Sustainability and Optimal Design of Small-scale Photovoltaic Systems for Rural Applications in Ethiopia

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This is to certify that the thesis prepared by Lemu Kebede, entitled: *Sustainability and Optimal Design of Small-scale Photovoltaic Systems for Rural Applications in Ethiopia* and submitted in partial fulfillment of the requirements for the degree of Master of Sciences (Energy Technology) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in this or any other Universities, and that all source of materials used for the thesis work have been duly acknowledged.

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LIST OF ACRONYMS

AAU:	Addis Ababa University
BOS:	Balance of System
COOPI:	Cooperazione Internazionale
CPV:	Concentrator Photovoltaic
CSA:	Central Statistical Agency
EEPCo:	Ethiopian Electric Power Corporation
ERG:	Ethio Resource Group
FDRE:	Federal Democratic Republic of Ethiopia
GOs:	Governmental Organizations
HoAREC-N:	Horn of Africa Regional Environment Center and Network
ICB:	International Competitive Bid
KWh:	Kilo Watt hour
KWh/m^2/day:	Kilo Watt hour per square meter per day
KWp:	Kilo Watt peak
MDGs:	Millennium Development Goals
MPPT:	Maximum Power Point Tracker
MW:	Mega Watt
MOH:	Ministry of Health
MoWIE:	Ministry of Water Irrigation and Electricity
NASA:	National Aeronautics and Space Administration
NGOs:	Non-Governmental Organizations
NMSA:	National Meteorological Service Agency
NREL:	National Renewable Energy Laboratory
OMERDA:	Oromia Mines and Energy Resources Development Agency
OWMEB:	Oromia Water, Mines & Energy Bureau
PMU:	Project Management Unit
PV:	Photovoltaic
PWM:	Pulse Width Modulation
REF:	Rural Electrification Fund
RETs:	Renewable Energy Technologies
SBCS:	Solar Battery Charging Station
SHS:	Solar Home System
SNNPR:	Southern Nations, Nationalities, and Peoples' Region
WMS:	Welfare Monitoring Survey

ABSTRACT

The government of Ethiopia placed a high priority on providing access to energy for remote locations. Despite this policy and the expenditure of millions of birr, the majority of the population still remains without access to electricity services today. To meet the lighting and other basic energy needs, many households continue to depend on polluting and non-efficient energy means such as kerosene and dry cell batteries. Electrification through grid extension was the only electrification options available to the rural population in this country. More recently, there is a dramatic increase in the use of renewable energy solutions, mostly off-grid solar PV systems by governmental and non-governmental organizations. Off-grid solar photovoltaic (PV) system is an obvious choice for bringing modern energy supply to the remote Ethiopian communities. In the past ten years, different governmental as well as non-governmental organizations in Ethiopia have implemented thousands of solar photovoltaic systems for homes and institutions across the four regions in Amhara, Oromia, SNNP and Tigray regions of Ethiopia. However, to date there has not been a major study conducted in regards to the sustainability and PV systems design considerations. Accordingly, this study assessed the different systems implemented in the four regions (Amhara, Oromia, SNNP and Tigray regions) with the main objective to identify factors affecting the sustainability of solar PV system dissemination thereby suggesting best ways for designing stand-alone solar PV systems for rural applications. In order to meet these objectives, scientific methodologies were followed which include literature review, site visit, data collection and analysis.

All the necessary data were collected by conducting surveys of solar PV systems installed in the selected sample Woredas of the four regions, and also by conducting interviews of PV system users and energy experts working in the respective Woredas, Zones and Regions. The thesis presents the major findings from the result of the data analysis which is evaluated in order to summarize the sustainability aspects of solar PV systems dissemination and to propose the most feasible solutions for the problems raised by the study. Based on the survey data analysis result, load estimations were done for homes and institutions found in off-grid areas. The solar radiation data of the regional capitals were retrieved from NASA which has been taken as an input for an optimized PV module and battery design that is simulated using PVSyst.

This thesis also examines issues of optimal designing and as such provides optimum sizes of photovoltaic panels and batteries for two types of homes with different load considerations, and for institutions such as schools and health facilities. The findings show that there are different system sizes that exist for the same kinds of institutions. In addition, similar sized systems were supplied and installed for all regions. The simulated system using PVSyst shows, for Adama (Oromia region) and Mekele (Tigray region), smaller PV size is needed as compared to Bahir dar (Amhara region) and Hawassa (SNNPR).

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1. INTRODUCTION

The access to reliable and affordable energy services needs to be improved for many of the developing countries to facilitate alleviation of poverty. Solar Photovoltaic (PV) systems can play a useful role in realizing that, since they are clean, safe, require little maintenance and have low recurring cost. This is in contrast to its predominantly used alternatives: kerosene, dry cell batteries and home generators [1]. Grid extension is often highly costly and not feasible in isolated rural areas, or is unlikely to be accomplished within the medium term in many areas. In such situations, solar PV electricity can power household use and local businesses [2].

Many off-grid communities have economic activities that require energy or have a strong potential for initiating such activities but are constrained by a lack of modern energy supply. Economic activities are often related to agricultural production and processing, fishing or fish farming, livestock raising, water pumping, or small cottage industries. Many require only small amounts of power (from 100 W to 3 kW), which could be provided by stand-alone renewable energy technologies. Institutional or community applications are another important division for off-grid electrification [1].

The predominant role of PV systems in off-grid electrification is not the result of a technology bias by planners. Solar PV is the only technology that can function virtually anywhere despite geographic variations in the resource (i.e., solar radiation intensity or number of days without sunshine). In most areas of developing countries, the solar resource is more than sufficient throughout much of the year to enable PV systems to function usefully. There is usually no need to conduct a solar radiation measurement program during the pre-investment phase. PV systems are modular and rugged; they require little maintenance (mainly periodic cleaning of the glass panel), although arrangements must be made to obtain spare parts and repair services [3].

When it comes to the implementation of stand-alone renewable energy technologies in off-grid areas, there are different criteria that need to be considered. The main criterion for selecting appropriate technology appears to be the economic and technical. The experience in small off-grid facilities is there are no big loads running, which is a good indication that PV systems could be the best energy option. Nevertheless, for medium and large facilities, the energy demand is high and continuous, where powering using PV-alone could be -impractical. Designers of off-grid electrification projects are responsible for a range of critical decisions that affect sustainability. These decisions include technology choice, ensuring affordability, social safeguards and environmental considerations, as well as taking advantage of opportunities to initiate and enhance productive activities and institutional applications. Project designers must also consider ways to use appropriate business models, determine necessary regulatory actions, and explore opportunities for international co-financing.

1.1. PROBLEM STATEMENT

There is a huge potential for a successful use of renewable energy in Ethiopia. With regards to solar power development, potential lies in rural energy electrification. Small solar PV systems, which include solar lanterns (1-3Wp), pico PV (3 - 10Wp) and solar home systems (SHS) (10 - 200Wp) are the most widely used efficient and cost effective energy sources for rural electrification [4]. It is estimated that a total of some 5.3MWp of PV is now in use in Ethiopia [5]. The main area of application for PV is now off-grid telecom systems which account for 87% of total installations. PV systems are also used in social institutions including health stations, schools and for water pumping. Some thirty thousand residential customers are also electrified with PV in rural areas [5]. Strong growth is foreseen in the coming ten years for this segment due to the drive for universal access to mobile connectivity. This will result in doubling of installed PV capacity by 2015 then again doubling by 2020 [5].

Dominating the off-grid market are project-based supplies with fewer companies working with local level service companies (installers and service providers). There are no government regulations and industry guidelines for self-regulation. This often leads to distrust among end-users when products breakdown after short periods of use [6].

Not enough research has been made regarding the sustainability aspects of solar PV systems installed. On the other hand, there exists different ways of designing off-grid solar PV systems by governmental and non-governmental organizations. This lack of common standard could greatly affect the sustainability of off-grid solar PV systems in the country. So, this paper will look into the sustainability aspects by looking at the major factors which influenced the achievement or non-achievement of sustainability of solar PV systems in the country. Besides, the paper will also forward ways for designing off-grid solar PV systems in the country.

1.2. RESEARCH QUESTIONS

Solar PV could be used for different applications, such as for rural household, telecommunications, water pumping, and vaccine refrigerators, etc, in off-grid locations. However, there are obstacles that hinder its large scale implementation in Ethiopia, which could be classified as technical, institutional and regulatory. In order to overcome these difficulties, the following two main questions could be raised:

- What are the factors that enhance the sustainability of solar PV systems in Ethiopia? and
- What need to be considered when designing off-grid solar PV systems in Ethiopia?

1.2.1. Sub Research Questions

The sub research questions of the research will focus on:

- Investigating the different types and sizes of solar PV systems in the country,
- Investigating the different loads that were considered for solar PV systems design by GOs and NGOs, and
- Exploring the status of the solar systems installed in the particular region under study.

1.3. OBJECTIVES

1.3.1. General Objectives

As a major input to the thesis work, it looked into the different types of solar PV systems installed for electrifying off-grid rural communities in the selected regions under study, with the main objective of

- developing a sustainable and optimal mechanism for designing off-grid solar PV systems for the rural community in the country.

1.3.2. Specific Objectives

The specific objectives of the research are,

- to determine and summarize the different types of solar PV system installed by the different sectors,
- to identify the barriers that defer the sustainability and effectiveness of solar PV projects,
- to put forward strategies for developing a sustainable framework for solar PV systems implementation in the country/the particular region under study,
- to provide/suggest solar PV system sizes for the different types of solar PV systems that will serve as a guide for GOs and NGOs
- to identify and present the difference in off-grid PV systems implemented by the government and other sectors,
- to suggest the best ways for off-grid PV system design in four regions,

1.4. SCOPE AND SIGNIFICANCE OF THE STUDY

Except solar home systems where it was possible to find different systems for different households in one location (Kebele or village), it went difficult to find other types of systems localized in one Kebele/village. Because the bigger systems are located in different remote parts of the country, it will take time to retrieve data from all sites so that the study is limited to the assessment of only some selected sites. However the main goal is to apply the study in all the systems across the country.

The outcome of the study will help experts working in the solar energy sector as well as for policy makers as a reference to better understand the impacts and the conditions that influence the sustainability of off-grid PV systems in the country. It also will look in to the different angles that need to be seen in designing off-grid PV systems for rural country which again will help experts that work on this particular field.

1.5. CHALLENGES AND LIMITATIONS OF THE SURVEY

The major challenges and limitations encountered during the survey are:

- Since there are different systems implemented by different GOs and NGOs, it was difficult to assess all of the sites. Because of this, the assessment focused on those sites where all the information could be retrieved from either the site visit or the respective organization.
- As all the systems were in off-grid locations, accessing the sites was often difficult. It was possible to get different SHS in one location but not institutional systems which limited the assessment to only some of the selected sites.
- When conducting the interview with the SHS owners, some of them were reluctant to give the correct information because they thought we had come from the bank to collect the payment for the systems they own. Although SHS owners are obliged to pay for the systems they have with a down payment, almost all owners have not started paying for the system they have. Most of the time, they complain about the system, stating it has a problem even if there was none.
- The other difficulty faced was the inability to investigate the installed systems. This is due to the fact that most of the systems are protected from access due to warranty. Almost all of the systems being installed by the different PV system suppliers were found to be in a protected box where it is impossible to get access to the inside even when the system is not functional.

2. LITERATURE REVIEW

Energy overview of Ethiopia

There is a huge energy resource potential in Ethiopia, which, if utilized, could minimize the present energy crisis prevailing in the country and enhance the process of rural electrification. The total exploitable renewable energy that can be derived annually from primary solar radiation, wind, forest biomass, hydropower, animal waste, crop residue and human waste is about 1,959x103 Tcal per year. Out of this, the share of primary solar radiation is about 73.08 percent, while the share of biomass resources is about 12.8 percent [7].

In the past decades, Ethiopia has reported an economic growth in real GDP increase. The reported economic growth, as is usually the case, was followed by increase in energy demand. The average annual growth in electricity demand from 2012 to 2013 was approximately 14%, while petroleum consumption increased by 87% from year 2000 to 2009 [8,9]. Ethiopia's electricity consumption per capita is approximately 60 kWh on the year 2012, which is significantly lower than the 521 kWh averages per capita of sub-Saharan Africa [8,9]. According to some estimate only 23% of the population has access to electricity services in 2012 [8,9].

