share of the total cost of PV, DEG, Li-ion and battery. The distribution grid component contains only a capital cost due to the operation and maintenance cost are assumed to be included in it.

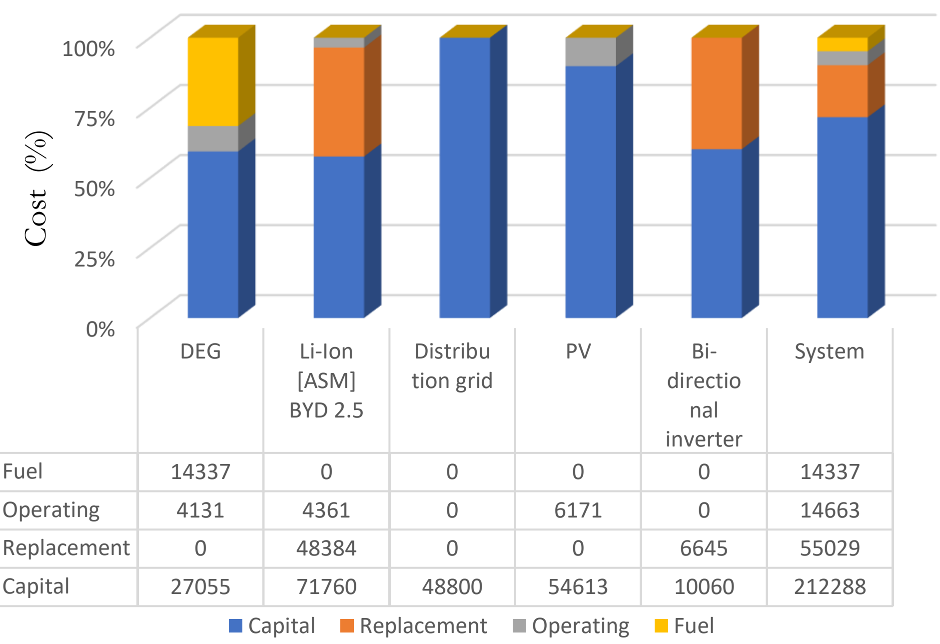


Figure 25. Cost figures for south oriented system with Li-ion battery

Scenario 2: PV modules with EW orientation
Tilt: 15°, Azimuth/orientation: -90°/90°

Under scenario 2, the load is covered by a system which includes, 33.25 kW PV system, 122.5 kWh of Li-ion battery and a diesel genset back-up. The optimal system with EW oriented PV in scenario 2 has a PV size and renewable fraction which is a bit less than the system in scenario 1. However, its NPV value for the system with Li-ion battery under scenario 2 is marginally lower than the system under scenario 2. However, concluding from this marginal difference in NPV value is prone to uncertainty. Table 29 shows the optimization result for the two scenarios defined for the system with Li-ion batteries.

Table 29 Optimization result for Li-ion battery

Description	Scenario 1-Li	Scenario 2-Li
PV (kW)	35.5	33.25
DEG (kW)	35	35
Li-battery (kWh)	120	122.5
Bi-directional inverter (kW)	20	20
NPV ($)	274 572	271 683
LCOE ($/kWh)	0.167	0.165
Renewable fraction (%)	95	95

The cost for the optimal system with EW PV orientation is also given the Figure 26. The same way with the system in scenario 1, capital cost has the largest share in each of the mini-grid components.

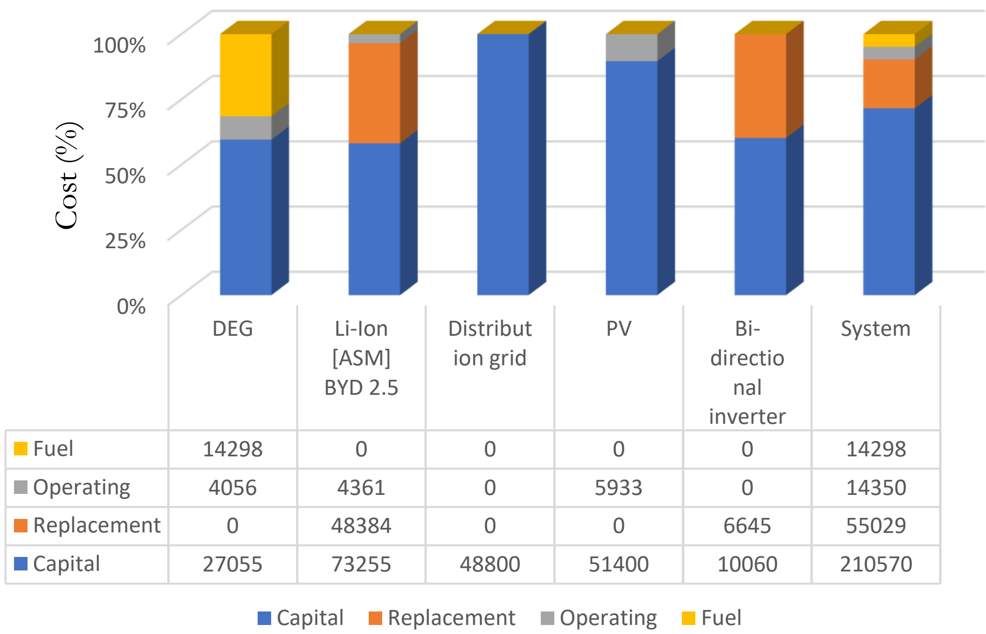


Figure 26. Cost figure for EW optimized system with Li-ion battery

The Homer Pro optimization result summary is shown in Table 30. From the Table 30, the system with lead acid batteries needs a kWh capacity of battery which is almost twice higher than its Li-battery counterpart. The economic figures and component sizing for other systems almost looks similar for system with representative lead acid battery and Li-ion battery.

Table 30 Homer Pro optimization result summary

Description	Scenario 1-lead	Scenario 2-lead	Scenario 1-Li	Scenario 2-Li
PV (kW)	35.5	35.5	35.5	33.25
DEG (kW)	35	35	35	35
Battery (kWh)	245	242	120	122.5
Converter (kW)	20	20	20	20
NPV ($)	277 492	274 148	274 572	271 683
Capital ($)	181 442	180 941	212 288	210 570
LCOE ($/kWh)	0.169	0.167	0.167	0.165
Renewable fraction (%)	94	94	95	95

Since the maximum difference between the NPV for the least NPV system with EW orientation and the highest NPV system for south oriented system is less than 3 %, the benefit from EW orientation is marginal and is also prone to uncertainty. Due to this reason the sensitivity analysis, and the comparison between the state of the mini-grids with lead acid and Li-ion battery technology mainly focus on systems with south oriented PV system. In fact, since the since this small margin can also be diminished with intentional demand side management strategies, by shifting loads to times where PV electricity output is available.

5.2.3. **Sensitivity Analysis**

5.2.3.1. Temperature Sensitivity Analysis

The sensitivity analysis is done to check the effect of temperature change in the cost sensitivity of the mini-grid NPV and LCOE. This is due to the temperature effect on the efficiency of the solar modules and batteries. Particularly, the effect of operating temperature being a critical factor on the lifetime of battery, the sensitivity analysis will show the performance of the two battery technologies at different temperatures. The sensitivity analysis will be done only for south oriented PV system with lead acid battery, and Li-ion battery technology. The temperature range in sensitivity analysis are intentionally ranged from 10 ℃ to 40 ℃. This is to consider different climatic conditions in Ethiopia and SSA. The sensitivity analysis helps to interpolate the result from the study to different climatic conditions. The average annual temperature for the case study village of Walta Jalala village, 17.5 ℃, is used as reference value. The sensitivity analysis is done for 10 ℃, 20 ℃, 25 ℃, 30 ℃, and 40 ℃. The result for temperature sensitivity of lead acid battery is given in the Table 31.

Table 31 Sensitivity analysis of system with lead acid battery with temperature

Temp (℃)	10	17.5	20	25	30	40
PV (kW)	35.5	35.5	35.5	37	37.5	24.6
Battery (kWh)	275	245	237	217	210	97
NPV ($)	283 723	277 492	275 983	286 959	310 889	388 710
LCOE ($/kWh)	0.173	0.169	0.168	0.174	0.189	0.236
RE (%)	94	94	94	94	93	62

As it can be seen in the Table 31, the LCOE of the mini-grid with lead acid battery increases with the increase in the temperature of beyond 20 °C. This is true for the NPV of the whole mini-grid system too. The reason behind this is related with the lower performance of the PV modules with higher ambient temperature, and lead acid batteries temperature sensitivity but the later one may have a higher effect compared with increase in module temperature. Though the LCOE of the system with lead acid battery in lower temperature than its design temperature of 20 °C has a higher value than systems operating in higher temperature than 20 °C, still the LCOE is lower than the baseline system. In Table 32, the effect of temperature change on the mini-grid system with Li-ion battery is shown.

Table 32 Sensitivity analysis of system with Li-ion battery with temperature

Temp (°C)	10	17.5	20	25	30	40
PV (kW)	34	35.5	33.25	33.25	33.25	34
Battery (kWh)	132.5	120	120	115	107.5	105
NPV ($)	285 815	274 185	271 889	266 853	263 267	259 558
LCOE ($/kWh)	0.174	0.167	0.165	0.162	0.160	0.158
RE (%)	94	95	94	94	94	94

The impact of higher temperature increase on the LCOE of the system with Li-ion is much less compared to the system with lead acid batteries, on the contrary, Li-ion batteries performance at lower temperature is poorer compared to higher temperature. This might be true if the comparison is made at the same DOD consideration. As it is seen in the Table 32, the LCOE of the mini-grid with Li-ion batteries have an increment inclination with less operating temperature, and vice versa. This being said, the recommended operating temperature of the batteries suggested by the manufactures have to be strictly followed.

5.2.3.2. Load Sensitivity

The load sensitivity analysis is done to study the effect of the deferable and community load on the overall LCOE of the mini-grid. For studying the impact of the deferable load on the LCOE, a sensitivity analysis done with assuming that the deferable irrigation water need and clean water supply unit have annual average deferable load of, 0 kWh/day, 47.5 kWh/day (initial system), and 95 kWh /day. In the case of 95 kWh/day, it means that the deferable load is doubled to irrigate 10 hectare of farm, and 2 Yamaha clean water supply unit each with a capacity to filter 8000 l per day. From table 33, without the inclusion of deferable load the LCOE is $0.196/kWh. However, with the inclusion of deferable load, the LCOE is reduced to $0.169/kWh; it is also further reduced to $0.156/kWh with inclusion of more deferable load. Though the DEG size is increased with deferable load of 95 kWh/day, the RE energy penetration difference is marginal. The result of Homer Pro simulation is given in Table 33.

Table 33 Deferable load sensitivity for system with lead acid battery

Component	Deferable load (0 kWh/day)	Deferable load (47.5 kWh/day)	Deferable load (95 kWh/day)
PV (kW)	29.25	35.5	39.75
Battery (kWh)	250	245	254
DEG (kW)	35	35	41
Bi-directional inverter (kW)	20	20	30
NPV ($)	262 210	277 492	303 591
LCOE ($/kWh)	0.196	0.169	0.156

A deferable load sensitivity, for south oriented PV system with Li-ion battery is executed with annual average deferable load of, 0 kWh/day, 47.5 kWh/day (the initial), and 95 kWh /day. The LCOE of mini-grid with Li-ion battery technology is also reduced with the inclusion of deferable load. Table 34 shows the deferable load sensitivity of mini-grids with Li-ion battery.

Table 34 Deferable load sensitivity for system with Li-ion battery

Component	Deferable load (0 kWh/day)	Deferable (47.5 kWh/day)	95 kWh/day
PV (kW)	29.25	35.5	39.5
Batt (kWh)	125	120	120
DEG	35	35	41
Bi-directional inverter (kW)	20	20	30
NPV ($)	259 917	274 572	302 518
LCOE ($/kWh)	0.194	0.167	0.155

The load sensitivity is also checked with, and without PUE and agricultural loads. A sensitivity analysis is also done without PUE load (commercial and deferable). Table 35 shows that, the LCOE for system without PUE loads is almost two times higher than the LCOE for system with PUE loads. This is true for systems with lead acid battery and Li-ion battery.

Table 35 Sensitivity without PUE and deferable load

Component	With lead acid	With Li-ion
	0 -PUE load	0- PUE load
PV (kW)	12.2	12..75
Batt (kWh)	100	50
DEG (kW)	-	-
Bi-directional inverter (kW)	15	10
NPV ($)	126,610	124,728
LCOE ($/kWh)	0.365	0.360

5.3 Comparison with Grid Connection

The LCOE implication of the mini-grid system designed for this village is also compared with average unsubsidized grid energy cost for the existing infrastructure in Ethiopia. The existing unsubsidized grid energy cost in Ethiopia is estimated $0.09 per kilowatt-hour (kWh) [75]. Though the current electricity tariff in the country is subsidized and is between around $0.04 and $0.06 per kWh, the comparison with the unsubsidized grid electricity price is made to show where the mini-grid system can be cost optimal solutions in comparison with the grid extension. Medium Volt (MV) grid extension price is estimated to be $20 000 /km, and O&M cost of $1000/year/km [74]. The break even grid extension distance for south oriented PV system with lead acid battrey is 3.43 km ,and the break even grid extension distance for yeraly optimized sytem with Li-ion battrey is obtained 3.35 km. This means that mini-grids with the LCOE proposed here ($0.169/kWh and $0.167/kWh) can be competetive for areas which are more than 3.4 km a way from the exsiting grid. Figure 27 and Figure 28 shows the break even grid extension distance for south oriented PV system with lead acid battrey and Li-ion battrey in comparison with the mini-grid LCOE.

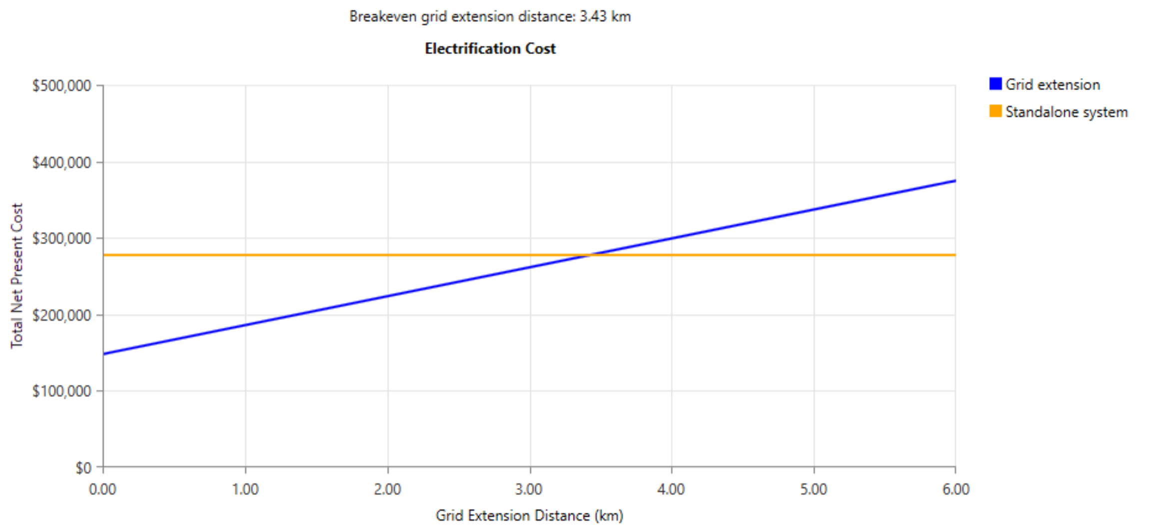


Figure 27 Comparison of mini grid with the existing grid for south oriented PV system with lead acid battery (Snap shoot from Homer Pro result)

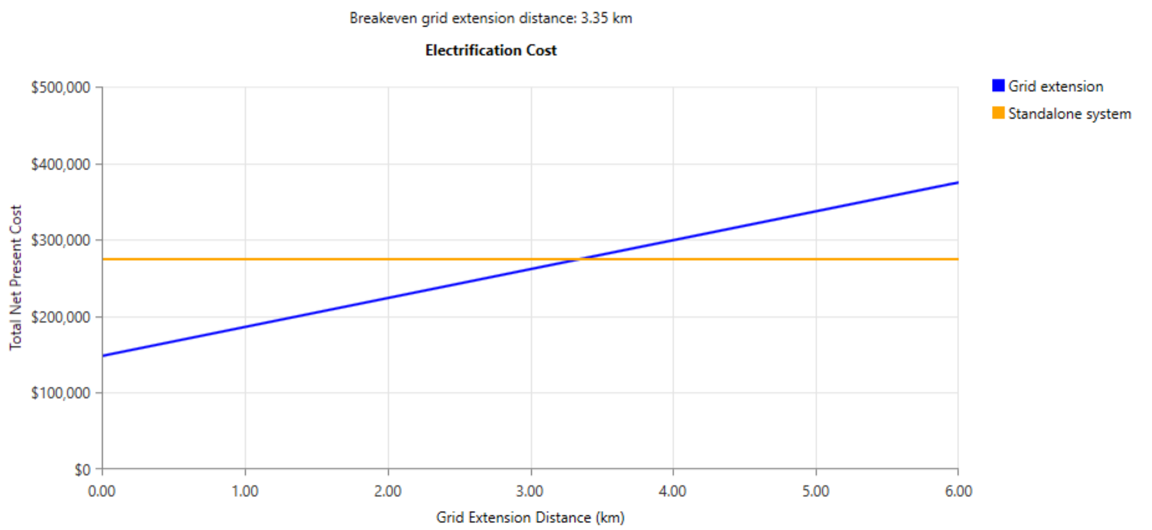


Figure 28 Comparison of mini-grid with the existing grid for south oriented system with Li-ion battery (Snap shoot from Homer Pro result)

6 Discussion and conclusion

6.1 Discussion

This specific study aimed at designing a low-cost renewable energy based mini-grids for powering rural productive hubs in SSA. This is intended to improve the financial sustainability of mini-grids in the context of Ethiopia and SSA. According to World Bank report, the baseline LCOE for solar -hybrid mini-grid is estimated $0.55/kWh while average cost reflective tariff of 39 utilities across SSA is $0.27/kWh [4]. In Ethiopia, the energy generation, distribution, and transmission cost for already operating national grid is estimated $0.09/kWh however reaching 56 % of people without access to electricity with only grid extension is cost and time intensive [8] [75]. Due to this GOE´s new energy policy, NEP 2.0, has included off-grid electrification and roll out of mini-grids as technically feasible option which can complement grid extension. But the question is more of on financial sustainability of mini-grids than technical feasibility. How the roll out of these mini-grids can be made cost optimal and competitive with grid extension?

Especially most of the unelectrified areas in Ethiopia and SSA being in rural areas where industry is in a primitive stage, the question of financial sustainability requires investigation. The aim of this study is to show the potential of stimulating agriculture led productive use of energy (PUE) for financially sustainable rural mini-grid systems in SSA. A case study site from a rural village in Ethiopia is studied in consideration of agricultural sector such as water pumping for supplemental irrigation as one of the anchor or main loads. The approach to achieving this objective was mainly through introducing PUE services and agricultural loads for irrigative water pumping, clean water supply unit. More batteries being one of the expensive mini-grid components with a risk of failure [21], the study is intentionally extended to evaluate the operational characteristic of two representative commercial battery storage technologies in mini-grids, one from each of lead Acid and Li-ion batteries. The characteristics of the two commercial battery technologies is collected from the manufacturers data sheet and imported in Homer Pro lead and Li-ion battery models; so, no field test is made on the characteristics of the batteries.

The method primarily involves estimating the household community and PUE load profile. Since the village in the case study will be connected to electricity for the first time, having organized energy audit data was not plausible. Instead, a proxy data approach is followed to estimate the primary load profile. The load profile contains primary load and deferable load. The primary load contains household and commercial load profiles. The primary load profile estimated through proxy data approach has no random variability instead stochastic random variability is introduced into the daily profile for weekdays, weekends, and seasons by Homer Pro tool (10 % day to day variability and 20 % step to step). The proposed commercial PUE loads are methodically considered to operate in sunshine hours but Milk chiller and Egg incubators are exceptions working for 24 hours period.

The deferable load contains water pumping load for supplemental irrigation and clean water supply unit. The clean water supply unit also addresses the problem of access to clean water. The deferable load (5 kWh/day) for Yamaha clean water supply unit is coined from the manufactures data sheet however the water requirement for different crops is studied from FAO guidelines, and the energy demand of irrigation pump for 5 hectares of farming is calculated based on the seasonality of rainfall in the area and a selected pump capacity from the market. The calculated crop water requirement in practice has to be reinforced with a ground tested soil and meteorological data however for areas where specific measurement data is not available, the general FAO recommendations can work [64].

The method also involves estimating the PV production output from PVsyst tool. This is to use the advantage of PVsyst´s strength on PV systems modelling, and Homer Pro´s strength on techno-optimization of hybrid systems simultaneously. Since the area has no ground measured metrological data, PVsyst default metrological database, Meteonorm, generated satellite based solar radiation data for the village. Due to the uncertainty in the satellite data and PVsyst model´s uncertainty, the PV production from PVsyst can have inaccuracy. The PV production modelled from PVsyst is imported in to Homer Pro, and Homer Pro calculated the PV size requirement for the load based on its input from PVsyst. This can also introduce uncertainty in the accuracy of Homer Pro result on sizing and economic figures. In addition to uncertainty caused by economic and technical inputs of the user, Homer Pro simulation result has also uncertainties due to its simulation precision level. The uncertainty associated with the PVsyst simulation model and Homer Pro tool is discussed in section 6.1.1 and section 6.1.1.2

Based on the method, the techno-optimized RE mini-grid system with lower LCOE is obtained with the help from PVsyst and Homer Pro tools. In PVsyst simulation, the PV electricity output for south oriented PV system is estimated as an input parameter to Homer Pro. To study if the EW orientation of PV modules instead of south oriented PV system can foster the direct consumption of PV with major cost implication or not, the PVsyst output for EW oriented system is also studied. The PV electricity output for the fixed tilt system has almost 4 % increase in electricity generated compared to the EW system. Figure 29 shows the daily average of the monthly production of the electricity from the two systems. The output from the south oriented PV system has a higher output than the EW oriented system except for the 5 months, April to August. The comparison of EW orientation with south oriented system can show that the EW orientation can also be a good choice without much loss.

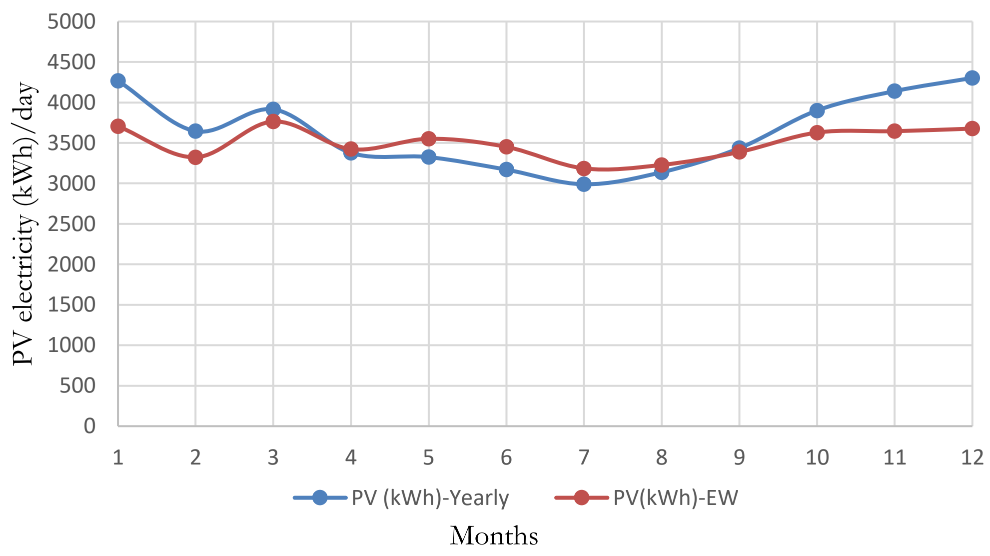


Figure 29. South oriented and EW system PVsyst output from the grid inverter

The Homer Pro optimization output summary for the min-grids with south oriented system and EW oriented PV modules, in conjunction with lead and Li-ion battery is shown in Table 30. All the mini-grids cover the load fully. From the Table 30 , the LCOE found for south oriented, and EW system with lead acid battery is $0.169/kWh and $0.167/kWh respectively. For system with Li-ion, an LCOE of $0.167/kWh for south oriented system, and $0.165/kWh for system with EW orientation is obtained.