Table 2.1. Ethiopian energy resources gross and economic potential for electrical power generation and energy production [10]

No.	Energy Resource	Exploitable Potential [MW]	Average Capacity Factor [%]	Estimated Energy [GWh/year]	Gross Potential
1	Hydro	45,000	50.55	199,268	650,000 GWh/year
2	Wind	10,000	30.91	27,077	1035 GW
3	Solar	NA	20	526	5.2 KWh/m^2
4	Geothermal	7,000	90	55,188	NA
5	Biomass	530	89.38	4,150	50 million tons/year
6	NG	600[4]	84.85	4,459	112 billion m^3
7	Coal	100	68	596	320 million tons
Total		**63,530**		**291,264**	

Ethiopia generates most of its electricity from renewable energy sources, mainly hydropower. In 2011, over 96% of Ethiopia's electricity was from hydropower [11]. The midterm expansion plan to 2015 contains mainly hydropower plants thus increasing the hydropower share to nearly 100%. There are benefits and risks with such high specialization: the benefits are mainly in low economic cost of generation, improving technical and managerial capability to design, develop and manage hydropower projects, potential for export; the risks are related to the vulnerability of the power system to natural hazards and in its social and environmental impacts [12]. Solar, wind and geothermal were considered, in the Growth and Transformation Plan, to offset seasonal differences in water levels which could be caused by natural hazards.

The other parts of the energy usage in Ethiopia are bio fuels for cooking, heating, and off-grid lighting. Petroleum, including gasoline, diesel and kerosene comprises to only a small portion of the country's energy demand. Nearly 85% of the Ethiopian population lives in the rural areas and very few have access to electricity. To offset the fuel-based lighting in the rural community, solar photovoltaic is being promoted [13].

Solar Energy potential in Ethiopia

Ethiopia, a landlocked country, is located in the horn of Africa and bordered by Eritrea, Djibouti, Somalia, Kenya, Sudan and South Sudan. It is located between 3^{o} and 15^{o}North of Latitude and 33^{o} and 48^{o} East of Longitude which belongs to the tropic zone near the equator.

Figure 2. 1. Political map of Ethiopia [14]

Studies indicate that for Ethiopia as a whole, the yearly average daily radiation reaching the ground is 5.26 KWh/m^2. This varies significantly during the year, ranging from a minimum of 4.55 KWh/m^2 in July to a maximum of 5.55 KWh/m^2 in February and March. On regional basis, the yearly average radiation ranges from values as low as 4.25 KWh/m^2 in the areas of Itang in the Gambella regional state (western Ethiopia), to values as high as 6.25 KWh/m^2 around Adigrat in the Tigray regional state (northern Ethiopia) [7]. This is clearly shown in Figure 2.2 which shows areas in the Northern and Eastern parts of the country that have irradiances which could reach well above 6 KWh/m^2. Most of the regions in the North and Eastern parts also get irradiances in the range from 5.5 – 6.0 KWh/m^2 as described by the yellow dark color.

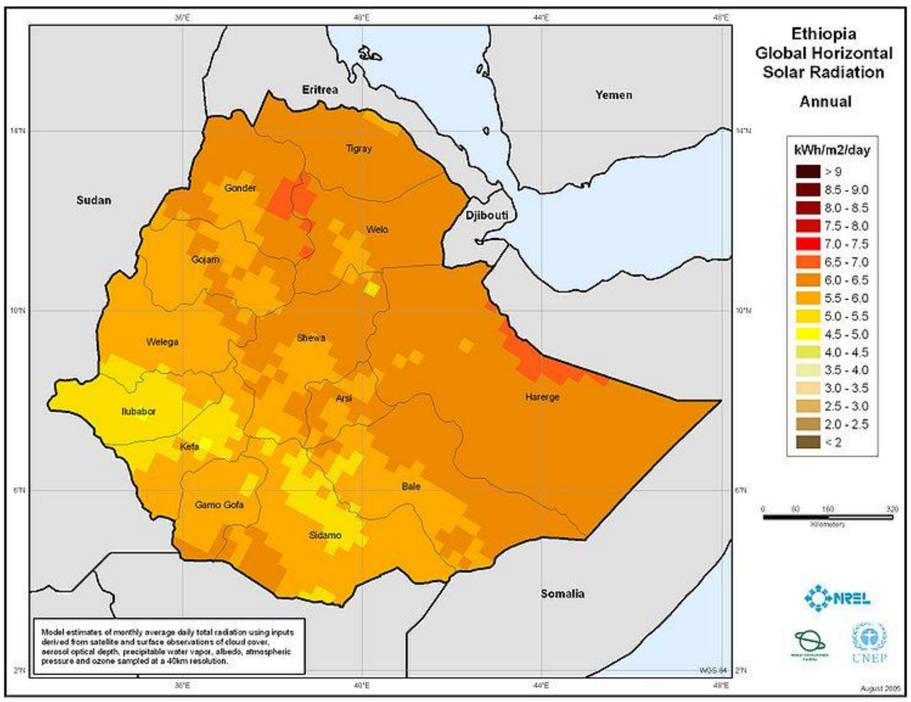


Figure 2. 2. Ethiopian Global Horizontal Solar Radiation [15]

Located very close to the equator, between 3^0 and 15^0 degrees north, Ethiopia receives a solar irradiation of 5,000 – 7,000 Wh/m^2 according to region and season and thus has great potential for the use of solar energy [16].

Ethiopia’s potential for solar PV projects is immense. Considering the country’s high levels of solar irradiation, which averages around 5.2 $kWh/m^2/day$, utility-scale PV power plants would benefit greatly from a dramatically increased level of output. This is especially valid for the eastern and northern parts of the country, where irradiation levels can reach as high as 6.25 $kWh/m^2/day$ [17].

Electrification challenges and opportunities

Energy is widely recognized as an essential input for socioeconomic development and it is important to address the challenges to the provision of energy services to Sub-Saharan Africa. Africa has the lowest electrification rate in the world. Excluding South Africa and Egypt, it is estimated that less than 20% overall, and in some countries as little as 5%, of the population in Africa has direct access to grid electricity. In rural areas, this figure is as low as 2% [18]. The number of people without access to modern energy services, defining those lacking access to electricity and clean cooking facilities, has decreased significantly. However, 2.6 billion people still lack access to affordable and reliable energy services to meet their basic energy needs [19].

More than 80% of the 1.4 billion people in the world that has no access to electricity live in rural areas of developing countries. Georeferenced analysis of solar irradiation of those regions where the people without access to electricity live confirms that a majority of them has access to very good up to excellent solar resources of about 1,800 – 2,200 $kWh/m^2/y$ irradiation but have to pay significant amounts of their income for conventional energy supply. Small photovoltaic (PV) applications, like solar home systems (SHS) and Pico PV systems (PS), can enormously improve local standards of living and also enable a fast financial amortization compared to conventional energy costs. Increasing demand for small PV applications and constant reduction of financial amortization create large market potentials in countries with low electrification rates [20].

Lack of access to electricity is one of the biggest issues facing the world's poor. The vast majorities of these people live in rural areas of developing countries because they are too poor and may be in too remote a location to be reached by the national grid. For their lighting needs, they rely on candles, kerosene lanterns, and firewood. This results in a daily expense that is expensive in the long run. Furthermore, this type of indoor lighting causes indoor pollution and chronic lung problems. Long-term, solar energy, small-scale, distributed solar home systems (SHS), is the most practical and economical way of bringing power to poor and remote communities. The target market for this particular application of SHS includes individuals living in rural villages of developing countries who are not connected to the grid and without a sustainable or reliable source of electricity. The main barriers to SHS adoption include lack of rural infrastructure (supply chain and financing), suspicion and lack of knowledge among rural people, lack of skilled labor for installation and maintenance, and most significantly the high upfront cost. It is essential to invest time to understand the needs and characteristics of the target communities [21].

Due to Ethiopia's lack of operational utility-scale solar PV plants, there is ample opportunity for entrepreneurial firms to enter this new market in its earliest stages of development. The government of Ethiopia is actively encouraging foreign direct investment, especially directed towards the development of the country's young solar energy sector [17].

Of course, despite Ethiopia's enormous energy potential, the country continues to be plagued by challenges to its development. Although huge progress has been made in the national electrification rate, which has more than doubled over the past ten years, it still remains at a low 26%. The national electricity grid uses outdated loss-prone technology. In addition, the majority of Ethiopia's population lives in rural areas without a functional grid connection. Although this is a great opportunity for the development of off-grid or microgrid solar solutions, Ethiopia's decentralized population and insufficient power grid present serious developmental challenges for utility-scale solar [17].

Sustainability of solar PV systems

Sustainability is the most precious gift that we can give to our future generations. Renewable energy is not an entirely new concept, but it continues to rapidly emerge as an alternative to fossil fuels and other deleterious energy sources. Products within this industry are being created on an unprecedented scale, and various systems are available for use. However, none are as applicable to the sustainability of the lives and families of millions of underprivileged peoples in developing countries as is solar power [22]. Renewable energy resources can improve quality of life by promoting sustainable development. Systems such as solar power are "practical, reliable, cost-effective, and healthier for people and the environment" [23]. PV systems can contribute considerably towards realizing sustainability in health facilities. The main challenge, however, is how to keep installed systems properly working and efficiently utilized throughout their lifetime [24].

PV systems can contribute considerably towards realizing sustainability in health facilities. The main challenge, however, is how to keep installed systems properly working and efficiently utilized throughout their lifetime. Lessons learned, and crucial pillars of success, which significantly enhance the sustainability of PV systems, are shown in Figure 2.3 [24].

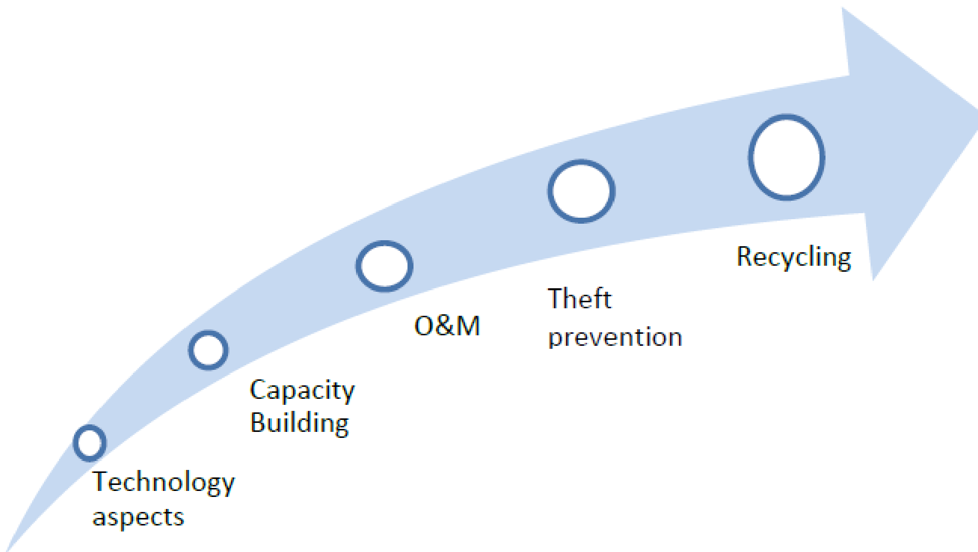


Figure 2. 3. Main factors towards enhancing sustainability of solar PV systems [24]

Technology Aspects

While PV systems are meanwhile a mature technology, many projects failed in the past due to the poor quality of system components including batteries, charge controllers and inverters. PV system components should comply with one of the recognized international standards (e.g. IEC, DIN, IEEE).

Capacity Building

A specific training program on operation and maintenance of PV systems for local working staff is required. The training program can be launched in parallel with the installation of the PV systems. In addition, training of local staff on management of energy stored in batteries is necessary; including the operation of critical, important and non-important loads.

Operation and Maintenance

Most PV systems are designed by independent consultants in developing regions. The task of consultants includes system design, field survey, and preparing the technical specifications of PV systems. Existing experience shows that most health facilities in rural areas are owned by district councils. Hence, it is their responsibility to operate and maintain the installed systems. This is a challenging situation, as most of the district councils do not have a maintenance budget set aside. This leads to premature failure as the systems are not attended in time.

Recycling

Batteries are the main components in stand-alone PV systems that need to be recycled. Basically, they contain toxic materials which have negative effects on the environment if disposed of inadequately. Therefore, recycling of batteries should be considered mainly when designing maintenance mechanisms.

Theft prevention
The investment costs of PV systems are high; therefore systems can be stolen in remote areas. Some health facilities lack the safety of fences or other measures that prevent installed systems from being stolen. Anti-theft screws can keep the PV modules secured. Another option to secure the PV modules is through the welding of module frames together, if possible with a fixed foundation.

In the growing field of evaluation practices in development activities it is important to determine the terms and objectives of an evaluation. While relevance, effectiveness and efficiency should be analyzed in the earlier steps of the project cycle, impact and sustainability can and should be assessed post implementation. These types of ex-post evaluations are particularly helpful in answering the question of what works and why and, consequently, can guide future improvements in project design and practice by identifying success factors and explaining failure [25]. As previously mentioned, access to sustainable and affordable energy services is a crucial factor in reducing poverty in developing countries. Small-scale projects can improve and increase access to energy for individuals and communities that would not have been supplied by market structures. This is similar to conclusions drawn by other evaluations that focus on photovoltaic energy [26].