The difference in LCOE for mini-grids with south oriented system and EW oriented system is around 1 %, which is prone to uncertainty to conclude from. However, the LCOE result show that EW orientation can also be a good option for areas in comparable latitude to the village in this specific study. For the rest of the evaluation, the comparative study between lead and Li-ion battery will stick to only south oriented system. The LCOE for south oriented system with lead acid and Li-ion battery, $0.169/kWh and $0.167/kWh, have also almost 1 % difference. This means the LCOE for mini-grid system with Li-ion battery and for system with lead acid battery is comparable for the specific case study village. However, the capital cost of the mini-grid system with Li-ion battery is more than 14 % higher than the mini-grid with lead acid battery. The renewable energy penetration of the mini-grid system with both lead acid and Li-ion battery is higher than 90 %.

The LCOE found for south oriented system with this study, $0.169/kWh and $0.167/kWh, are less compared to the World Bank report, which is $0.42/kWh for mini-grids with income generating machines of 40 % utilization factor [4]. This result is achieved due to the introduction of commercial PUE and deferable loads. From Table 36, which is an excerpt from section 5.2.3.2, the LCOE of the mini-grid system increased from the initial system by more than 13 % when there is no deferable load included in the mini-grid with both lead Acid and Li-ion battery. When the deferable load is increased by two-fold, the LCOE decreased by more than 7 %. When there is no PUE load, the LCOE increases by more than 200 %. The analysis results the same outcome with system with lead acid battery and Li-ion battery, confirming the contribution of deferable and PUE load to a low cost mini-grid.

Table 36 Load sensitivity analysis result

Component	No deferable load		Initial system		2-fold deferable		No PUE	
	Lead	Li-ion	Lead	Li-ion	Lead	Li-ion	Lead	Li-ion
LCOE ($/kWh)	0.196	0.194	0.169	0.167	0.156	0.155	0.365	0.360

Temperature sensitivity of the system is also done for south oriented system with lead acid battery and Li-ion battery. The temperature range considered is between 10 °C and 40 °C, which is the expected annual temperature range in Ethiopia. From the sensitivity analysis in Figure 30, the advantage of mini-grid with Li-ion battery begins to be clearly obvious when the average temperature starts to raise above 25 °C. The sensitivity analysis also shows that the modeled Li-ion battery have a flatter LCOE at various temperatures compared to the lead acid battery.

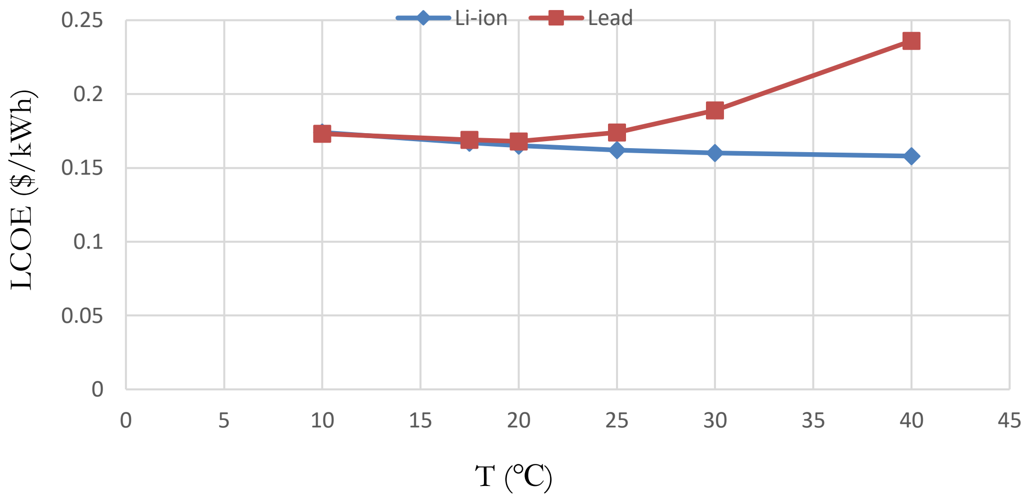


Figure 30. Temperature sensitivity of lead and Li-ion battery

6.1.1. **Uncertainty Calculation**

The uncertainty of the result from the PVsyst and Homer Pro simulation study is done based on the uncertainty and precision level recommended by the simulation tool providers. Literature is also reviewed to assess the uncertainty value obtained in this study with another similar research.

6.1.1.1. PVsyst Uncertainty Calculation

The PV electricity output simulation result from PVsyst tool depends on different parameters related with the modelling tool and metrological inputs. According to PVsyst page and literature, the result from the tool with its default values have an accuracy of ± 5 % [76]. The ± 5 % uncertainty of PVsyst is with assumption that the default soiling loss, albedo, system loss and other errors are included in the simulation output. The uncertainty of solar resource from Meteonorm database which PVsyst uses to source its input has also an estimated uncertainty of 2 to 8 % for areas with high solar radiation source [77]. Uncertainty of 2 % and 8 % represent high solar radiation sites with high quality ground measurements and uncertainties for satellite-based data respectively. For the site in this specific study, 8 % uncertainty is selected since the solar radiation data used during PVsyst simulation study is satellite information. The other parameter which will be used for the uncertainty calculation is year to year solar radiation variability. The inter annual solar radiation variability suggested by the PVsyst tool for this specific site 5.4 % (from PVsyst).

Based on the three uncertainty variables defined above, the combined uncertainty can be calculated in a simpler method for example rule of squares [78]. Previous studies have shown this simple method of uncertainty calculation can be used in lieu of statistical simulation approach for uncertainty calculation [79]. The PV electricity output can be assumed as a product of linear factors and the combined uncertainty will be calculated in rule of square equation, in Equation *6.1*.

$$U_c = \sqrt{U_m^2 + U_s^2 + U_v^2}$$ *Equation 6.1*

Where Uc: Combined uncertainty

Um: Model uncertainty, 5 %

U_s: Solar radiation resource uncertainty, 8 %
U_v: Inter annual variation,5.4 %

Inserting the value of U_m, U_s and U_v in the equation, the combined uncertainty becomes 10.87 % (~ 11 %) which is almost equal to 11 %. So, the uncertainty for PV production from PVsyst is around 11 %.

6.1.1.2. Homer Pro Result Uncertainty Calculation

Homer Pro simulation tool has a relative system design precision and NPV precision which can be edited by the user. In this study, the default relative precision of 0.01 (1 %) is used for system precision. This means the relative system precision value can have a relative error of 1 % of the range between minimum and maximum range of each component size which is feed into Homer Pro as an input. For example, if Homer Pro optimizer is optimizing the size of PV with a minimum of 0 kW and maximum of 100 kW, then the system precision is 1 % of the range between 0 kW and 100 kW which is 1 kW. For the NPV, Homer Pro precision is 1 % of the best optimized NPV system found during Homer Pro simulation study.

However since, the result from Homer Pro tool depends on its different technical and economic input, drawing an accurate uncertainty span for the outputs is sophisticated. In fact, there are a lot of uncontrolled inputs parameters which can change in the project time frame such as fuel price, cost reduction in technology, inflation, discount rate and so on. This necessitates a more complicated financial model for accurately estimating uncertainty. For this specific report, the uncertainty calculation is instead made for Homer Pro tool assuming that the techno-economic data inputs are reliable. Table 37 shows the Homer Pro precision level used for this specific study.

Table 37 Homer Pro simulation precision level for system components and NPV

Inputs for Homer Pro tool	System with lead battery	System with Li-ion battery	Precision (0.001)
PV Size (kW)	0 - 200	0 - 200	± 2
Battery size (kWh)	0 - 407	0 - 250	± 4 (for lead acid)
			± 2.50 (for Li-ion battery)
NPV (%)			± 1

Based on the precision level defined on Table 37 the Homer Pro modelling uncertainty is calculated for the mini-grids system with south oriented system including the battery storage (lead acid and Li-ion battery). For example, the Homer Pro simulation uncertainty for PV size is calculated based on percentage value of its precision value, ± 2 kW. The 2 kW can be changed to percentage value of the PV size as in Table 38 i.e.,5.64 %. The same procedure is used to calculate the Homer Pro simulation model uncertainty for other components of this specific study. Assuming that all the technical and economic inputs to Homer Pro are true, the uncertainty for this specific Homer Pro simulation study made is given in Table 38.

Table 38 Homer Pro uncertainty of simulation result for fixed oriented systems with lead and Li-ion battery

Components	System with lead acid -magnitude	System with Li-ion -magnitude	Lead-Homer Pro tool uncertainty (%)	
			Lead	Li-ion
PV (kW)	35.5 ± 2	35.5 ± 2	~ 6	~ 6
Battery (kWh)	245 ± 4	120 ± 2.5	~ 2	~ 2
NPV ($)	277 492 ± 2775	274 572 ± 2746	1	1
LCOE ($/kWh)	0.169 ± (1.69×10^{-3})	0.167 ± (1.67×10^{-3})	1	1

The uncertainty calculation in Table 38 is only Homer Pro modeling uncertainty, without including the uncertainty introduced by PVsyst result, and other inputs. With considering that all input parameters except the PV production input from PVsyst are true and constant, the effect of the PVsyst output uncertainty into Homer Pro obtained result can be estimated. As described in section 6.1.1.1, the PVsyst PV production which will be an input to Homer Pro has calculated uncertainty of 11 %. This makes the uncertainty calculation of the result from Homer Pro a bit sophisticated. However, a simple method will be used to estimate the total combined uncertainty of the result from Homer Pro tool. The uncertainty from Homer Pro tool will be calculated by inserting the PVsyst uncertainty as sensitivity variable into the Homer Pro tool, derating factor input. The derating factor is an option to increase the output from PVsyst exported PV electricity up or down. This sensitivity study result by Homer Pro can give us the upper and lower limit of the result which also have an additional Homer Pro introduced uncertainty described in Table 37.This means the combined uncertainty will be the combination of PVsyst introduced uncertainty in to Homer Pro, which will be obtained by the sensitivity analysis, and Homer Pro´s optimization precision.

Here, a simple method is used to estimate the range for the size of PV, battery and NPV of south oriented system with lead acid battery and Li-ion battery. Table 39 shows the Homer Pro result for PVsyst scaled input by ± 11 %. For system with lead Acid battery, for the PV component, the Homer Pro optimized output at 11 % decrement and increment of PVsyst output is 39. 25 kW and 35 kW, respectively. This numbers have also Homer Pro precision uncertainty of 2 kW given in Table 37. Using the Homer Pro precision level and PV sizes at ± 11 % uncertainty; the minimum and maximum range where the PV size for the initial system is estimated to be in the range of 35 kW - 2 kW up to 39.25 kW + 2 kW. Which means, the PV array size is between 33 kW and 41. 25 kW. To put a single number as uncertainty, the mean value of 33 kW and 41.25 kW is chosen, and for indeterminacy the average value of the difference between these two numbers is calculated. The optimal PV size with assuming that the only uncertainty source of Homer Pro inputs is PVsyst´s electricity output is given by $\frac{(33 + 41.25)}{2} \pm \frac{(41.25 - 33)}{2}$. PV size for system with lead acid battery can be given by 37 kW ± 4 kW (11 %).

Table 39 Homer Pro result for ± 11 % scaled PVsyst input

Description	(-11 %)		(+11 %)	
	Lead	Li-ion	Lead	Li-ion
PV (kW)	39.25	37.5	35	32.25
Battery (kWh)	248	122.5	242	120
NPV ($)	284 554	281 488	271 497	268 138
LCOE ($/kWh)	0.173	0.171	0.165	0.163

In the same way, PV size uncertainty in a mini-grids system with Li-ion batteries is given by $\frac{(30.25 + 39.5)}{2} \pm \frac{(39.5 - 30.25)}{2}$. The estimated PV size for system with Li-ion battery can be expressed by 35 kW ± 5 kW (13 %). For lead acid battery component, the range of optimized battery capacity can be given by $\frac{(252 + 238)}{2} \pm \frac{(252 - 238)}{2}$. The estimated optimal lead acid battery range for the system is therefore 245 kWh ± 7 kWh (3 %). For Li-ion battery component, the optimal capacity range is given by $\frac{(125 + 117.5)}{2} \pm \frac{(125 - 117.5)}{2}$. The estimated optimal battery range for the system with Li-ion battery is therefore, 121 kWh ± 4 kWh (3 %). The estimated range for NPV of south oriented system with lead acid battery is given by $\frac{(287\,399.54 + 268\,782.03)}{2} \pm \frac{(287399.54 - 268782.03)}{2}$.

The estimated NPV range for system with lead acid battery can then be expressed by \$278 091 ± \$ 9309 (3 %). The NPV with Li-ion battery is estimated to be in the range $\frac{(284\,302.88 + 265\,456.62)}{2} \pm \frac{(284\,302.88 - 265\,456.62)}{2}$. The NPV range for system with Li-ion battery is therefore \$274 880 ± \$ 9423 (3 %). Based on 1 % Homer Pro uncertainty, the range for LCOE (\$/kWh) of system with lead acid battery is estimated to be between $(0.165 - (1.65\times10^{-3}))$ and $(0.173 + (1.73\times10^{-3}))$. The range for LCOE of system with lead acid battery is given by $\frac{(0.17473 + 0.16335)}{2} \pm \frac{(0.17473 - 0.16335)}{2}$. The optimal LCOE range for system with lead acid battery is given by $0.169/kWh ± 5.69×10^{-3}/kWh (3 %). For Li-ion battery, the range is estimated to be in the range of $(0.163 - (1.63\times10^{-3}))$ and $(0.171 - (1.71\times10^{-3}))$. The range for LCOE (\$/kWh) of system with Li-ion battery can be calculated as $\frac{(0.17271 + 0.16137)}{2} \pm \frac{(0.17271 - 0.16137)}{2}$. The optimal LCOE range for system with Li-ion battery is therefore \$0.167/kWh ± 5.67×10^{-3} (3 %).

In Table 40, a summary of Home output uncertainty estimation is given with introduction of PVsyst´s electricity output. Since the increment and decrement of PV output has no linear implication in the cost, the deviation in PV sizing from the optimal or initial one cannot be linear. In fact, the uncertainty for Li-ion and lead acid battery can also be different as it is evidenced in this case. However, the range where the system is located is estimated based on a simple method and tabulated in Table 40.

Table 40 Homer Pro output with PVsyst uncertainty consideration

Description	South oriented system with lead acid		South oriented PV system with Li-ion	
	Initial- Homer Pro result	Range	Initial- Homer Pro result	Range
PV (kW)	35.5	37 ± 11 %	35.5	35 ± 13 %
Battery (kWh)	245	245 ± 3 %	120	121 ± 3 %
NPV (\$)	277 492	278 091 ± 3 %	274 572	274 880 ± 3 %
LCOE (\$/kWh)	0.169	0.169 ± 3 %	0.167	0.167 ± 3 %

The precision level for the DEG and bi-directional inverter is not included in the uncertainty tables because the backup DEG size and bi-directional inverter size will be decided by the Homer Pro based on the peak load. Thus, the uncertainty due to solar radiation have a negligible impact on these components.

6.2 Conclusion

Mini-grids could be a cost optimal solution for rural electrification in SSA through promoting PUE. The majority of SSA population residing in rural region, and agriculture being the income source for more than half of the population, energy systems which power agriculture can stimulate the economic growth [80]. In this study, an agrarian community in Ethiopia is considered to represent a typical rural community in SSA which are dependent on subsistence farming for their living. The mini-grid-based power with PUE which include primary load for community service and local businesses, and deferable load for the purpose of irrigation and drinking water is proposed. The deferable load is instilled as a flexible load element to gain cost benefit from tapping excess electricity which could have been wasted.

The mini-grid system proposed for the case study village has an estimated LCOE of $0.169/kWh for south oriented PV system with lead acid battery, and it has an LCOE of $0.165 /kWh for south oriented PV system with Li-ion battery. However, the LCOE estimates have a combined uncertainty of 3 %, which is higher than the 1 % difference for LCOE of the south oriented system with lead acid and Li-ion battery. Due to this reason, it is difficult to conclude that either of the battery technologies has lesser LCOE than the other for the case study village with yearly average ambient temperature of 17.8 °C. The proposed systems are also designed for 100 % availability with renewable energy penetration of more than 90 %.

The cost of electricity obtained for the proposed mini-grid system in the Walta Jalala village has lower LCOE value than the reported figures in the World Bank report. The World Bank estimate on the average LCOE of unsubsidized solar hybrid mini-grids with income generating activities of load factor of 40 % is $0.42/kWh. The mini-grid system proposed for this specific village has an LCOE of $0.17/kWh which is lower than the average LCOE reported by the World Bank study. This increase is related with the high community load and PUE introduced in the mini-grid design. The flexibility added to the mini-grid to address the deferable anchor load for irrigation and drinking water is also a main factor.

For the proposed village and climatic condition, system with both Li-ion battery technology and lead acid battery have shown almost equivalent LCOE. The preference of the better battery technology for the case study village depends on the decision makers choice to pay an extra money for covering a little higher Capex for mini-grid with Li-ion or not. Otherwise, this battery manufacturer data sheet-based study shows, the mini-grid with either lead acid or Li-ion battery have a fairly comparable LCOE. However, temperature sensitivity analysis shown that the LCOE for the two batteries technology starts to differ when the operating temperature is above 25 °C. For the average yearly temperature between 25 to 40 °C, Li-ion battery technology results a lower LCOE than its lead acid counterpart. Li-ion battery technology is also less sensitive to higher temperature compared with lead acid battery and could be a good choice particularly for areas where the yearly average temperature is higher than 25 °C.

One other key takeaway of policy directive from this study will be, mini-grids can be potential cost optimum option for rural SSA electrification. This can be achieved by promoting localized design of mini-grids to power local economic activities such as irrigation. More, energy-water-agriculture nexus mini-grids to power rural productive hubs can address the challenge inflicted by climate change on subsistence-based farmers in SSA. This can help the financial sustainability of mini-grids, and the development of the local economic activities. More the rollout of mini-grids can conjugate with other options such as grid extension. For the LCOE obtained for Walta Jalala village, Homer Pro simulation study shown that mini-grids can cost optimal options for villages more than 3.4 km away from nearest grid point.

7 Recommendation and Future Study

The simulation study based on the PUE application is made based on the consideration of the local agricultural resources and anchor load for the case study village under study. Since there is no specific study made for water requirements of different crops in the context of the specific village, FAO recommendations for different regions is taken for estimating crop water and irrigation requirement. This can be enhanced through making on site study on water requirements for different crops and yearly rainfall data. Moreover, this simulation study modelled the battery technologies characteristics based on a manufacturers data sheet. This have to be confirmed with systems which are working in real word setting. Evaluations made to assess the environmental impact of energy-agriculture-water nexus approach and also different battery technologies for balancing the synergy and trade-off is also one of the areas where further research is needed.

8 References

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9 Appendix

9.1 PVsyst Simulation Result

9.2 Homer Pro Simulation Result

9.3 Byd 2.5 kWh Data Sheet

9.4 Hoppecke 2 520 Ah Data Sheet

Appendix A: PVsyst Simulation Result

General parameters

Grid-Connected System

No 3D scene defined, no shadings

PV Field Orientation

Orientation
Fixed plane
Tilt/Azimuth 15 / 0 °

Models used
Transposition Perez
Diffuse Perez, Meteonorm
Circumsolar separate

Horizon
Free Horizon

Near Shadings
No Shadings

User's needs
Unlimited load (grid)

PV Array Characteristics

PV module

Manufacturer	Generic
Model	CS6V - 250MS
(Original PVsyst database)	
Unit Nom. Power	250 Wp
Number of PV modules	100 units
Nominal (STC)	25.00 kWp
Modules	4 Strings x 25 In series
At operating cond. (50°C)	
Pmpp	22.56 kWp
U mpp	604 V
I mpp	37 A

Inverter

Manufacturer	Generic
Model	Sunny Tripower 25000TL-30
(Original PVsyst database)	
Unit Nom. Power	25.0 kWac
Number of inverters	2 * MPPT 50% 1 units
Total power	25.0 kWac
Operating voltage	390-800 V
Pnom ratio (DC:AC)	1.00

Total PV power

Nominal (STC)	25 kWp
Total	100 modules
Module area	135 m²
Cell area	122 m²

Total inverter power

Total power	25 kWac
Nb. of inverters	1 Unit
Pnom ratio	1.00

Array losses

Array Soiling Losses
Loss Fraction 3.0 %

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 29.0 W/m²K
Uv (wind) 0.0 W/m²K/m/s

DC wiring losses
Global array res. 271 mΩ
Loss Fraction 1.5 % at STC

Serie Diode Loss
Voltage drop 0.7 V
Loss Fraction 0.1 % at STC

LID - Light Induced Degradation
Loss Fraction 2.0 %

Module Quality Loss
Loss Fraction -0.5 %

Module mismatch losses
Loss Fraction 2.0 % at MPP

Strings Mismatch loss
Loss Fraction 0.1 %

Module average degradation
Year no 1
Loss factor 0.4 %/year

Mismatch due to degradation
Imp RMS dispersion 0.4 %/year
Vmp RMS dispersion 0.4 %/year

IAM loss factor
Incidence effect (IAM): User defined profile

10°	20°	30°	40°	50°	60°	70°	80°	90°
1.000	0.998	0.995	0.995	0.986	0.970	0.917	0.763	0.000

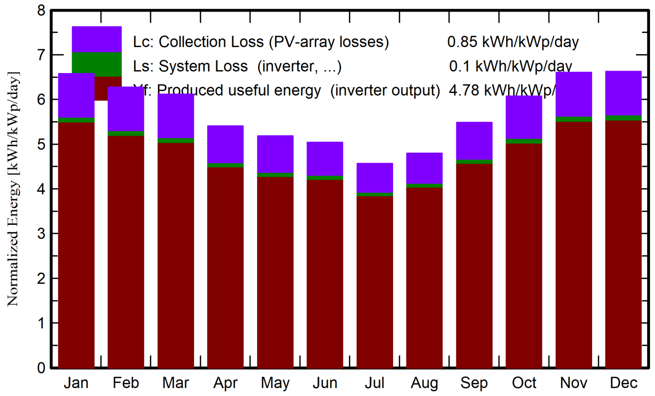
PVsyst V7.1.0
Simulation date:
06/12/20 17:15
with v7.1.0

Main results

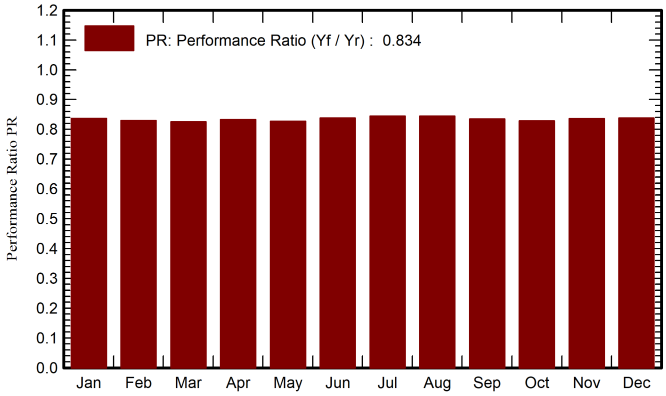
System Production

Produced Energy	43.61 MWh/year	Specific production	1744 kWh/kWp/year
		Performance Ratio PR	83.44 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	ratio
January	179.0	56.01	16.97	204.0	194.6	4.354	4.268	0.837
February	162.4	53.32	18.07	175.7	167.6	3.719	3.645	0.830
March	186.0	68.06	18.74	189.8	180.9	3.996	3.915	0.825
April	167.6	80.05	18.46	162.2	154.1	3.447	3.377	0.833
May	174.5	69.32	19.23	160.8	152.2	3.394	3.325	0.827
June	167.3	72.77	17.84	151.3	143.1	3.235	3.170	0.838
July	154.0	72.60	16.45	141.5	134.0	3.052	2.989	0.845
August	156.1	82.00	16.98	148.7	141.2	3.204	3.138	0.844
September	165.1	67.44	16.72	164.6	156.6	3.507	3.435	0.835
October	179.0	64.00	17.61	188.4	180.1	3.984	3.901	0.828
November	177.7	55.11	16.25	198.1	189.5	4.227	4.140	0.836
December	178.6	48.98	16.49	205.4	196.4	4.391	4.303	0.838
Year	2047.2	789.67	17.48	2090.3	1990.3	44.511	43.607	0.834