Solar PV system design

By building a solar design house even before attaching solar PV panels, the most can be made out of the sun's energy. This will absolutely ensure the greatest efficiency and cheapest. Houses built in this way contribute to sustainability, by "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [27].
The three components of the optimization are: technology choice, optimized system design and the system cost [1]. Critical preconditions of a successful system design include proper sizing, technical and economic efficiency, modularity, simplicity and safety [28]. Proper sizing means to configure a PV system in such a way that it supplies the demand for energy services. The system needs a techno-economic optimized design to provide reliable and affordable energy services. In order to size an optimized design, either an analytical or simulation-based sizing method is used [1].

Technology choice

A decentralized PV system is classified according to the number of users and its power capacity, shown in Table 2.2 [1].

Table 2. 2. Classification of decentralized PV systems [1]

PV system option	Abbreviation	System voltage	Approximate size
Pico PV System	Pico PV	6 / 12 V	1 -10 Wp
Solar Home System	SHS	12 / 24 V	10 – 200 Wp
Multi-user PV system	MUS	12 / 24 / 48 V	200 – 5,000Wp
Micro-grid System	MGRID	24 / 48V	< 4,000Wp

Optimized system design

An optimized system design is achieved in several steps. First, the availability of appliances to provide the energy services is assessed through a market. Secondly, an inventory of the available PV system components is established from wholesale suppliers. Thereafter, a selection of appropriate technology is made. Finally, the battery bank, PV module and charge controller are sized with an analytical and simulation-based sizing method [1].

i. Size of PV

The monthly energy produced by the system per unit area is denoted: $E_{pv,m}$ (kWh/ m^2) and $E_{L,m}$ is the monthly energy required by the load (where m = 1,2,…, 12 represents the month of the year.). The minimum surface of the generator needed to ensure full (100%) coverage load (EL) is expressed by [26]:

$$A_{pv} = \max_{m} \frac{E_{L,m}}{E_{pv,m}} \tag{2.1}$$

Surface larger than Eq. 2.1 can be needed for taking into account the limited size of the batteries or for including a security factor.

The total energy produced by the photovoltaic generator which supplies the load can be expressed by:

$$E_L = E_{pv}.A_{pv} \tag{2.2}$$

The calculation of the photovoltaic generator size (A_{pv}) is established from the annual mean of the monthly contribution ($\overline{E_{pv}}$). The load is represented by the average annual monthly$\overline{E_L}$.

$$A_{pv} = ff.\frac{\overline{E_L}}{\overline{E_{pv}}} \tag{2.3}$$

where ff is the fraction of load supplied by the photovoltaic energy.

The number of photovoltaic generator is calculated using the surface of the system unit $A_{pv,u}$ taking the entire value:

$$N_{pv} = ENT\left[\frac{A_{pv}}{A_{pv,u}}\right] + 1 \tag{2.4}$$

ii. Size of Battery Bank

Always, before tackling the calculations, we start by identifying:

- the electricity usage per day
- number of days of autonomy
- depth of discharge limit
- ambient temperature at battery bank.

Electrical Usage

Firstly, we have to know the amount of energy we will be consuming per day $E_{L,max}$ (Wh/day).

Number of Autonomy Days

In the second step, we have to identify days of autonomy N_j (backup days). We multiply $E_{L,max}$ by this factor N_j.

$$RES = E_{l,max}.N_j \tag{2.5}$$

Depth of Discharge Limit

The depth of discharge (DOD) needs to be identified and converted it to a decimal value. Divide Eq. 2.5 by this value (DOD).

$$ANT = \frac{RES}{DOD} = \frac{E_{l,max}.N_j}{DOD} \tag{2.6}$$

Ambient Temperature at Battery Bank

The battery banks need to be derated for ambient temperature effect. Select the multiplier corresponding to the lowest average temperature that batteries will be exposed to. This multiplier depends on the battery type (Table 2.3 gives such data).

Table 2.3. Factor (FT) calculation [29]

Temperature (^{o}C)	Factor (FT)
+26	1.00
+21	1.04
+15	1.11
+10	1.19
+4	1.30
-1	1.40
-6	1.59

Multiply Eq. 2.2 by this factor (FT) and then the minimum capacity of battery bank (Wh) will be obtained.

$$C_{bat,min}(Wh) = \frac{ANT.FT}{N_m.\eta_{batt}} \tag{2.7}$$

Finally divide the minimum capacity of battery bank by battery voltage V_{batt} to obtain the minimum capacity (Ah) of the battery bank.

$$C_{bat,min}(Ah) = \frac{C_{bat,min}(Wh)}{U_{batt}} \tag{2.8}$$

The battery capacity of storage can be written as:

$$C_{bat,min}(Ah) = \frac{E_{l,max}.N_j.FT}{U_{batt}.DOD.N_m.\eta_{batt}} \tag{2.9}$$

Where U_{batt} is the battery voltage, DOD is the depth of discharge, η_{batt} is the battery efficiency, N_m is the number of days in the month which has the maximum energy consumed.
The number of batteries to be used is determined from the capacity of a battery unit $C_{batt,u}$ is given by:

$$N_{batt} = ENT\left[\frac{C_{bat,min}}{C_{batt,u}}\right] \tag{2.10}$$

iii. Inverter size

The selection and number of inverters is based on three criteria: the voltage compatibility, the current compatibility and the power compatibility. From these three criteria, the design of inverters will impose how to wire the photovoltaic modules together

Voltage compatibility

An inverter is characterized by a maximum admissible input voltage Vmax. If the voltage delivered by the PV is greater than Vmax, the inverter will be damaged. We will consider that the voltage delivered by a PV is its open circuit voltage Voc. Thus, the maximum number of photovoltaic modules in series is calculated by the following simple equation:

$$N_{pv\_serial} = ENT\left[\frac{Vmax}{Voc * 1.15}\right] \tag{2.11}$$

The coefficient 1.15 is a safety factor.

Compatibility with current

As currents are added when panels are in parallel, the value of the current Imax will determine the maximum number of parallel panels. In the design sizing, it is assumed that the current delivered by a PV system is equal to the short-circuit current (Isc) given on the datasheet. The maximum number of panels in parallel is calculated by the following equation:

$$N_{pv\_parallel} = ENT\left[\frac{I_{max}}{I_{sc} * 1.25}\right] \tag{2.12}$$

The coefficient 1.25 is a safety factor.

Compatibility in power

The value of the maximum power input of the inverter will limit the number of panels connected. Indeed, we must ensure that the power of a PV system does not exceed the maximum allowable power. As the power delivered by the PV system varies with radiation and temperature, we can consider for the sizing that the calculated power is less than the maximum allowable power by the inverter. Ideally, the power delivered by the PV system must be substantially equal to the maximum allowable power inverter.

iv. Sizing of DC wiring

The array cabling ensures that energy produced by PV array is transferred efficiently to the load. In theory, connections are made up of perfect current conductors with a zero resistance. In practice, a conductor is not perfect. It works like a resistance (Fig. 2.4).

The resistance of an electric conductor is very low but not zero. We have the following expression:

$$R = \frac{\rho . L_c}{S} \tag{2.13}$$

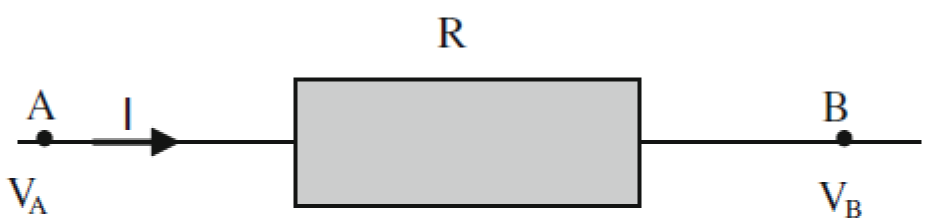


Figure 2. 4. Modeling of a cable [30]

Table 2. 4. Material resistivity [30]

$\rho_c(\Omega . m)$	**Material**
2.7 X 10^{-8}	Aluminum cable
1.7 X 10^{-8}	Copper cable
1.6 X 10^{-8}	Silver cable

with L_c the conductor length (m), S the cross-section area (m^2), ρ_c (Ω. m) the resistivity of the cable. It depends on the material [30]:

The conductor resistance, defined above, will cause a potential drop between conductor input and the conductor output. We have:

$$U = V_A - V_B = R . I$$

Thus, if the conductor is perfect:

$$R = 0$$

$$U = 0$$

Then:

$$V_A = V_B$$

As R > 0 for a non-perfect conductor, V_A will be greater than V_B which corresponds to a potential drop.

The voltage drop in a DC conductor is related to power losses.

$$E_{J,i} = R_i . I_i^2 . T_{dur} \tag{2.14}$$

where E_i is the energy dissipated by Joule losses in the conductor i, R_i and I_i are the resistance and the (quadratic) mean current of that conductor and T_{dur} the considered time duration (in hours is the energy is expressed in Wh). Of course, the total Joule losses of the DC cabling are, replacing each R_i by its value from Eq. 2.9:

$$E_J = \sum_i \rho_c \frac{L_i}{S_i} I_i^2 T_{dur} = \rho_c T_{dur} \sum_i \frac{L_i}{S_i} I_i^2 \tag{2.15}$$

It is easy to proof that, in order to low the losses for a given conductor volume, all the conductors need to be kept at the same ratio

$$\lambda_c = \frac{S_i}{I_i} \tag{2.16}$$

Thus, the Joule losses in the DC cabling are

$$E_J = \frac{\rho_c T}{\lambda_c} \sum_i L_i I_i \tag{2.17}$$

In practice, the DC cabling losses need to be limited to a fraction Ɛ of the energy produced N_{pv} E_{pv} (Ɛ ≈ …1% … 3%). Thus, from Eq. 2.12, it is found:

$$\lambda_j = \frac{\rho_c T_{dur}}{E_J} \sum_i L_i I_i = \frac{\rho_c T_{dur}}{\varepsilon N_{pv} E_{pv}} \sum_i L_i I_i \tag{2.18}$$

Finally, from Eq. 2.11 the minimum section of each conductor will be

$$S_i = \lambda_c I_i \tag{2.19}$$

v. Sizing of DC fuses

In a photovoltaic system, fuses have to protect the photovoltaic modules against the risk of overload. The information needed to define a good protection against over current by fuses is:

- $N_{pv\text{-}Serial}$ Serial number of modules: in a photovoltaic system, panels are connected in series to obtain the desired DC voltage.

- $N_{pv\text{-}parallel}$, the number of PV in parallel: Up to three panels in parallel ($N_{pv\text{-}parallel} \leq 3$), protection against over current is not necessary. From four panels in parallel ($N_{pv\text{-}parallel} \geq 4$), the over current, can heat the cables and damage photovoltaic panel. It must be eliminated with a fuse placed at each panel.
- I_{sc}, the current short-circuit (under standard test conditions STC).
- The fuse rating current should be between 1.5 and 2 times the current I_{sc}.
- V_{oc}, the open circuit voltage (under standard test conditions STC).

The operating voltage of a fuse should be 1.15 times the open circuit voltage ($1.15 * V_{oc} * N_{pv\text{-}Serial}$).
Generally, fuses and switching equipment should be rated for DC operation.

3. METHODOLOGY AND DATA COLLECTION

This thesis investigates the sustainability and optimal design of small-scale photovoltaic systems for rural applications in Ethiopia. First, we will study the circumstances of the present dissemination in Ethiopia, which was planned to be conducted using desk review, key informant interview and on site survey. Then, we will study issues of optimal design. The site survey has been in Amhara, Oromia, SNNP and Tigray regions to examine the status of installed PV systems installation, end-users understanding of the installed systems and characteristics associated with the sustainability of the PV systems. As indicated in the scope, one of the major problems to look at the institutional systems has been their location. Almost all of them were located in remote rural areas which made the process to gather data very difficult. Unlike the institutional system, solar home systems somehow were possible to be accessed at some locations. It was possible to look at the systems directly where at the same time we interviewed the SHS users.

During the site visit to some selected off-grid locations, energy experts from the Zones and Woredas have been consulted and in some sites, they have been part of the team during the survey. Cooperative members have provided some of the details of the systems found in their respective regions which remained the main contributor of the data that was collected on the field.

The approach followed refers to the way the research problem was identified to the way how the sustainability impact of the problem to be examined. As indicated in the flow chart below the approach starts with literature revision to primary data collection of the different SHS and institutional system users and then followed by the secondary data collection from the different stakeholders. The overall process of the methodology from problem identification to report is summarized in the following flow chart (Figure 3.1).