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

PVsyst V7.1.0
Simulation date:
06/12/20 17:32
with v7.1.0

General parameters

Grid-Connected System — **No 3D scene defined, no shadings**

PV Field Orientation

Orientation

Fixed planes	2 orientations
Tilts/azimuths	15 / -90 °
	15 / 90 °

Models used

Transposition	Perez
Diffuse	Perez, Meteonorm
Circumsolar	separate

Horizon
Free Horizon

Near Shadings
No Shadings

User's needs
Unlimited load (grid)

PV Array Characteristics

PV module

Manufacturer	Generic
Model	CS6V - 250MS
(Original PVsyst database)	
Unit Nom. Power	250 Wp
Number of PV modules	100 units
Nominal (STC)	25.00 kWp

Inverter

Manufacturer	Generic
Model	Sunny Tripower 25000TL-30
(Original PVsyst database)	
Unit Nom. Power	25.0 kWac
Number of inverters	1 Unit
Total power	25.0 kWac

Array #1 - PV Array1

Orientation	#1		
Tilt/Azimuth	15/-90 °		
Number of PV modules	50 units	Number of inverters	1 * MPPT 50% 0.5 units
Nominal (STC)	12.50 kWp	Total power	12.5 kWac
Modules	2 Strings x 25 In series		
At operating cond. (50°C)		Operating voltage	390-800 V
Pmpp	11.28 kWp	Pnom ratio (DC:AC)	1.00
U mpp	604 V		
I mpp	19 A		

Array #2 - PV Array #2

Orientation	#2		
Tilt/Azimuth	15/90 °		
Number of PV modules	50 units	Number of inverters	1 * MPPT 50% 0.5 units
Nominal (STC)	12.50 kWp	Total power	12.5 kWac
Modules	2 Strings x 25 In series		
At operating cond. (50°C)		Operating voltage	390-800 V
Pmpp	11.28 kWp	Pnom ratio (DC:AC)	1.00
U mpp	604 V		
I mpp	19 A		

Total PV power

Nominal (STC)	25 kWp
Total	100 modules
Module area	135 m²
Cell area	122 m²

Total inverter power

Total power	25 kWac
Nb. of inverters	1 Unit
Pnom ratio	1.00

Array losses

Array Soiling Losses
Loss Fraction 3.0 %

Thermal Loss factor
Module temperature according to irradiance

Uc (const)	29.0 W/m²K
Uv (wind)	0.0 W/m²K/m/s

DC wiring losses

Global array res.	542 mΩ
Global wiring resistance	271 mΩ
Loss Fraction	1.5 % at STC

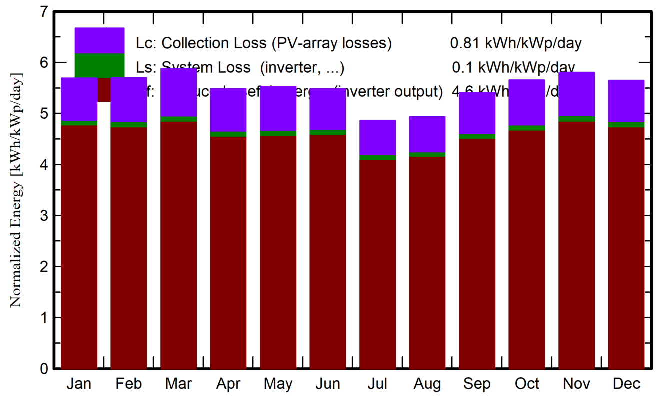
PVsyst V7.1.0
Simulation date:
06/12/20 17:32
with v7.1.0

Main results

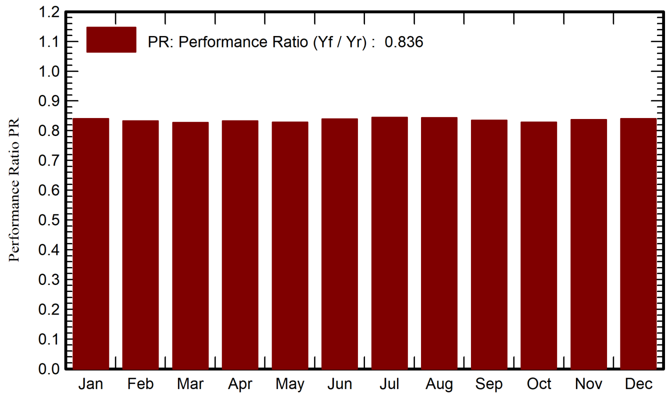
System Production

Produced Energy	41.97 MWh/year	Specific production	1679 kWh/kWp/year
		Performance Ratio PR	83.55 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR ratio
January	179.0	56.01	16.97	176.4	167.5	3.781	3.706	0.840
February	162.4	53.32	18.07	159.6	151.9	3.391	3.323	0.833
March	186.0	68.06	18.74	182.2	173.7	3.843	3.765	0.827
April	167.6	80.05	18.46	164.5	156.6	3.495	3.423	0.832
May	174.5	69.32	19.23	171.5	163.2	3.625	3.551	0.828
June	167.3	72.77	17.84	164.5	156.5	3.522	3.451	0.839
July	154.0	72.60	16.45	150.9	143.5	3.252	3.185	0.844
August	156.1	82.00	16.98	153.0	145.6	3.295	3.228	0.844
September	165.1	67.44	16.72	162.3	154.5	3.460	3.388	0.835
October	179.0	64.00	17.61	175.3	166.7	3.705	3.628	0.828
November	177.7	55.11	16.25	174.2	165.4	3.722	3.645	0.837
December	178.6	48.98	16.49	175.0	166.1	3.753	3.677	0.840
Year	2047.2	789.67	17.48	2009.3	1911.0	42.845	41.970	0.836

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		

Appendix B: Homer Pro Simulation Result

File: South Oriented System with Lead Acid Battery

Author: Israel.Biramo

Location: Walta Jalala, Ethiopia (9°10.5'N, 41°31.7'E)

Total Net Present Cost: $277,492.50

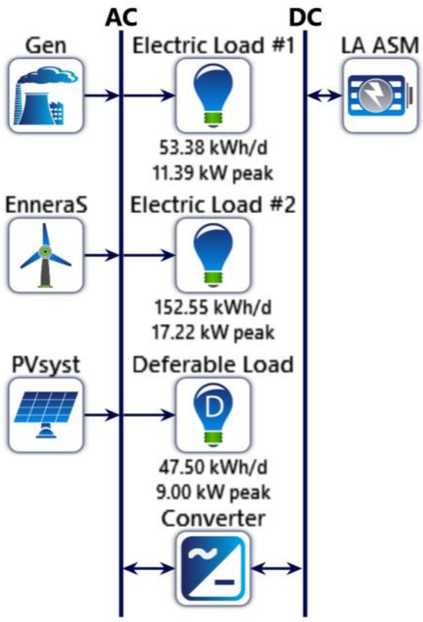
Levelized Cost of Energy ($/kWh): $0.169

Notes: Walta Jalala Village-Yearly optimized with Lead Acid battery

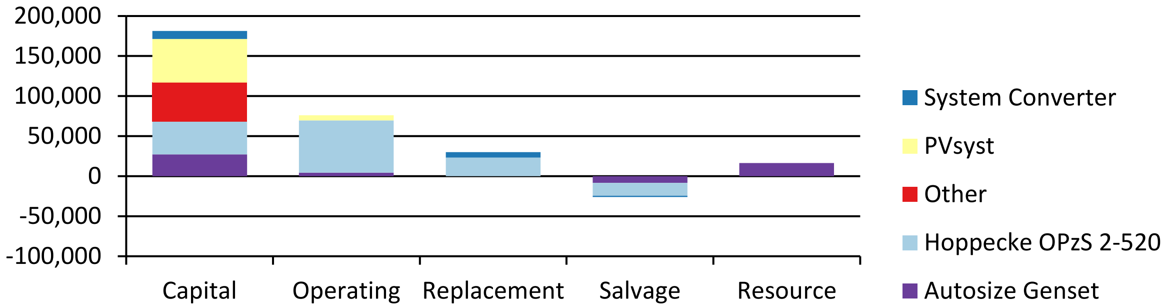
System Architecture

Component	Name	Size	Unit
Generator	Autosize Genset	35.0	kW
Storage	Hoppecke OPzS 2-520	245	strings
System converter	System Converter	20.0	kW
Custom component	PVsyst	1.42	
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



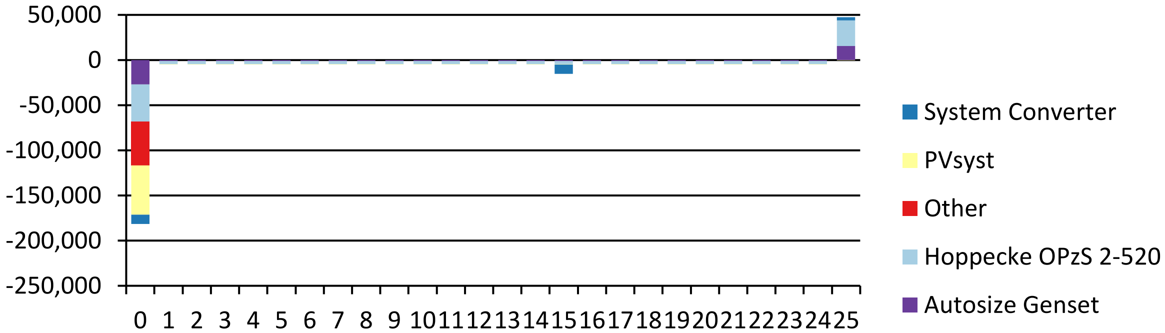
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$27,055	$4,243	$0.00	-$8,425	$16,327	$39,199
Hoppecke OPzS 2-520	$40,915	$65,416	$23,213	-$15,992	$0.00	$113,552
Other	$48,800	$0.00	$0.00	$0.00	$0.00	$48,800
PVsyst	$54,612	$6,304	$0.00	$0.00	$0.00	$60,917
System Converter	$10,060	$0.00	$6,645	-$1,680	$0.00	$15,025
System	$181,442	$75,962	$29,858	-$26,097	$16,327	$277,492

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$1,520	$238.35	$0.00	-$473.32	$917.24	$2,202
Hoppecke OPzS 2-520	$2,299	$3,675	$1,304	-$898.44	$0.00	$6,379
Other	$2,742	$0.00	$0.00	$0.00	$0.00	$2,742
PVsyst	$3,068	$354.17	$0.00	$0.00	$0.00	$3,422
System Converter	$565.16	$0.00	$373.29	-$94.37	$0.00	$844.08
System	$10,193	$4,268	$1,677	-$1,466	$917.24	$15,589

Cash Flow



Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	91,738	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Autosize Genset	5,892	3.04
PVsyst	188,099	97.0
Total	193,991	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	75,164	81.4
DC Primary Load	0	0
Deferrable Load	17,228	18.6
Total	92,392	100

Generator: Autosize Genset (Diesel)

Autosize Genset Electrical Summary

Quantity	Value	Units
Electrical Production	5,892	kWh/yr
Mean Electrical Output	26.0	kW
Minimum Electrical Output	8.75	kW
Maximum Electrical Output	35.0	kW

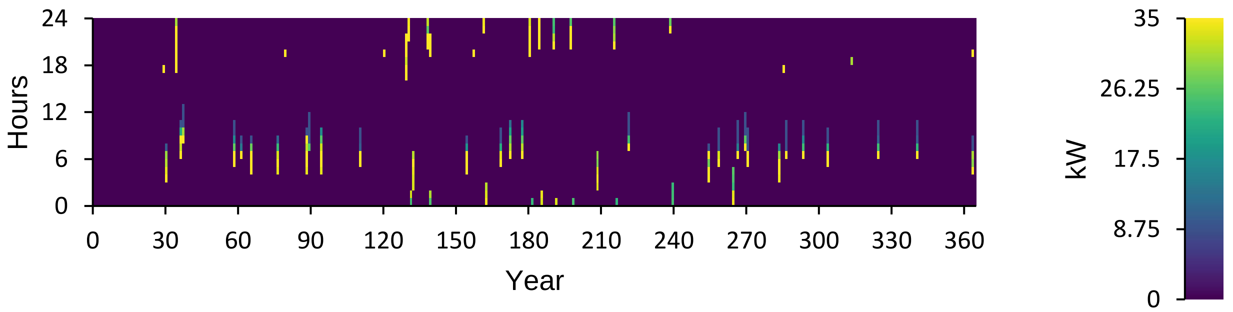
Autosize Genset Fuel Summary

Quantity	Value	Units
Fuel Consumption	1,834	L
Specific Fuel Consumption	0.311	L/kWh
Fuel Energy Input	18,051	kWh/yr
Mean Electrical Efficiency	32.6	%

Autosize Genset Statistics

Quantity	Value	Units
Hours of Operation	227	hrs/yr
Number of Starts	50.0	starts/yr
Operational Life	66.1	yr
Capacity Factor	1.92	%
Fixed Generation Cost	3.83	$/hr
Marginal Generation Cost	0.118	$/kWh

Autosize Genset Output (kW)



Storage: Hoppecke OPzS 2-520

Hoppecke OPzS 2-520 Properties

Quantity	Value	Units
Batteries	245	qty.
String Size	1.00	batteries
Strings in Parallel	245	strings
Bus Voltage	2.00	V

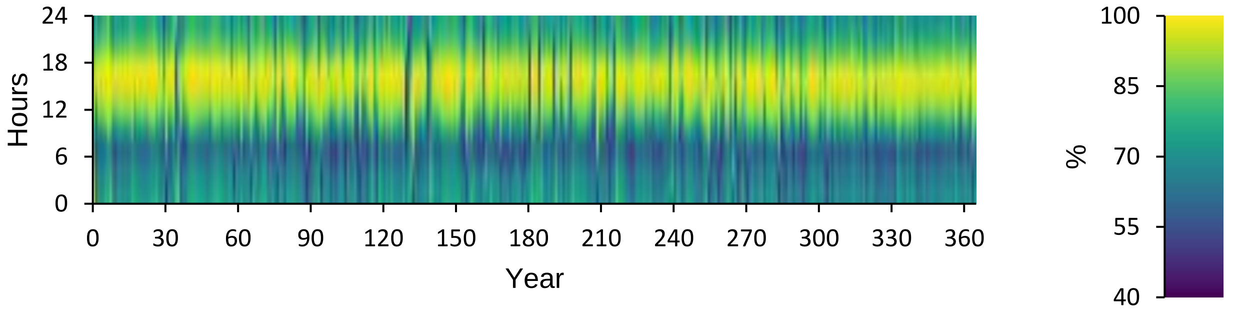
Hoppecke OPzS 2-520 Result Data

Quantity	Value	Units
Average Energy Cost	0.0116	$/kWh
Energy In	41,917	kWh/yr
Energy Out	35,211	kWh/yr
Storage Depletion	82.5	kWh/yr
Losses	6,788	kWh/yr
Annual Throughput	38,362	kWh/yr

Hoppecke OPzS 2-520 Statistics

Quantity	Value	Units
Autonomy	19.3	hr
Storage Wear Cost	0.0520	$/kWh
Nominal Capacity	255	kWh
Usable Nominal Capacity	153	kWh
Lifetime Throughput	786,284	kWh
Expected Life	20.5	yr

Hoppecke OPzS 2-520 State of Charge (%)



Converter: System Converter

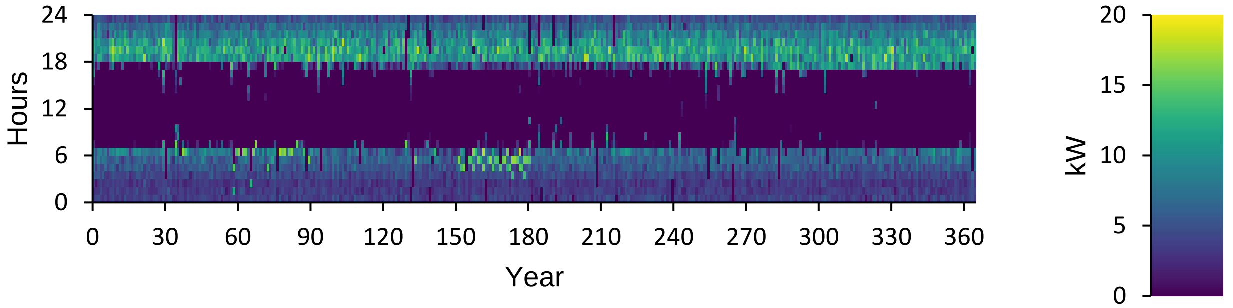
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	5,063	hrs/yr
Energy Out	33,803	kWh/yr
Energy In	35,211	kWh/yr
Losses	1,408	kWh/yr

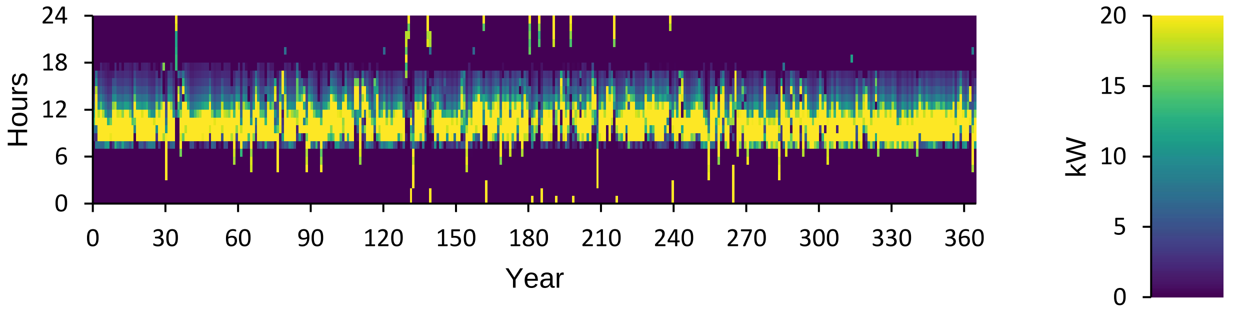
System Converter Statistics

Quantity	Value	Units
Capacity	20.0	kW
Mean Output	3.86	kW
Minimum Output	0	kW
Maximum Output	18.1	kW
Capacity Factor	19.3	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



HOMER Pro

Custom Component: PVsyst

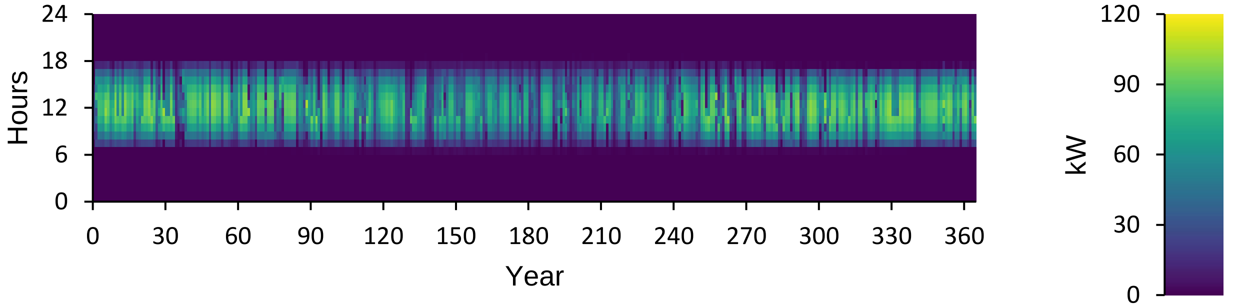
PVsyst Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	105	kW
Hours of Operation	4,266	hrs/yr
Levelized Cost	0.0182	$/kWh

PVsyst Statistics

Quantity	Value	Units
Rated Capacity	1.42	
Mean Output	21.5	kW
Mean Output	515	kWh/d
Capacity Factor	20.5	%
Total Production	188,099	kWh/yr

PVsyst Output (kW)

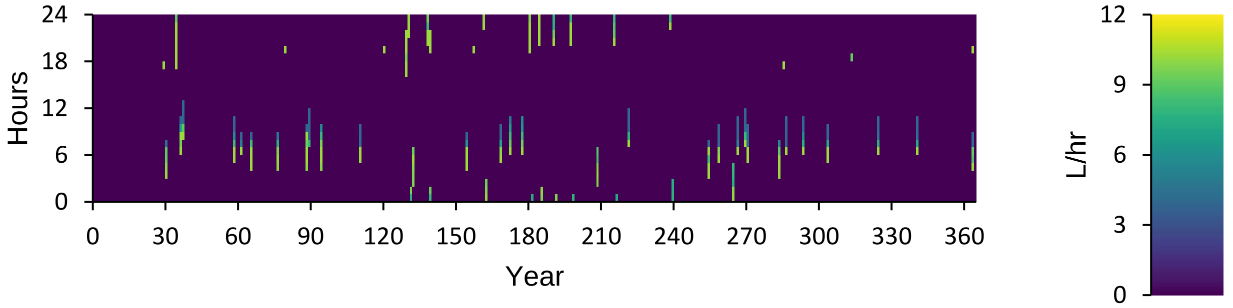


Fuel Summary

Diesel Consumption Statistics

Quantity	Value	Units
Total fuel consumed	1,834	L
Avg fuel per day	5.03	L/day
Avg fuel per hour	0.209	L/hour

Diesel Consumption (L/hr)



Emissions

Pollutant	Quantity	Unit
Carbon Dioxide	4,802	kg/yr
Carbon Monoxide	30.3	kg/yr
Unburned Hydrocarbons	1.32	kg/yr
Particulate Matter	0.183	kg/yr
Sulfur Dioxide	11.8	kg/yr
Nitrogen Oxides	28.4	kg/yr

File: South Oriented System with Li-ion Battery

Author: Israel.Biramo

Location: Walta Jalala, Ethiopia (9°10.5'N, 41°31.7'E)

Total Net Present Cost: $274,185.50

Levelized Cost of Energy ($/kWh): $0.167

Notes: Walta Jalala, Li-ion battrey

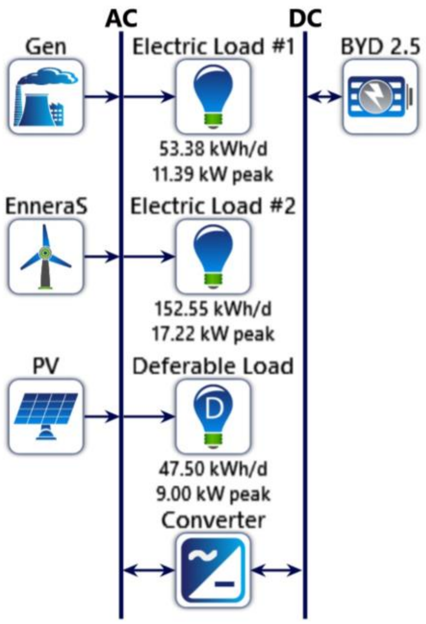
Sensitivity variable values for this simulation

Variable	Value	Unit
Deferable Load Scaled Average	47.5	kWh/d
Electric Load #2 Scaled Average	153	kWh/d

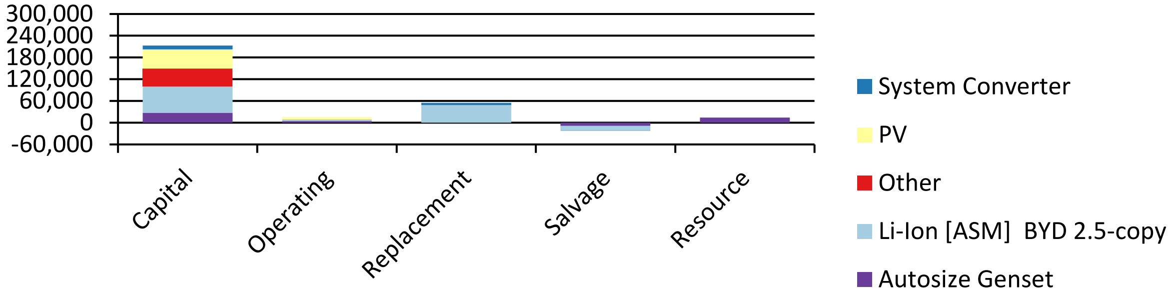
System Architecture

Component	Name	Size	Unit
Generator	Autosize Genset	35.0	kW
Storage	Li-Ion [ASM] BYD 2.5-copy	49	strings
System converter	System Converter	20.0	kW
Custom component	PV	1.39	
Dispatch strategy	HOMER Cycle Charging		