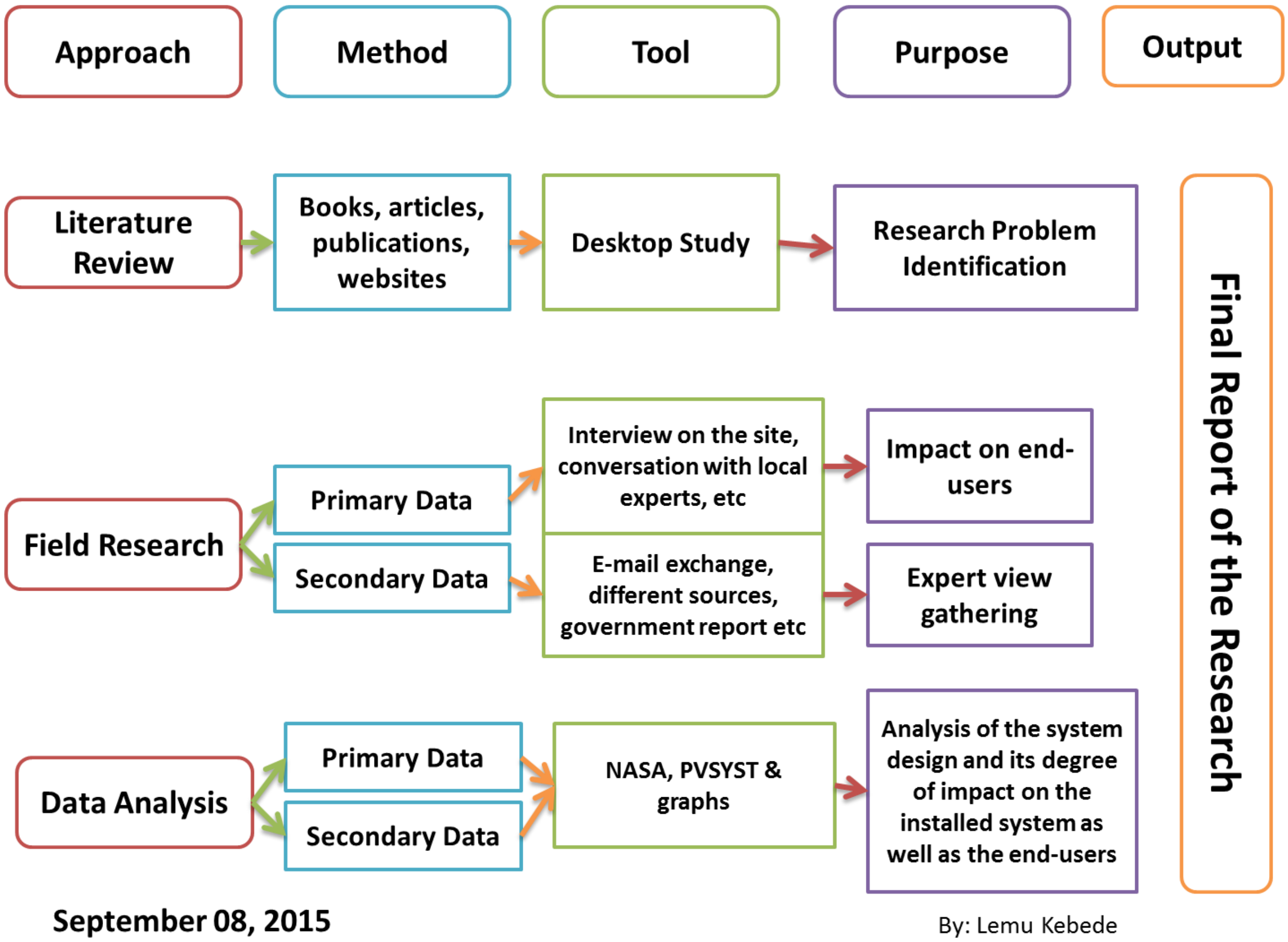


Figure 3.1. Methodology flow chart

3.1. SURVEY AREA

Due to budgetary issues, sites with appropriate location to look at overall performances were selected. The selection also considered logistical issues which otherwise would be difficult to look at the sites in the restricted time we had. During the visit, regional energy experts' sometimes Zonal energy experts were involved. The site selection has been conducted together with the experts considering the logistical and financial issues. The selection of the site visits were based on composite criteria to ensure that significant features of solar PV projects can be captured in short span of time. Within the study duration, it was tried to visit multiple solar project sites that would make it representative of all the solar projects operating in Ethiopia.

Table 3. 1. Sites selected for the survey

No.	Region	Zone
1	Amhara	North Shoa
2	Oromia	East Shoa
3	SNNPR	Sidama and Bench Maji
4	Tigray	North Western Tigray

Even if the sites found in Table 3.1 were visited, there were also sites around the regional capitals which have been visited. But regional capitals from the four regions have been taken for the design which could still represent other areas in the respective regions.

3.2. DATA COLLECTION, ANALYSIS AND INTERPRETATION

The data collection phase of the project was divided into primary and secondary data sources. The respondents for the primary data collection were SHS users and Institutional PV system users. The data collection for SHS has been conducted from house to house. Only some of the selected houses, in coordination with the cooperatives which were present by the time of our survey, were visited. The same mechanisms were used to collect data from the institutions, Schools and Health facilities, where data from regional energy bureaus have also been used.

The secondary data were gathered from reports, bid documents and online source published by various researchers, governmental and non-governmental organizations. Some of these organizations were where the secondary data collected were REF, MoWIE, MoE, MoH, GIZ EnDev Ethiopia, Plan Ethiopia, HoAREC-N and Doctors with Africa - CUAMM. The secondary data mainly cover the following important areas in the research,

- Solar photovoltaic supply, demand as well as consumption trend
- Solar Photovoltaic potential of the regions
- PV implementation in the regional towns
- Status of the different photovoltaic systems implemented

Furthermore, PVSYST was employed for the solar PV detailed system design. The detailed results of the analysis were presented in the form of graphs and tables in the report.

Solar Home Systems

Solar home systems (SHS), which range between 10 and 200W [29], are basically used for lighting, mobile charging and the usages of appliances like a radio and TV. There are two different designs used in SHS, direct current (DC) and alternating current (AC). SHS designed using 12V/24V DC will only work for appliances suited for DC operations whereas for homes that use 220V AC appliance, an additional inverter is integrated in the system for converting the DC power from the battery to AC power. All the SHS visited were installed by REF.

The site survey addressed the following areas based on system user and needs:

- General information about the SHS user,
- General information about the household and their energy consumption,
- Technical data about the installed solar PV system,
- General information about their usage of the system,
- General information about system performance,
- General information about service and maintenance of the installed system,

Institutional PV Systems

On the other hand, the institutional PV systems fall in the range of 200 – 5000 Wp. The institutional PV systems use inverters to supply AC power for AC appliances and are larger in size as compared to the SHS. But, the institutional PV systems reviewed had two types of system configurations, DC coupled and AC coupled. All the systems which have been installed by governmental bodies such as Rural Electrification Fund (REF), Ministry of Health (MoH) and Ministry of Education (MoE) were designed using DC coupling. AC coupled PV systems were first installed by GIZ EnDev Ethiopia in 2009 which were later adopted by non-governmental organizations working with GIZ such as USAID, Doctors with Africa and EECMY. These two types of system configurations are explained in the next chapter.

There are different solar PV systems installed for different institutions located in off-grid community across the country. These institutions include schools (primary as well as secondary), health facilities (health posts and health centers including veterinary clinics), farmer training centers and community centers. These PV systems provide electricity for schools and public buildings, electricity for vaccine refrigerators and smaller medical equipment’s in the health facilities including power for lights, radios and TVs.

The site survey addressed the following areas based on the system user and needs:

Schools and Health Centers/Health Posts

- General information about the school and HC/HP,
- Technical data about the installed solar PV system,
- General information about the loads in the school and HC/HP,
- General information about their system usage,
- General information about the solar PV system performance,
- General information about service and maintenance of the installed system,

3.3. LOAD ASSESSMENT

In order to design PV system sizes of solar home systems and institutions, the main loads to be powered by the solar system need to be determined. The term load refers to electrical appliances present in rural homes and institutions. The load assessment includes a listing of the quantity, power and daily hours of the loads. This information can be evaluated to yield the total daily electricity consumption. For homes, the loads described are on the assumption of substituting kerosene fuel which was used for lighting whereas for institutions, especially health facilities, the loads are electrical appliances owned by the institutions. In addition, the load demands were described based on the availability of the local market with the largest market being in the capital or other large cities.

The average power rating of the most abundantly available light bulbs, radios and televisions are obtained through a market study at suppliers of electrical materials. The average power rating of the electrical items is assumed equal for all households and similar institutions.

To design SHS, two major groups with the above services were identified, smaller systems that can provide basic needs (lighting, radio and mobile charging) using DC power and another that includes a TV using AC power.

For health facilities, the most common refrigerator Dometic TCW 3000 found was considered. Medical equipment's such as microscope, centrifuge and others like sterilizers were described based on the interview with the health post and health center staff. For schools, interviewees are asked which electrical items they own in the institution, how many of them and their duration of daily use. Finally, the load for an average rural household, health center, health post and schools are calculated. The load profile for the bigger systems, health centers and health posts, are presented in Table 3.2 and Table 3.3 respectively.

Table 3.2. Daily load profile for a health center

Energy demand analysis for selected load profile

No	Appliances	Specification/ purpose	Power rating(W)	Qty	Total power	Running hour/ 24hr (h)	Energy consumption / 24 hr (Wh)	Appliance working hour (O'clock) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	Total energy consumption per day (kwh/day)
1	**Lamp**	Energy saving lamp/ for HC rooms	11	30	330	4	1,320	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	330	330	330	330	0	0	
2	**Lamp**	Energy saving lamp/ for HC compund	11	8	88	12	1,056	88	88	88	88	88	88	0	0	0	0	0	0	0	0	0	0	0	0	88	88	88	88	88	88	
3	**Lamp**	Energy saving lamp/ for staff residence	11	10	110	4	440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	110	110	110	110	0	0	
4	**Refrigerator**	TCW 3000 vaccine storage	150	1	150	8	1,200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	
5	**Microscope**		20	1	20	4	80	0	0	0	0	0	0	0	0	20	20	0	0	0	0	20	20	0	0	0	0	0	0	0	0	
6	**Sterialiser**	Hot dry air (1 cycle / day, around noon)	500	1	500	2	1,000	0	0	0	0	0	0	0	0	0	0	0	500	500	0	0	0	0	0	0	0	0	0	0	0	
7	**Centrifuge**		90	1	90	2	180	0	0	0	0	0	0	0	0	0	90	90	0	0	0	0	0	0	0	0	0	0	0	0	0	
8	**Suction pump**		150	1	150	2	300	0	0	0	0	0	0	0	0	0	0	0	0	150	0	0	0	0	0	0	0	0	0	150	0	
9	**TV**		80	1	80	4	320	0	0	0	0	0	0	0	0	80	80	80	80	0	0	0	0	0	0	0	0	0	0	0	0	
10	**Satelite dish**	Reciever	30	1	30	4	120	0	0	0	0	0	0	0	0	30	30	30	30	0	0	0	0	0	0	0	0	0	0	0	0	
11	**Radio/Tape player**		20	1	20	8	160	0	0	0	0	0	0	0	20	20	20	20	20	20	20	20	0	0	0	0	0	0	0	0	0	
12	**Mobile charger**		5	15	75	2	150	0	0	0	0	0	0	0	0	0	75	0	0	0	0	0	0	0	0	0	75	0	0	0	0	
	Total				1,643		6,326																									
	Hourly energy consumption(Wh)							138	138	138	138	138	138	50	70	200	365	270	680	720	70	90	70	50	50	578	653	578	578	288	138	**6.326**

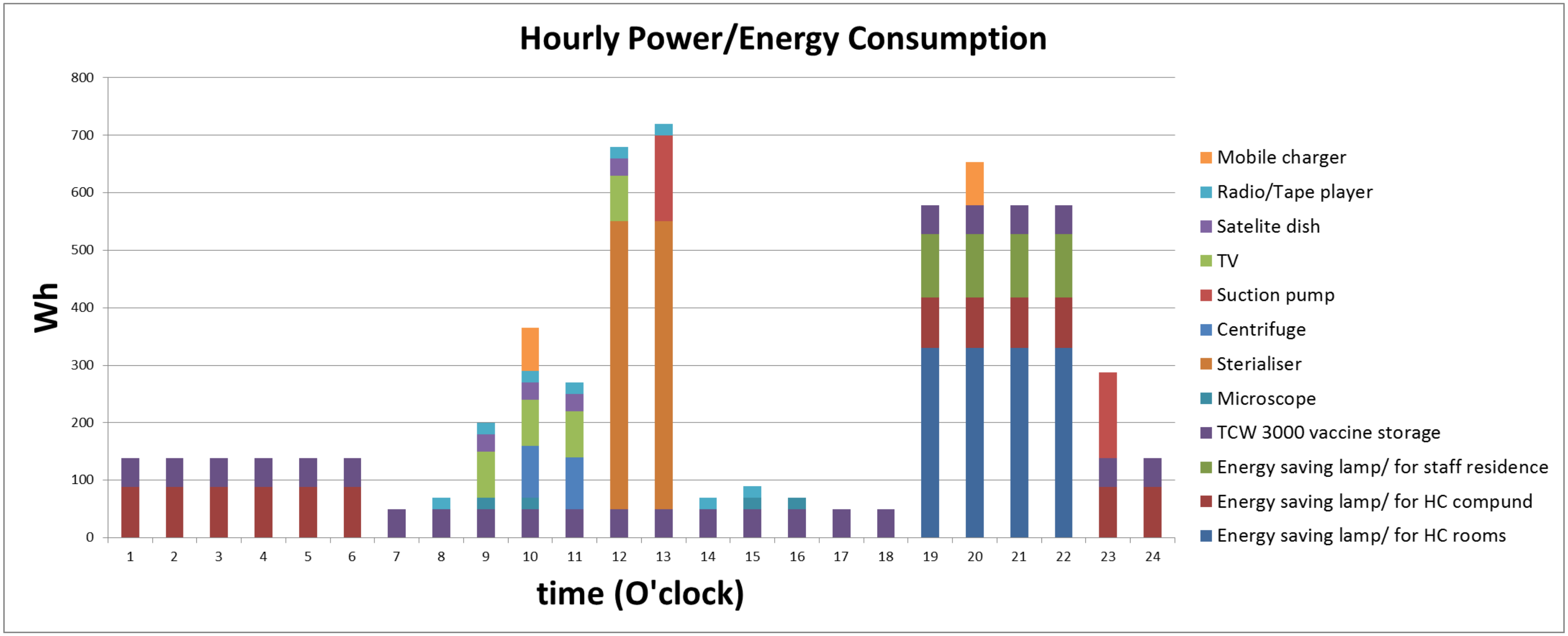


Figure 3.2. Daily load profile of the health center

Table 3.3. Daily load profile of a health post

Energy demand analysis for selected load profile

Appliance working hour (O'clock)

No	Appliances	Specification/ purpose	Power rating(W)	Qty	Total power	Running hour/ 24hr (h)	Energy consumption / 24 hr (Wh)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	Total energy consumption per day (kwh/day)
1	**Lamp**	Energy saving lamp/ for HC rooms	11	6	66	4	264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	66	66	66	66	0	0	
2	**Lamp**	Energy saving lamp/ for HC compund	11	2	22	12	264	22	22	22	22	22	22	0	0	0	0	0	0	0	0	0	0	0	0	22	22	22	22	22	22	
3	**Refrigerator**	TCW 3000 vaccine storage	150	1	150	8	1,200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	
3	**Delivery lamp**		20	1	20	2	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	20	0	0	0	
3	**Cassette player/radio**		10	1	10	8	80	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	
3	**Mobile charger**		5	4	20	2	40	0	0	0	0	0	0	0	0	0	20	20	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Total				288		1,888																									
	Hourly energy consumption(Wh)							72	72	72	72	72	72	50	50	50	80	80	60	60	60	60	60	60	50	138	158	158	138	72	72	1.888

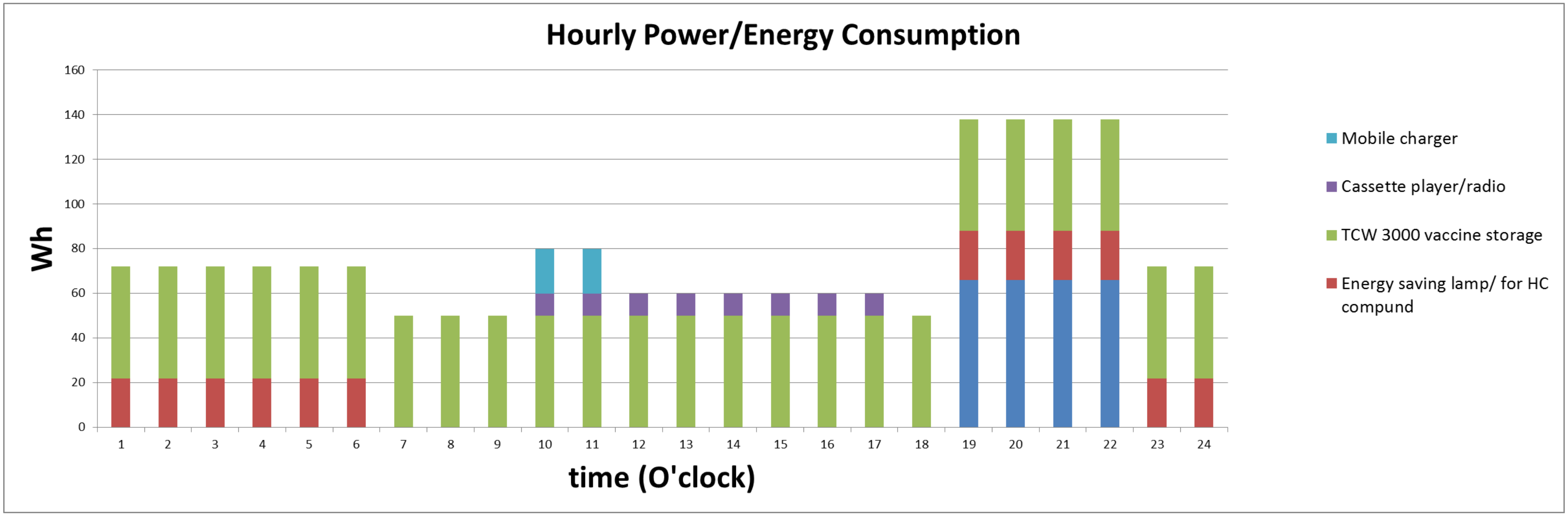


Figure 3.3. Daily load profile of a health post

The daily load profile is drawn by the consultation of health facility workers and reviewing different documentations related to similar system installations. Reports show that some appliances, such as three phase sterilizer and refrigerators like RCW 50 EK (2.46 kWh/24hr) and Sibir (6.3 kWh/24hr), in health institutions consume very high energy. This high energy demanding equipment cannot be considered to be powered by PV, in which case the respective health offices, were advised to delivery energy efficient medical equipment's.

In all the locations assessed, all the health center staffs tend to use their light bulbs from 7 PM onwards, since it gets dark around that time. The television and radio are predominantly used during the day time when there are lots of patients coming to the health facility. The majority of the other loads such as microscope, sterilizer, suction pump, examination lamp, delivery lamp and mobile charge are used during the day. Refrigerators, even though they are plugged in the whole time, will not be consuming power throughout their connection period. Dometic TCW 3000 ice liner refrigerator consumes 1.17 kWh/24 hours with continuous icepack freezing and 1.07 kWh/24 hours without icepack freezing intermittently, both at an average of 32^0c. In addition, it needs electricity for a minimum of 8 hours out of its 24 hours' time connection to reach its adjusted internal temperature. This doesn't mean the fridge will be unplugged every three hours, but rather the refrigerator adjusts its consumption in accordance with the temperature.

Table 3.2 and Table 3.3 show a daily load of 6.326 kWh and 1.888 kWh for health center and health post, respectively. The resulting daily load profile for the health center shows two peaks: one during the morning hours and one in the early evening with the morning pick bigger than the evening. This is an indication for one design factor to use AC coupling system for the health centers.

The resulting daily load profile for the health post shows one peak in the early evening hours. There are appliances running during the day time but when compared with the loads running in the evening, they are not significant.

Figure 3.2 and Figure 3.3 also indicates providing the selected medical equipment's using PV requires a relatively large amount of electricity for health centers as compared to health posts. The daily load of 6.326 kWh for the health center and 1.888 kWh for health post are used for PV system design in this paper.

3.4. OPTIMIZATION TOOLS AND INPUT DATA

The goal of the optimization assessment is to find the optimal PV and battery size for a specific load. Accurate sizing of off-grid PV system is very important as improper size of the system leads to over sizing or under sizing of the system by which system cost and system performance is affected. Various GOs and NGOs have employed different size of PV module and battery for the same facility which is still difficult to select the best type of system that meets the needed loads. Hence, a pre sizing of PV module and battery is very important before installation of the PV systems.

In order to size an optimized design, simulation based sizing method (PVSyst) is used. PVSyst is an energy modeling tool used by the solar industry to simulate the energy harvest of a potential project site. The energy harvest is a result of the effects of several parameters in PVSyst. Most of these parameters can be customized to produce a more accurate result.

The field work included the assessment of different institutions and households in different Woredas located in Amhara, Oromia, SNNPR and Tigray regions. The respective regional capitals were considered for the optimization according to their coordinates in Table 3.13.

Table 3. 4. Coordinates of the region capital

Region	Region capital	Latitude	Longitude
Amhara	Bahir Dar	11.5742° N	37.3614° E
Oromia	Adama	8. 5263° N	39.2583° E
SNNPR	Hawassa	7.0504° N	38.4955° E
Tigray	Mekelle	13.4936° N	39.4657° E

Because of the similarities in environmental conditions from region to region, data from one area is used for the other depending on the coordinates and similarities in irradiance. The cities coordinates from Table 3.4 are the input to obtain the monthly averaged irradiation data, which is shown in ANNEX-I.

The PV system sizing covers only PV and battery sizing based on the hourly load data presented in *Table 3.2 and 3.3*. The results of the simulation are based on the following findings.

- The optimized angle of inclination for Bahir dar is taken 16^0, for Adama, Hawassa, and Mekelle 15^0 [31].
- The system voltage for simulation has been selected based on the daily energy demand [32].

4. RESULTS AND DISCUSSIONS

This chapter discusses the installed PV system sizes and their status including the loads considered by governmental as well as non-governmental organizations. Factors affecting the sustainability of the installed Solar PV systems will be discussed by presenting the statuses and the design aspects. This chapter will end by discussing and comparing the designed PV system with the systems installed by different organizations discussed.

There are different system sizes of solar PV systems installed by governmental and non-governmental organizations for SHS and institutions. The loads that have been used by GOs and NGOs for SHS and institutional PV systems are compiled below.

4.1. LOADS CONSIDERED FOR SYSTEM DESIGN BY GOs AND NGOs

The loads described in the Table 4.1 are for SHS installation by Rural Electrification Fund. From Table 4.1, there are different light bulbs used 1W, 2W and 7W where on the local market it is difficult to find the 2W and 7W. The commonest LED next to 1W on the local market is 3W. This is a real problem for the systems sustainability because as the light bulbs fail, the system user might not care to search for the exact light bulb specification. It is also difficult to find DC light bulbs in the rural kiosks and when found in the nearby town; they are expensive and wouldn't be possible to get the exact wattage lamp. Hence, designing systems using 1W and 2W light bulbs will not be the best way as there are 3W DC light bulbs on the local market. The same trends were used when designing home systems using AC light bulb. It is appropriate to use 11W AC bulb, the commonest light bulb in a lot of kiosks on the market, even if there are various sizes such as 6W, 7W or 8W which are very rare to find in the rural towns. So, the loads taken to design for SHS systems are based on this assumption which is presented in ANNEX II.

Table 4. 1. Loads taken for solar home system design by Rural Electrification Fund [31]

No	PV System size	Users Demand	Designed Daily Energy [wh/day]
1	8Wp	1*1w, 1*2w LED light lamp + hand radio + mobile Charge	**20**
2	10Wp	2*1w, 2*2w LED light lamp + hand radio + mobile Charge	**30**
3	20Wp	1*5W LED, 3*2W dc LED light lamp + small radio + mobile Charge	**60**
4	40Wp	1*7W LED, 3*2W dc LED light lamp + 1*15W hair cut machine or Black & White TV + small Tape & Radio + mobile Charge	**160**
5	60Wp	1*7W LED, 3*2W dc LED light lamp + Tape & Radio + mobile Charge + 12" or 14" TV (low power ac/dc TV mostly used in Bus for long distance passengers)	**200**

6	75Wp	2*7W LED, 2*2w dc LED light lamp + Tape & Radio + 12" or 14" TV (low power ac/dc TV mostly used in Bus for long distance passengers)	**250**
7	80Wp	2*7W LED, 4*2w dc LED light lamp + Tape & Radio + mobile Charge + 12" or 14" TV (low power ac/dc TV mostly used in Bus for long distance passengers)	**270**
8	100Wp	2*7W LED, 6*2w dc LED light lamp + Tape & Radio + mobile Charge + 12" or 14" TV (low power ac/dc TV mostly used in Bus for long distance passengers)	**320**
9	130Wp	2*7W LED, 3*2w, 3*1w dc LED light lamp, + Tape & Radio + mobile Charge + 12" or 14" TV (low power ac/dc TV mostly used in Bus for long distance passengers) + dc operate refrigerator (low power consumption normally called solar refrigerator)	**420**

For institutional PV systems, there are different load assumptions thought by governmental as well as non-governmental organizations. Loads for health institutions and schools used by GOs and NGOs are described from Table 4.2 through Table 4.8.