Schematic



Cost Summary



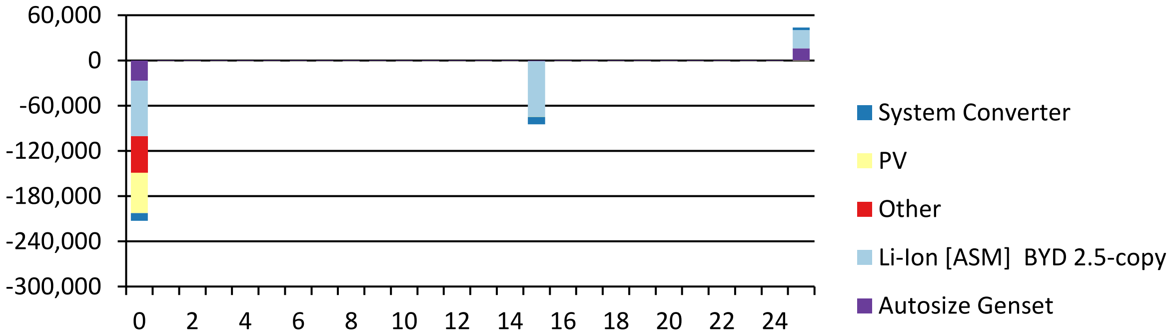
Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$27,055	$4,131	$0.00	-$8,561	$14,337	$36,962
Li-Ion [ASM] BYD 2.5-copy	$73,255	$4,361	$48,384	-$12,232	$0.00	$113,768
Other	$48,800	$0.00	$0.00	$0.00	$0.00	$48,800
PV	$53,460	$6,171	$0.00	$0.00	$0.00	$59,631
System Converter	$10,060	$0.00	$6,645	-$1,680	$0.00	$15,025
System	$212,630	$14,663	$55,029	-$22,472	$14,337	$274,185

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Autosize Genset	$1,520	$232.05	$0.00	-$480.94	$805.44	$2,076
Li-Ion [ASM] BYD 2.5-copy	$4,115	$245.00	$2,718	-$687.18	$0.00	$6,391
Other	$2,742	$0.00	$0.00	$0.00	$0.00	$2,742
PV	$3,003	$346.69	$0.00	$0.00	$0.00	$3,350
System Converter	$565.16	$0.00	$373.29	-$94.37	$0.00	$844.08
System	$11,945	$823.74	$3,091	-$1,262	$805.44	$15,404

Cash Flow



Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	92,054	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Autosize Genset	4,994	2.64
PV	184,128	97.4
Total	189,123	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	75,164	81.4
DC Primary Load	0	0
Deferrable Load	17,228	18.6
Total	92,392	100

Generator: Autosize Genset (Diesel)

Autosize Genset Electrical Summary

Quantity	Value	Units
Electrical Production	4,994	kWh/yr
Mean Electrical Output	22.6	kW
Minimum Electrical Output	8.75	kW
Maximum Electrical Output	35.0	kW

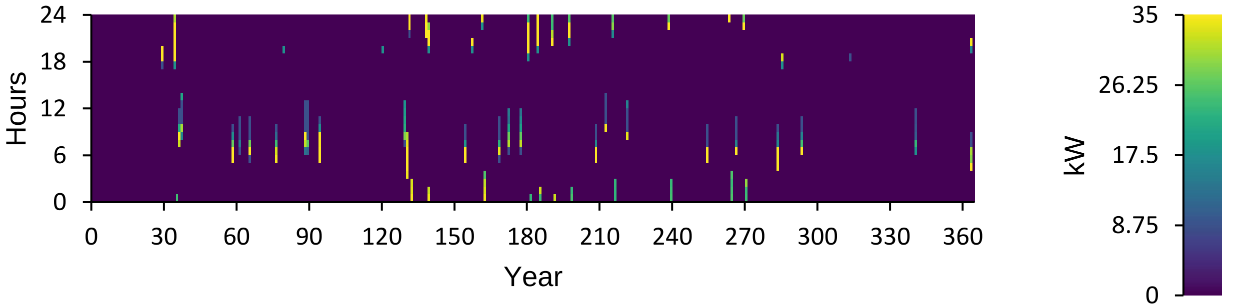
Autosize Genset Fuel Summary

Quantity	Value	Units
Fuel Consumption	1,611	L
Specific Fuel Consumption	0.323	L/kWh
Fuel Energy Input	15,851	kWh/yr
Mean Electrical Efficiency	31.5	%

Autosize Genset Statistics

Quantity	Value	Units
Hours of Operation	221	hrs/yr
Number of Starts	44.0	starts/yr
Operational Life	67.9	yr
Capacity Factor	1.63	%
Fixed Generation Cost	3.83	$/hr
Marginal Generation Cost	0.118	$/kWh

Autosize Genset Output (kW)



Storage: Li-Ion [ASM] BYD 2.5-copy

Li-Ion [ASM] BYD 2.5-copy Properties

Quantity	Value	Units
Batteries	49.0	qty.
String Size	1.00	batteries
Strings in Parallel	49.0	strings
Bus Voltage	51.2	V

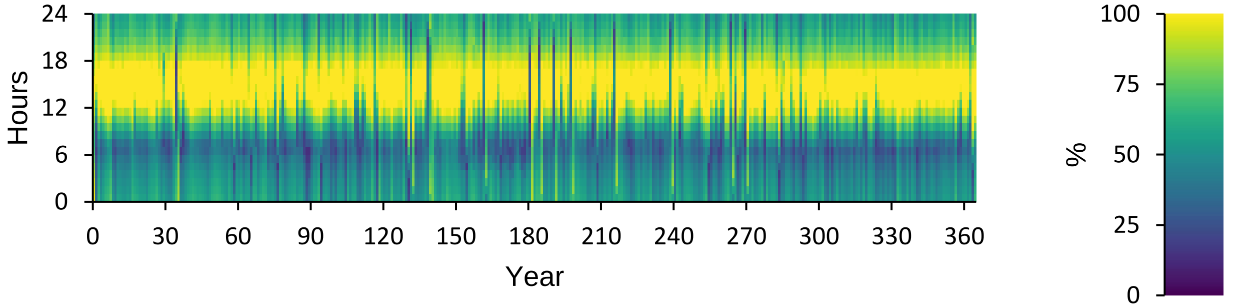
Li-Ion [ASM] BYD 2.5-copy Result Data

Quantity	Value	Units
Average Energy Cost	0.00932	$/kWh
Energy In	37,298	kWh/yr
Energy Out	35,598	kWh/yr
Storage Depletion	71.4	kWh/yr
Losses	1,771	kWh/yr
Annual Throughput	36,471	kWh/yr

Li-Ion [ASM] BYD 2.5-copy Statistics

Quantity	Value	Units
Autonomy	9.88	hr
Storage Wear Cost	0.134	$/kWh
Nominal Capacity	130	kWh
Usable Nominal Capacity	130	kWh
Lifetime Throughput	547,068	kWh
Expected Life	15.0	yr

Li-Ion [ASM] BYD 2.5-copy State of Charge (%)



Converter: System Converter

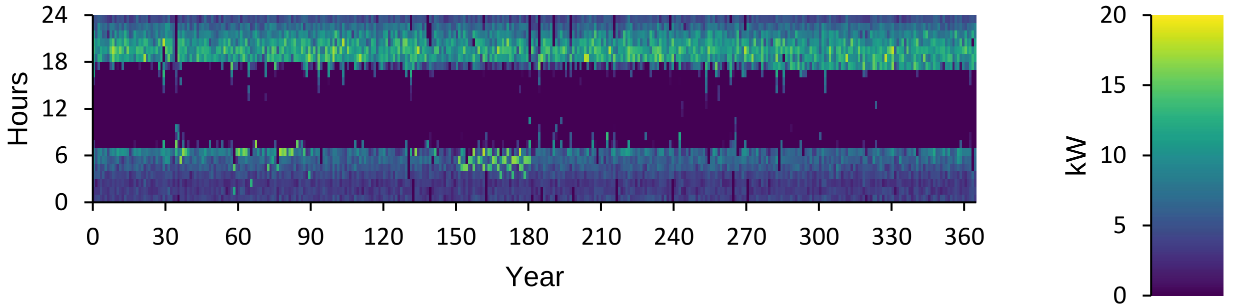
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	5,112	hrs/yr
Energy Out	34,175	kWh/yr
Energy In	35,598	kWh/yr
Losses	1,424	kWh/yr

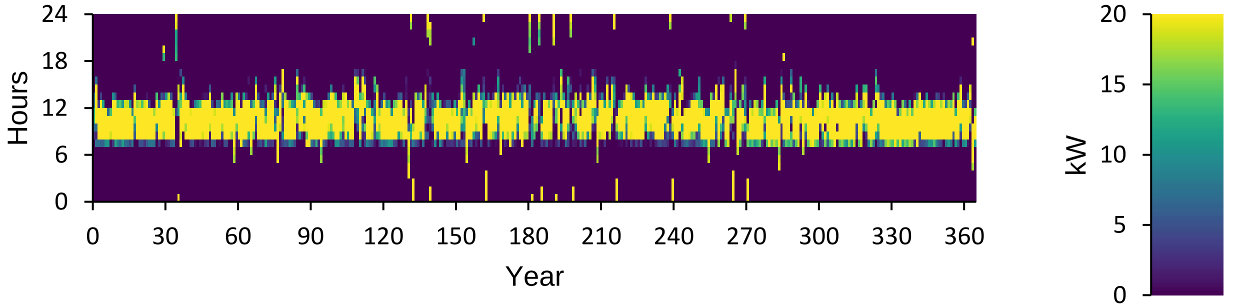
System Converter Statistics

Quantity	Value	Units
Capacity	20.0	kW
Mean Output	3.90	kW
Minimum Output	0	kW
Maximum Output	18.1	kW
Capacity Factor	19.5	%

System Converter Inverter Output (kW)



System Converter Rectifier Output (kW)



Custom Component: PV

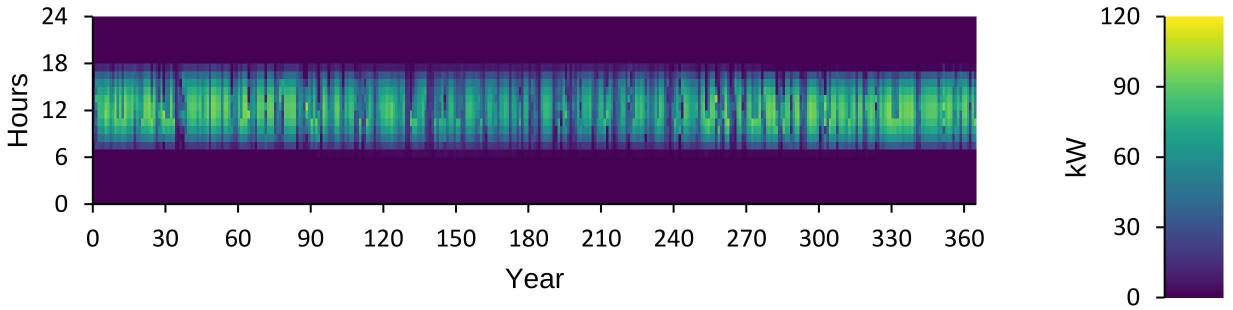
PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	103	kW
Hours of Operation	4,266	hrs/yr
Levelized Cost	0.0182	$/kWh

PV Statistics

Quantity	Value	Units
Rated Capacity	1.39	
Mean Output	21.0	kW
Mean Output	504	kWh/d
Capacity Factor	20.5	%
Total Production	184,128	kWh/yr

PV Output (kW)

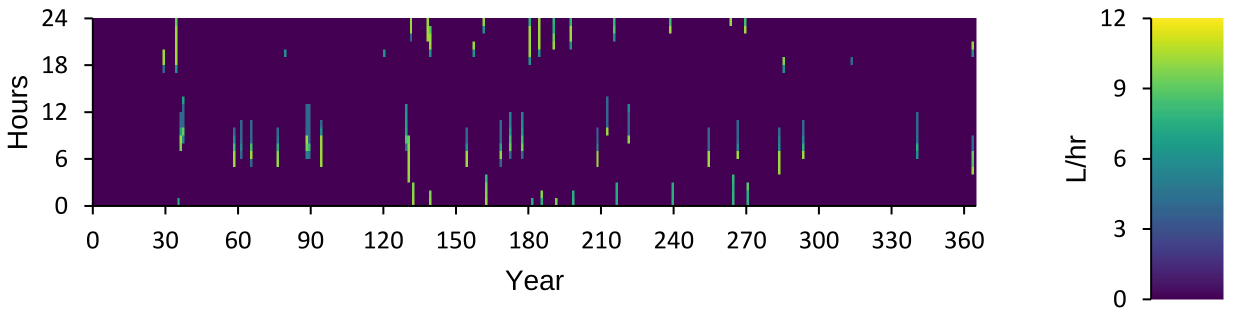


Fuel Summary

Diesel Consumption Statistics

Quantity	Value	Units
Total fuel consumed	1,611	L
Avg fuel per day	4.41	L/day
Avg fuel per hour	0.184	L/hour