Table 4. 2. Loads taken for health center system design by Doctors with Africa-CUAMM [33]

No.	Description	Load [w]	Qty	use hr	Use factor on weekly basis	daily Wh consumption
1	Inpatient room lighting (LED bulbs)	7	11	4	0.8	246.4
2	Inpatient room lighting (LED bulbs)	7	2	4	1	56
3	Inpatient room lighting (LED bulbs)	7	10	12	0.8	672
4	Inpatient room lighting (LED bulbs)	7	9	12	1	756
5	Outpatient room lighting (LED bulbs)	7	8	4	0.8	179.2
6	Outpatient room lighting (LED bulbs)	7	3	4	1	84
7	Mothers waiting block lighting	7	3	6	1	126
8	Mothers waiting block lighting	7	1	12	1	84
9	Other block lighting	7	2	4	0.8	44.8
10	Other block lighting	7	2	12	0.8	134.4
11	Staff residence lighting	7	8	6	0.8	268.8
12	Staff residence lighting	7	2	12	1	168
13	Administration room lighting	7	3	4	0.8	67.2
14	Pharmacy room lighting	7	3	4	0.8	67.2
15	Pharmacy room lighting	7	1	12	1	84
16	Registration room lighting	7	2	4	0.65	36.4
17	Registration room lighting	7	1	4	0.8	22.4
18	Examination lamp	80	1	4	0.3	96
19	Radio	10	1	4	1	40
20	Microscope	40	1	4	0.8	128

21	Centrifuge	50	1	4	0.5	100
22	Refrigerator	220	1	8	1	1760
23	Television	80	1	4	0.8	256
24	Sterilizer	500	1	3	0.8	1200
25	Infant heater	500	1	3	0.8	1200
26	Desktop computer	105	1	6	0.8	504
27	Printer	65	1	2	0.8	104
28	Mobile charger	5	4	8	0.8	128
		Energy consumption per day [Wh]				**8,612.8**

Table 4. 3. Loads taken for health center system design by GIZ EnDev [34]

No.	Description	Load [w]	Qty	use hr/day	daily Wh consumption	DC/AC
1	LED lamp for HC rooms	6	48	4	288	AC
2	LED lamp for HC compound	6	8	12	576	AC
3	LED lamp for staff residence	6	6	4	144	AC
4	Examination lamp	6	1	4	24	AC
5	Vaccine refrigerator (TCW 3000)	150	1	8	1200	AC
6	Microscope	20	1	4	80	AC
7	Sterilizer (hot dry air)	1200	1	1	1000	AC
8	Centrifuge	90	1	2	180	AC
9	Suction pump	150	1	2	300	AC
10	TV	130	1	4	520	AC
11	Satellite receiver	30	1	4	120	AC
12	Radio	10	6	4	240	AC
13	Tape player	20	4	2	160	AC
14	Mobile charger	7	10	2	140	AC
	Energy consumption per day [Wh]				**4,972**	

Looking at the loads for health centers in Table 4.2 and Table 4.3, the power of light bulbs taken was of different size that is difficult to find in the nearby towns. It is to be noted that the most common bulb found in a normal kiosk throughout the country is 11W. There are some differences in the construction of the health centers; health centers constructed by government, by Doctors with Africa-CUAMM and by GIZ. But the services of the health centers, including the appliances present, were all the same with the exception of the number of rooms. In addition, the medical equipment's were all delivered by the government or NGOs in consultation with the Ministry of Health that makes the loads delivered to be similar.

Table 4. 4. Loads taken for health post system design by REF [35]

No.	Description	Load [w]	Qty	use hr	daily Wh consumption	DC/AC
1	Patient waiting room lighting	11	1	5	55	AC
2	Treatment room lighting	11	1	5	55	AC
3	Delivery room lighting	8	1	4	32	AC
4	Vaccine store room lighting	8	1	3	24	AC
5	Outdoor lighting	11	1	12	132	AC
6	Toilet lighting	8	1	4	32	AC
7	Vaccine refrigerator	200	1	10	2000	AC
8	Television	60	1	6	360	AC
9	Tape/radio	30	1	4	120	AC
	Energy consumption per day [Wh]				**2,865**	

Table 4. 5. Loads taken for health post system design by REF [35]

No.	Description	Load [w]	Qty	use hr	daily Wh consumption	DC/AC
1	LED lamps	7	6	6	252	AC
2	LED lamp for guard, toilet and veranda	7	4	10	280	AC
3	solar Refrigerator WHO approved	-	-	-	600	AC
4	Solar powered LCD TV	15		12	180	AC
5	Mobile charge	2	10	4	80	AC
6	Tape / Radio	10		10	100	AC
					1492	

Table 4. 6. Loads taken for health post system design GIZ EnDev [34]

No.	Description	Load [w]	Qty	use hr/day	daily Wh consumption	DC/AC
1	LED lamps in MCH & inspection room	6	3	3	54	AC
2	Vaccine refrigerator (TCW 3000)	150	1	8	1200	AC
3	LED lights in power room and office	6	1	1	6	AC
4	Radio	6	1	4	24	AC
5	Mobile phone charging	2	2	2	8	AC
6	LED lamps for veranda	6	1	12	72	AC
7	LED lamps for latrine	6	1	0.5	3	AC
					1367	

From Table 4.4 to Table 4.6, the power of light bulbs should have considered the commonest bulb found on the local market as described above. The power taken for vaccine refrigerator by governmental health centers and health posts varies widely where as it is the same for GIZ EnDev Ethiopia. It is also not clear what type of refrigerator that were considered for the design of the health institutions in Table 4.4 and Table 4.5.

On the other hand, according to the electrification team from GIZ Ethiopia, they have supplied energy efficient refrigerators Dometic TCW 200AC that only consumes 0.55 kWh/24h. This type of refrigerators hasn't been supplied by MoH which makes the selection of loads for health facilities to consider the refrigerators currently available. Unlike health centers which have different way of constructions, it isn't different for health posts as there is very few staff which only provides basic treatment for emergency cases and first aid.

Table 4. 7. Loads taken for primary school system design by REF [35]

No.	Description	Load [w]	Qty	use hr	daily Wh consumption	DC/AC
1	LED lamps Class room	7	8	4	224	DC
2	LED lamps for guard and veranda	7	2	10	140	DC
3	Solar powered LCD TV	15	1	10	150	DC
4	Mini media	100	1	2	200	AC
5	Mobile charge	2	10	4	80	AC
6	Tape / Radio	10	1	10	100	AC
					894	

Table 4. 8. Loads taken for primary school system design by REF [35]

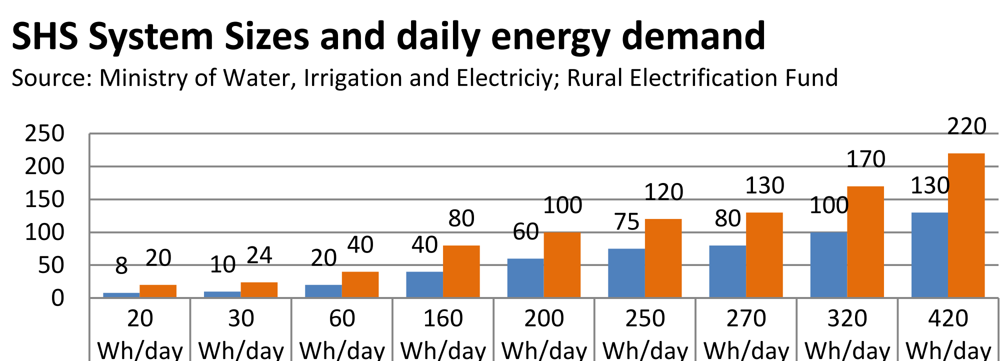
Description	No of Rooms	Load[w]	Bulb/ lantern Size [w]	Loads [w]	Use hours/ day	Watt Hr
Director office	1	8	8	8	4	32
Class rooms	2	22	44	22	4	88
Store	1	8	8	8	4	32
Outside light	2	11	22	22	12	264
Radio/tape	1	10	10	10	8	80
TV	1	50		50	8	400
					Sub Total	**896**
Description	**No of Rooms**	**No of Lantern/room**	**Lantern size[w]**	**Charging time/day**	**Watt Hr**	
For teachers' residence	5	2	7	4	280	**280**
					Sub total	**1176**

From Table 4.7 and Table 4.8, the different loads that were taken for primary schools systems design have been described. Like the health institutions, different power light bulbs have been taken. In Table 4.7, taking DC light bulbs while there is an inverter in the system would make it difficult for the schools that didn't have a budget for maintenance services to buy expensive DC bulbs as compared with the easily accessible AC bulbs. From site assessment to some schools in Amhara and Oromia regions, there are DC appliances such as a radio and megaphone for mini media service that work using D-size dry cell batteries in almost all primary schools. These were supplied by the regional education bureaus where in some schools; amplifiers, computers and printers were also supplied even if there is no power source to run them. The services of the schools are all the same with a slight difference in the construction and the number of classrooms.

4.2. DISSEMINATED SOLAR PV SYSTEMS AND THEIR STATUS

Solar Home Systems (SHS)

Large numbers of solar home systems (SHS) has been distributed in the four regions in the past 5 years. According to the information from MoWIE about 5,678 SHS in Amhara, 11,680 systems in Oromia, 7,161 SHS in SNNP and 2,167 SHS in Tigray have been installed in the past five years. Besides the infrastructure in these four regions, the distributions of these SHS systems were made according to their population size and geographic distribution. Currently all of these SHS has not been handed over to the government, which means any failure on the system must be maintained at own cost by the installation company, Poly Solar Technologies Ltd. The capacity overview of these installed SHS is presented in Figure 4.1.



	20 Wh/day	30 Wh/day	60 Wh/day	160 Wh/day	200 Wh/day	250 Wh/day	270 Wh/day	320 Wh/day	420 Wh/day
PV size (Wp)	8	10	20	40	60	75	80	100	130
Battery capacity (Ah)	20	24	40	80	100	120	130	170	220

Figure 4. 1. Capacity overview of SHS systems installed in 2013 by REF

Even if it was difficult to get the system performances from all the implemented areas, the SHS user and the status of different size PV systems were found from respective energy experts. All the SHS data gathered were from REF implementation as there are no NGO involved in installing PV systems for off-grid located homes.

In addition, data on system performances and technical details were collected through informal meeting, such as interviews and focused discussions, with stakeholders such as, system installers, cooperatives that monitor the SHS and the regional energy bureaus. Data collected from the visited areas were presented in Appendix VI that includes the SHS user, their system size and performances according to the energy bureaus and local cooperatives.

Even if Ethiopia is found between 3^{o} and 15^{o} North of Latitude and 33^{o} and 48^{o} East of Longitude, the same system size were used for the same daily energy demand for homes found in Amhara, Oromia, SNNP and Tigray regions. This has its main draw backs to the systems sustainability which will be discussed later by showing the results of the simulation which resulted in different PV sizes for the four regions under study.

Since the systems are still under the warranty period, it was not possible to open the boxes where batteries, charge controllers and inverters were integrated to check system problems encountered. But system failures have been recorded by different regional energy bureaus as summarized below.

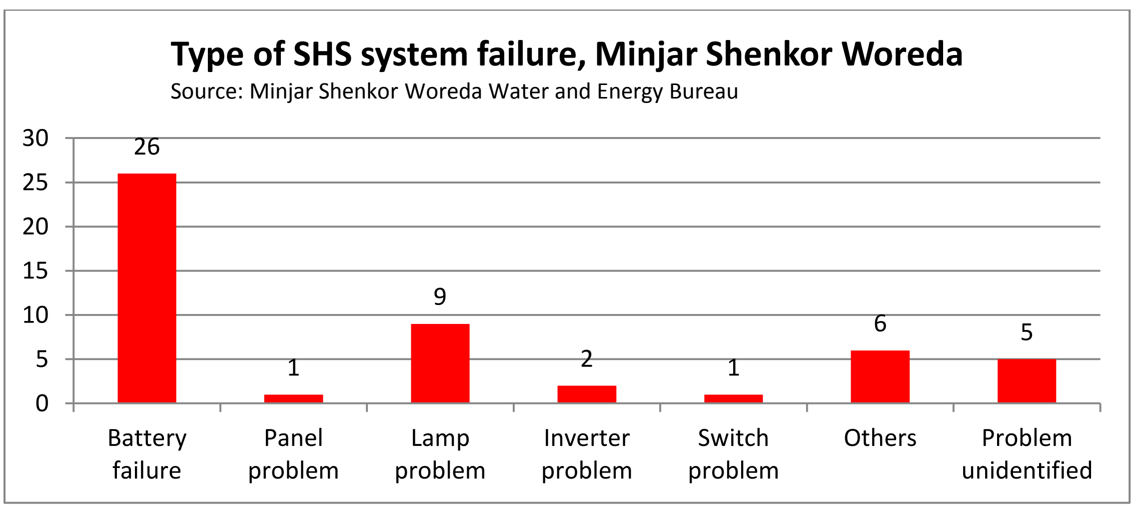


Figure 4.2. Types of problems on SHS in Minjar Shenkor Woreda

In addition, Mukiye Haro Cooperative electrification head in Oromia region has recorded system failures that occurred on different occasions as shown in Figure 4.3.

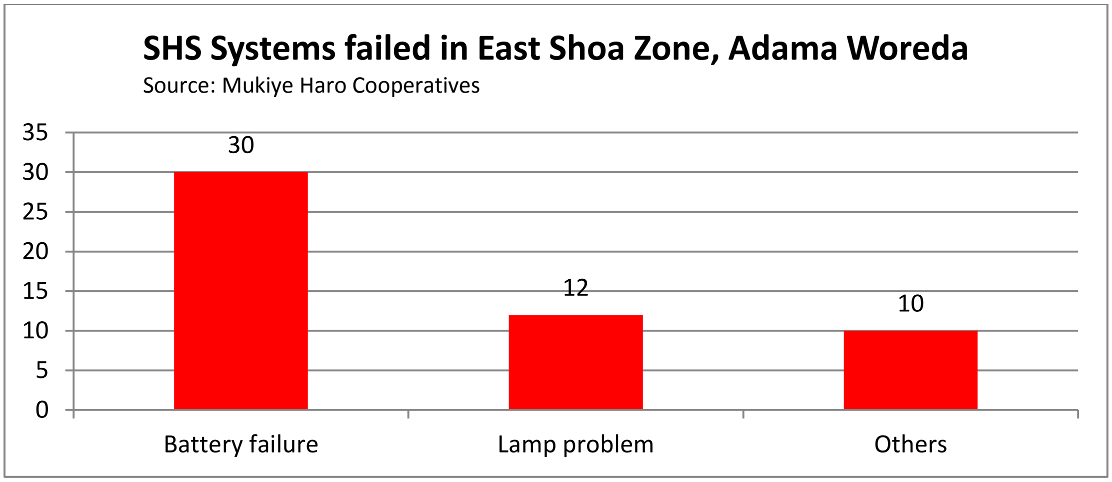


Figure 4.3. Types of problems on SHS in Adama Woreda

From Figure 4.2 and Figure 4.3 above, more than half of the system failures occurred on the batteries. Wrongly designing the batteries have an own impact in their premature failure. It is possible to overcome this problem by optimizing the systems to bigger solar panel or a smaller battery which will be discussed under the design section. It was tried to get SHS implemented by other non-governmental organizations in Ethiopia but it was not possible to find any.

Institutional PV systems

The institutional PV systems implemented in the country were of various system sizes. For schools, about 270 systems having a capacity of 300Wp using inverters for AC loads whereas lights using DC has been implemented in SNNP and Tigray regions. For health posts, 315 systems of 540Wp for fridges and medical appliances were installed. Additionally, considering the current systems under installation, about 1,260 health posts having a capacity of 450Wp and 300 health centers with a capacity of 2040Wp PV systems are under installation. These data and others described in Chapter 3 were obtained through desk review. As described in chapter 3, it was not possible to go to all institutional sites because of their location. Below are some of the data which were gathered from different sources.

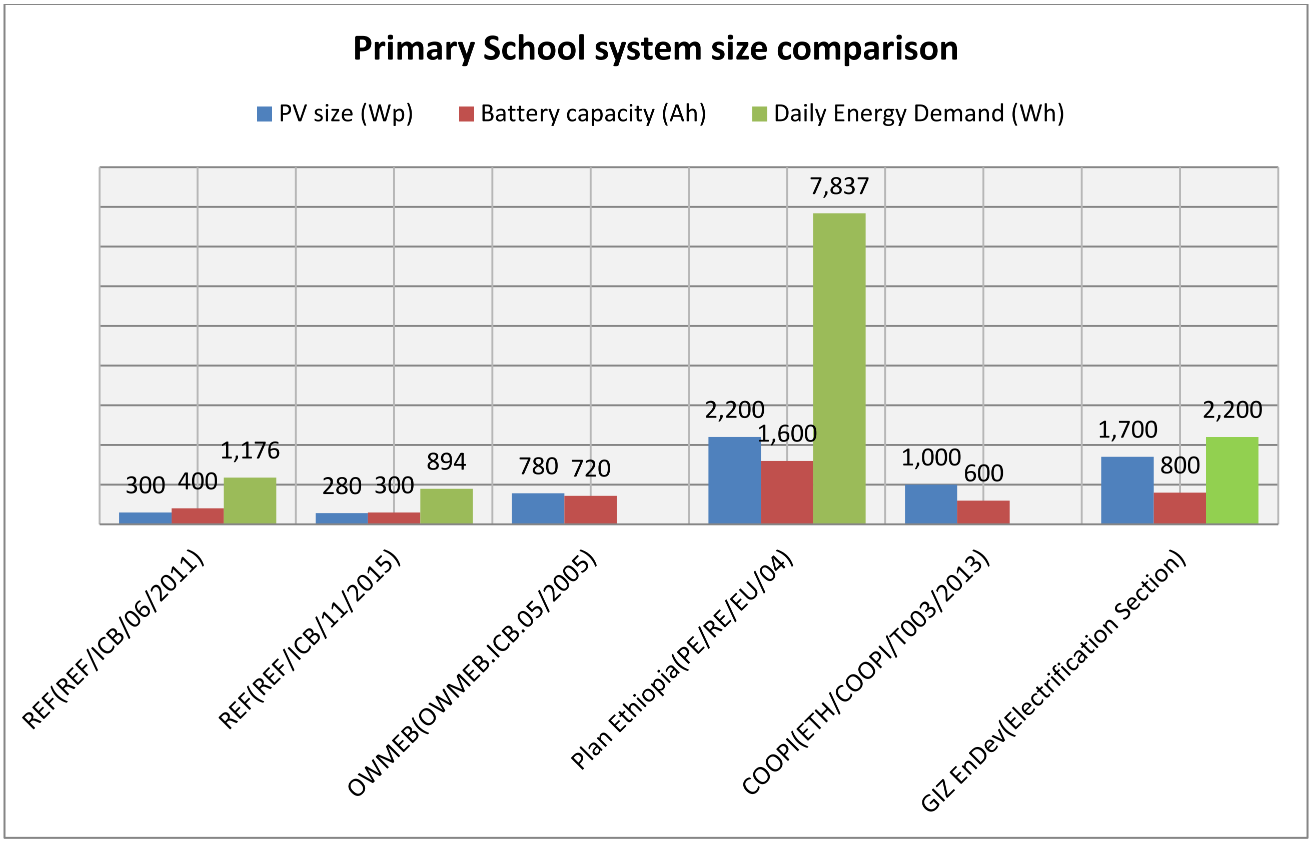


Figure 4.4. Comparison of primary school system sizes

From school system sizes in Figure 4.4, the objective of the governmental as well as non-governmental organizations is the electrification of primary schools. But the daily energy demands taken were so much different for a sector where the government has similar teaching and learning policy across the country.

The daily energy demand taken for PV system design is listed in Tables 4.7 and Table 4.8 with the exceptions for GIZ EnDev, OWMEB and COOPI which could not be found. Below are some of the observations on the daily energy demands taken by REF and Plan Ethiopia;

- A 7W DC LED bulb has been chosen for designing PV systems by REF from Table 4.7. If these bulbs fail, it would be difficult to get the exact wattage LED. It is also difficult to find DC bulbs in the rural kiosk (even in the regional capitals) and if found they are expensive as compared with the AC bulbs. In addition, REF used various wattage lamps for the same school. The problem with this assumptions are, if the 8W lamp fails then it is highly likely they would substitute with something which has a bigger wattage lamp that lead to premature system failure.
- REF has also taken almost similar energy demand in Table 4.7 and Table 4.8 with the exception of the lanterns being charged by the system for teachers' residence. Lanterns

with a separate panel were widely available which should have been the choice for teachers' residence according to need. From some of the school visits, the majority of these lanterns were broken.

- REF has considered DC TV as described in Table 4.7. Even if the PV system were installed in the planned schools, there was no any DC TV that has been supplied with the systems installation. This shows lack of market assessment before designing the systems where it was not possible to find a 15W DC TV on the market that is suitable for the schools which was mentioned in Table 4.7.
- The other observation from REF system design is, their way of designing the systems in both AC and DC. If inverter is incorporated for AC appliances, it would have been good to consider the light bulbs to be AC, with AC lamps being the most available and the cheapest on the market.