Diesel Consumption (L/hr)



Emissions

Pollutant	Quantity	Unit
Carbon Dioxide	4,217	kg/yr
Carbon Monoxide	26.6	kg/yr
Unburned Hydrocarbons	1.16	kg/yr
Particulate Matter	0.161	kg/yr
Sulfur Dioxide	10.3	kg/yr
Nitrogen Oxides	25.0	kg/yr

sun | power VL Series OPzS

Typical applications:

- Village power supplies
- Hybrid systems
- Peak Shaving/voltage stabilisation
- Stations for mobile communications
- Sustainable tourism
- Cathodic corrosion protection
- Pumping systems

Your benefits:

- Highest cycle stability during PSoC[1] operation – due to tubular plate design with efficient charge current acceptance
- Maximum energy efficiency by optimised electrolyte recirculation **sun** | air prepared as standard
- Maximum compatibility – dimensions according to DIN 40736-1
- Higher short-circuit safety even during the installation – based on HOPPECKE system connectors

sun | power VL Series OPzS bloc

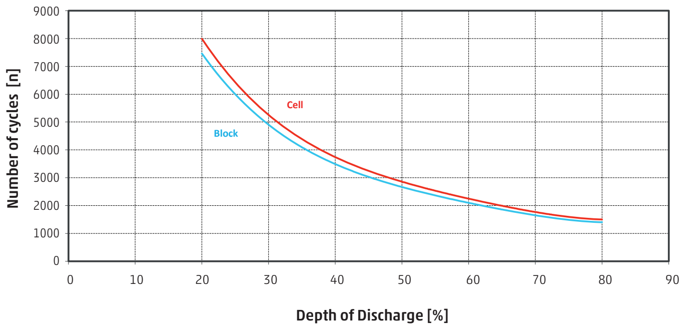
Typical applications:

- Solar home storage systems
- Street lighting
- Signalling systems
- Medical care facilities
- Hybrid systems
- Stations of mobile communications

Your benefits:

- Very high cycle stability during PSoC[1] operation – due to tubular plate design with efficient charge current acceptance
- Maximum compatibility – dimensions according to DIN 40737-3
- Easy assembly and installation – battery lid with integral handle
- Higher short-circuit safety even during the installation – based on HOPPECKE system connectors

Service life in cycles and Depth of Discharge



[1] Partial State of Charge

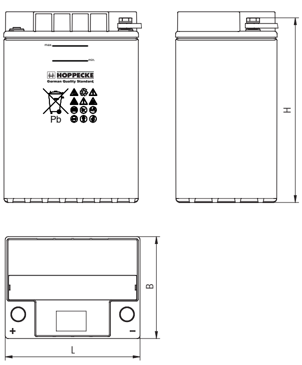
Capacities, dimensions and weights

Series OPzS bloc	Nominal voltage V	C_{100}/1.85 V Ah	C_{50}/1.85 V Ah	C_{24}/1.83 V Ah	C_{10}/1.80 V Ah	C_5/1.77 V Ah	ca. Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
sun | power VL 12-70	12	70	65	60	50	44	37.0	15.0	272	205	383	A
sun | power VL 12-130	12	130	130	120	101	88	48.0	13.0	272	205	383	A
sun | power VL 12-200	12	200	190	180	151	132	68.0	18.0	380	205	383	A
sun | power VL 6-270	6	270	255	240	202	176	47.0	13.0	272	205	383	B
sun | power VL 6-330	6	330	320	298	252	220	61.0	20.0	380	205	383	B
sun | power VL 6-400	6	400	380	358	302	264	67.0	18.0	380	205	383	B
Series OPzS												
sun | power VL 2-280	2	280	265	245	213	182	17.1	4.5	105	208	420	C
sun | power VL 2-350	2	350	330	307	266	227	20.7	5.6	126	208	420	C
sun | power VL 2-420	2	420	395	370	320	273	24.6	6.7	147	208	420	C
sun | power VL 2-520	2	520	490	454	390	345	29.1	8.5	126	208	535	C
sun | power VL 2-620	2	620	585	542	468	414	34.1	10.1	147	208	535	C
sun | power VL 2-730	2	730	685	634	546	483	39.2	11.7	168	208	535	C
sun | power VL 2-910	2	910	860	797	686	590	46.1	13.3	147	208	710	C
sun | power VL 2-1070	2	1070	1002	930	801	691	59.1	16.7	215	193	710	D
sun | power VL 2-1220	2	1220	1145	1063	915	790	63.1	17.3	215	193	710	D
sun | power VL 2-1370	2	1370	1283	1192	1026	887	72.4	20.5	215	235	710	D
sun | power VL 2-1520	2	1520	1425	1325	1140	985	76.4	21.1	215	235	710	D
sun | power VL 2-1670	2	1670	1572	1459	1256	1086	86.6	25.2	215	277	710	D
sun | power VL 2-1820	2	1820	1715	1591	1370	1185	90.6	25.8	215	277	710	D
sun | power VL 2-2170	2	2170	2010	1843	1610	1400	110.4	32.7	215	277	855	D
sun | power VL 2-2540	2	2540	2349	2163	1881	1632	142.3	46.2	215	400	815	E
sun | power VL 2-2900	2	2900	2685	2472	2150	1865	150.9	45.9	215	400	815	E
sun | power VL 2-3250	2	3250	3015	2765	2412	2097	179.1	56.4	215	490	815	F
sun | power VL 2-3610	2	3610	3350	3072	2680	2330	187.3	55.7	215	490	815	F
sun | power VL 2-3980	2	3980	3685	3382	2952	2562	212.5	67.0	215	580	815	F
sun | power VL 2-4340	2	4340	4020	3696	3220	2795	221.2	66.4	215	580	815	F
sun | power VL 2-4700	2	4700	4355	4004	3488	3028	229.6	65.4	215	580	815	F

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

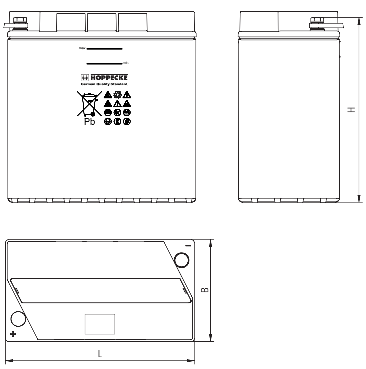
* According to DIN 40736-1 data to be understood as maximum values.

Fig. A Series OPzS bloc



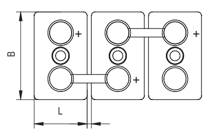
sun | power VL 12-70 -
sun | power VL 12-200

Fig. Series OPzS bloc



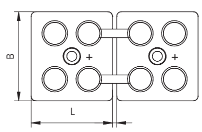
sun | power VL 6-270 -
sun | power VL 6-400

Fig. C Series OPzS



sun | power VL 2-280 -
sun | power VL 2-910

Fig. D Series OPzS



sun | power VL 2-1070 -
sun | power VL 2-2170

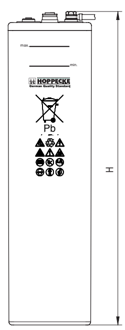
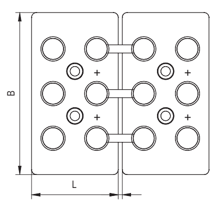
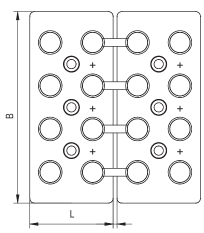


Fig. E Series OPzS



sun | power VL 2-2540 -
sun | power VL 2-2900

Fig. F Series OPzS



sun | power VL 2-3250 -
sun | power VL 2-4700

Optimal environmental compatibility –
closed loop for recovery of materials in an accredited recycling system

IEC 60896-11 · IEC 61427

BYD ENERGY STORAGE PRODUCTS(B-BOX)

B-BOX 2.5-10.0

Brief introduction

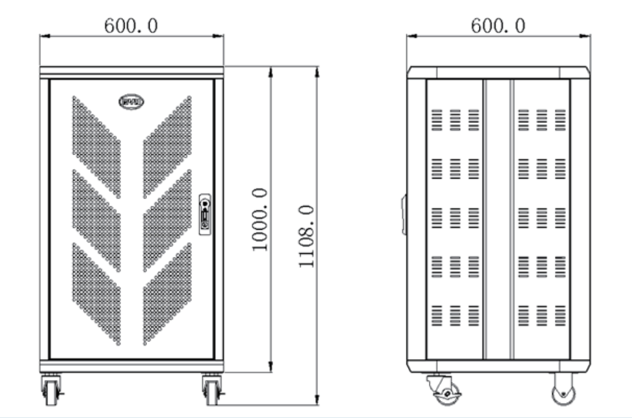
Battery Box takes along BYD reliable Fe battery which can be used as energy storage unit in energy storage system. The modular design gives flexibility of 1/2/3/4 pcs of battery modules in one battery rack.

B-Box is able to meet the requirement of different storage by increasing the capacity through parallel connection of battery rack.

Features of system

- Flexible capacity configuration
- Support system parallel connection
- Support RS485 or CAN communication
- Modular design
- Easy to Install
- Emergency stop function

System dimension



Application

- Residential PV Installations for self-consumption applications
- Commercial and Industrial installations for peak shaving
- Telecom industry for back up power
- Micro-grid

BYD ENERGY STORAGE PRODUCTS(B-BOX)

B-BOX 2.5-10.0

B-Plus2.5

BYD standard 3U battery—U3A1-50E-A which is CE and TUV certified, had been widely used in Telecom and Energy Storage applications in global market. The battery is manufactured by BYD LiFePo4 technology with annual capacity of 10GWh.

Features of battery

- Stable discharge plant
- Excellent safety performance
- Long cycle life
- High temperature performance
- High energy density
- High charge & discharge rate
- High energy transfer efficiency
- No pollution

	B-Box 2.5	B-Box 5.0	B-Box 7.5	B-Box 10.0
Battery Type	Iron phosphate battery			
Battery module	B-plus2.5*1PCS	B-plus2.5*2PCS	B-plus2.5*3PCS	B-plus2.5*4PCS
Rated battery energy (0.2C charge&discharge at @+25℃)	2.5 Kwh	5 Kwh	7.5 Kwh	10 Kwh
Output power	Max 2.5 Kw	Max 5 Kw	Max 7.5 Kw	Max 10Kw
Usable battery energy	2.3Kwh	4.5Kwh	6.8Kwh	9 kwh
Nominal voltage	51.2V			
Battery combine No	B-plus2.5*1PCS	B-plus2.5*2PCS	B-plus2.5*3PCS	B-plus2.5*4PCS
Energy efficiency	>97%			
BMS with Equalization	Yes			
Working voltage	44.8V-57.6V			
Communication	RS485/CAN			
Dimension of cabinet	Width 600* depth 600* mm height 1108 (with wheels)			
Net Weight of B-BOX	88Kg	126Kg	164Kg	202Kg
Dimension of B-plus 2.5	Width 482.6* depth 489.5* mm *height 130mm			
Net Weight of B-plus 2.5	38Kg			
Battery Cycle life	6000[100%DOD,+20℃,80% Capacity left]			
Operating temperature	0℃~+55℃			
Storage temperature	-20℃~55℃			
Transport	UN3480 & UN38.3			
Storage duration	12 months@+25℃; 6 months@+35℃; 3 months@+45℃			
EMC standard compliance	EN 61000 chapter 4.2,4.3,4.5,4.6/EN55022			
Safety standard compliance	UL1642 for cell; CE and TUV(JP) for battery module			
IP level	IP20			
Maintenance	Charge the battery half a year when storage or inactive status			
Scalability	/	/	/	Yes , Up to 40Kwh

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