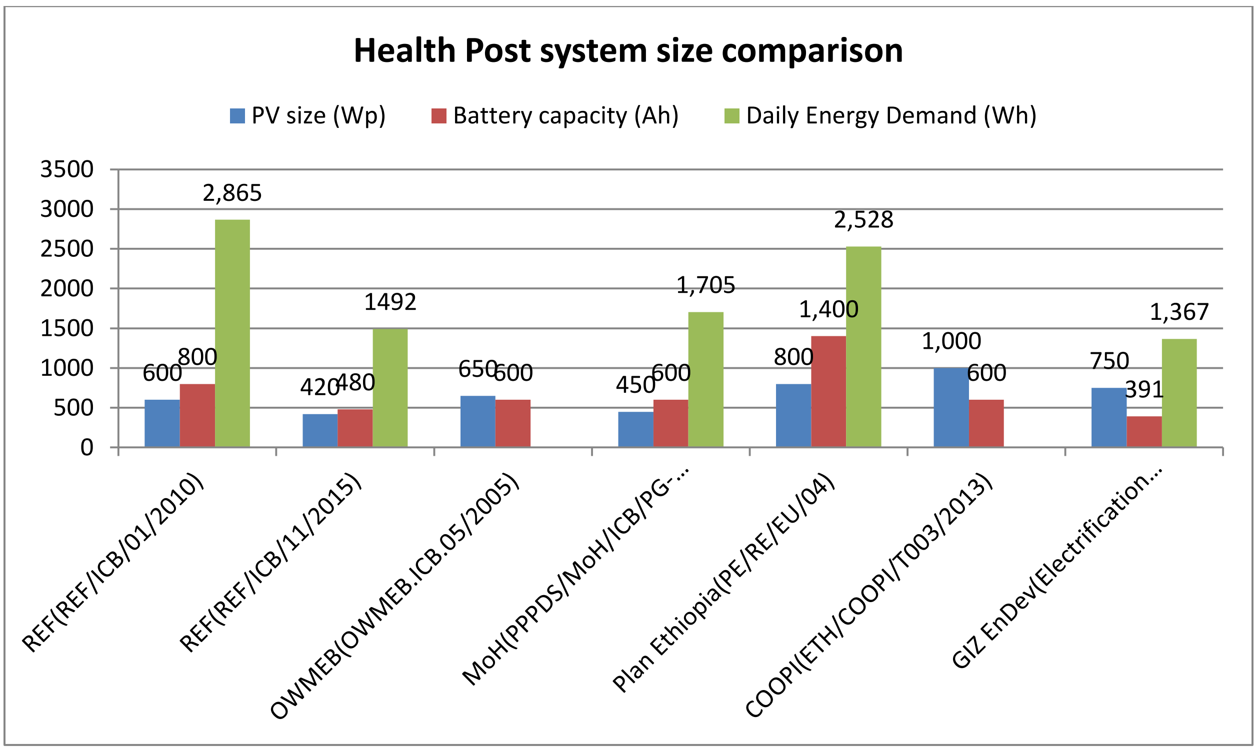


Figure 4.5. Comparison of health post system sizes

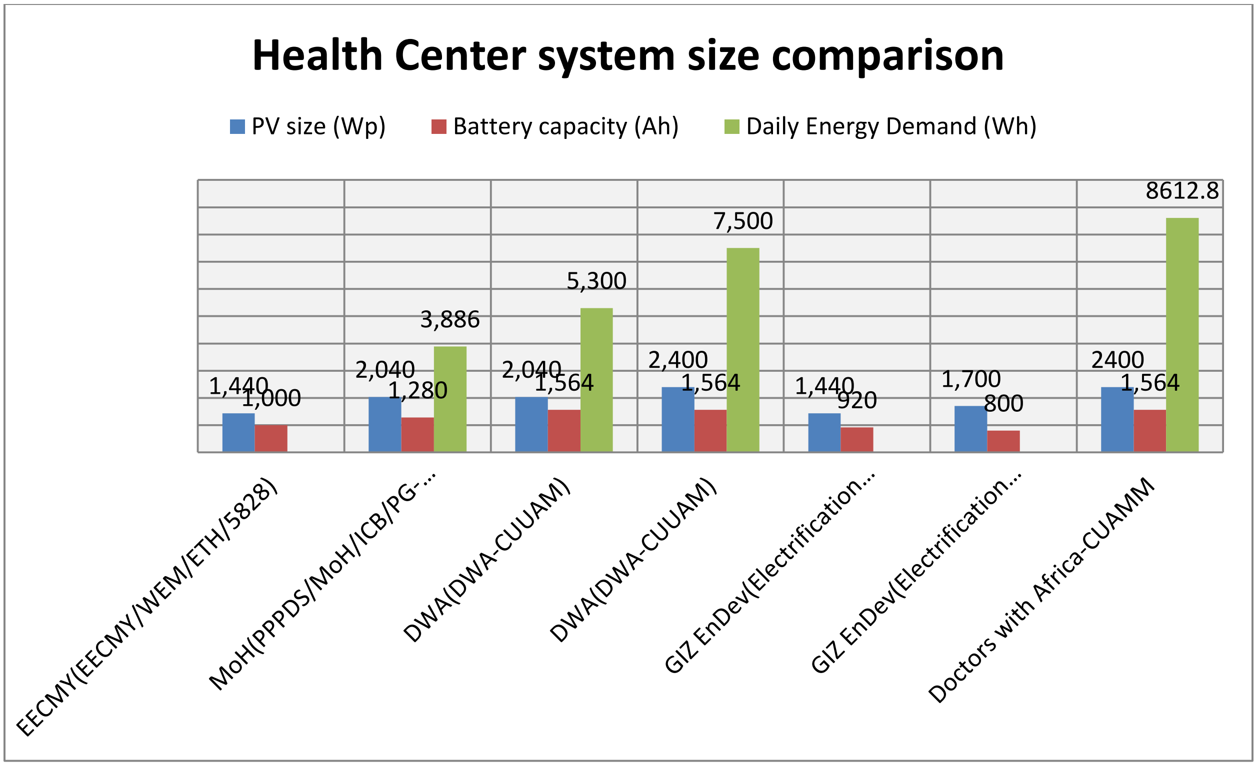


Figure 4.6. Comparison of health center system sizes

For the same health post in Figure 4.5 and health center in Figure 4.6, different GOs and NGOs have used different system sizes. These variations were due to the consideration of different loads as explained in sub section 4.1. On the other hand, different data that was collected from different sources has been compiled in this sub-section. During the collection of this data, the absence of clear standard and the presence of several types of solar PV systems and BOS have been observed. Besides, it was difficult to get the status of the PV systems that were listed.

Below are the different PV system implementation by GIZ Ethiopia and their status.

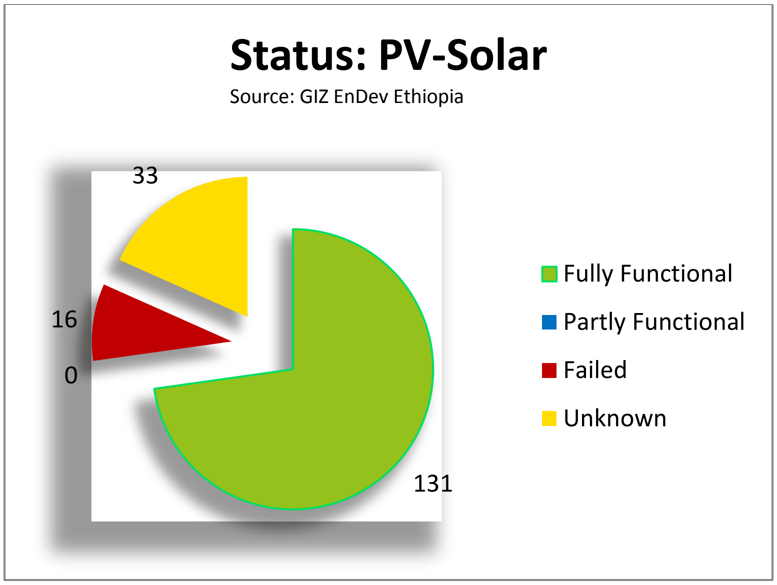


Figure 4.7. Status of GIZ installed sites in Ethiopia

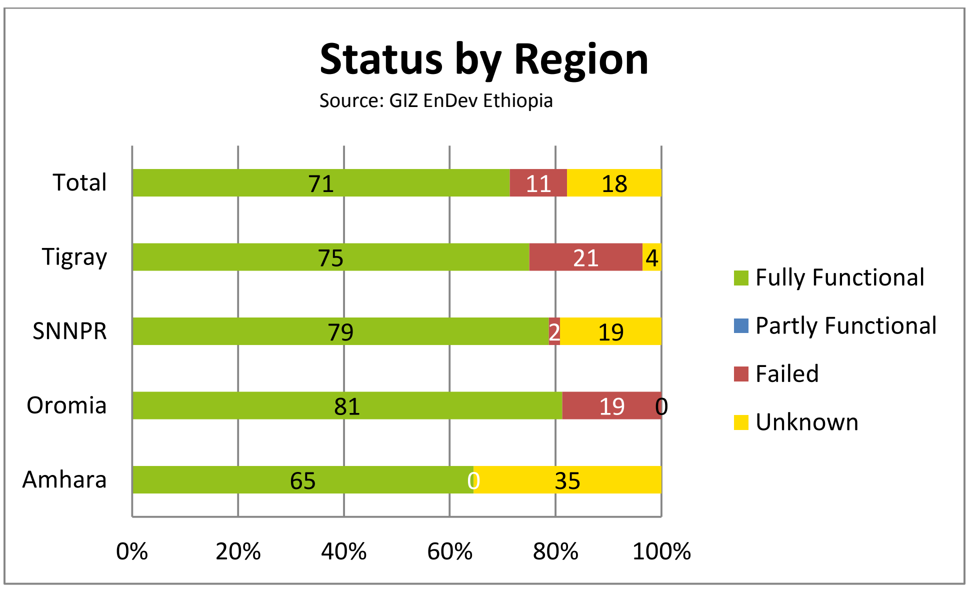


Figure 4.8. Status of GIZ installed sites by region

It was tried to get the status of the installed PV systems installed by GOs and NGOs which was not possible.

The ultimate purpose of GIZ Energizing Development (GIZ EnDev) initiative, together with its contributing partner countries, is to see the Ethiopian community, especially those in the rural areas, gain sustainable access to full set of health services. However, as can be analyzed from the handed-over systems from GIZ, some of the electrified facilities are no longer functional.

Hence, for one or more of the reasons mentioned above, many of the electrified health facilities which were designed with a minimum life span of 5-20 years with a necessary maintenance actions, fail early and are left abandoned.

The experience of GIZ EnDev shows, training improves the sustainability of the systems. There is a high turnover of staffs in the institutions in the rural community, such as teachers in the school and nurses in the health facilities, which greatly affect the systems as those who have been trained leaves the institution and when they left, there will be no one who would take care of the systems or has the knowledge to make simple maintenance. So, giving training on different occasions improves the sustainability of the systems by capacitating the staff members that will handle the solar systems appropriately. A well prepared user manual will help the end-users or staff members in their training.

Another important aspect to learn from GIZ-EnDev Ethiopia is, they give training for technicians living in the project implementation Woredas and engage them in the installation services. This has different advantages

- It will create jobs for the technicians and pave the way for income generation for them,
- It will help the local community in reducing the costs they would pay for maintenance services in the future,
- It will help with the sustainability of the system by creating locally trained technicians.

The findings further indicate that availability of knowledge, expertise and skills required to sustain the technical requirements was central to the technical viability of the projects.

Now that the government, along with various NGOs, is working on expansion of health facilities, a considerate focus should be given more towards strategies to making existing systems sustainable in parallel to adding new capacities, which sooner or later face similar problem as discussed above.

4.2.1. Observation from the installed PV systems

Even if some of the installations follow international standards and the equipment's used were of the European standard, the systems installed could not be guaranteed for functionality in a sustained period unless appropriate measures are taken for the service and maintenance.

Trainings for solar home system users and staffs working in different institutions where the systems were installed were given, according to the information from the end-users whom were interviewed. But, it is clear to see the need for a follow up to that training. During our visit, we have seen end-users are not fully equipped with the necessary knowledge in the usage of the systems. This was the main cause for the premature failure of the systems we have investigated. The following pictures are an example for the incapability of the end-users in handling the systems they are currently using.

[Photo taken by Lemu Kebede, February 2016]

Figure 4. 9. Picture taken in Sidama, SNNPR

High power consuming fridge plugged into the newly installed PV system in SNNPR (Embula Tenkaka health center).

This picture was taken from a health center PV installation in SNNPR. This fridge, called SIBIR, consumes 6.3kWh within 24 hours where the PV system was designed based on 6kWh per day. Currently the system is not functional, the result of lack of training given to the health center staff by the installers.

Figure 4. 10. Picture taken in Butajira, SNNPR

People guarding this solar water pumping system around ButaJira in SNNPR cover the solar panels when the rain comes, to protect the solar modules from damage by the rainfall.

4.3. DESIGN OF SOLAR PV SYSTEMS

4.3.1. Simulation Results of the PV system sizing

This section presents the simulation results for different days of autonomy for the regions. PV module and battery specification is optimized by PVSyst software for appropriate sizing of off-grid PV systems. The simulation has been done for different days of autonomy and from the simulation system specifications, system output power and loss of the system are found.

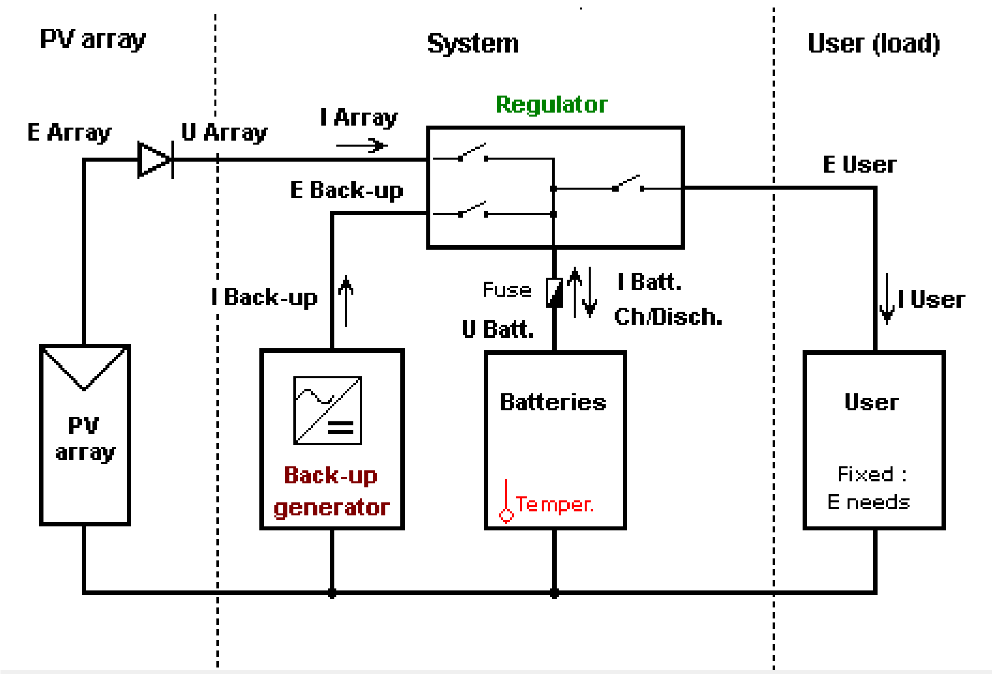


Figure 4. 11. Block diagram of a stand-alone system

System Configuration

Stand-alone photovoltaic system for the different institutions and SHS is simulated using PVSyst. For a health center in Amhara region, particularly Bahir dar, the simulation results indicate that we need a PV capacity around 1,500 Wp for different days of autonomy (1, 2, 3 and 4 days of Autonomy). Figure 4.11 shows the block diagram of a stand-alone PV system. Two PV modules are connected in series and for a string. Five strings of 2 PV modules are used in for a health center that could be located in Bahir dar. 13m^2 area will be required for the placement of the modules. At the maximum power point, current of the system will be about 22A.

The output of the PV system depends on the received solar radiation and temperature. The behavior of a SolarWorld PV module at 45^{0}C cell temperature based on incident irradiance in W/m^2 is displayed in Figure 4.12.

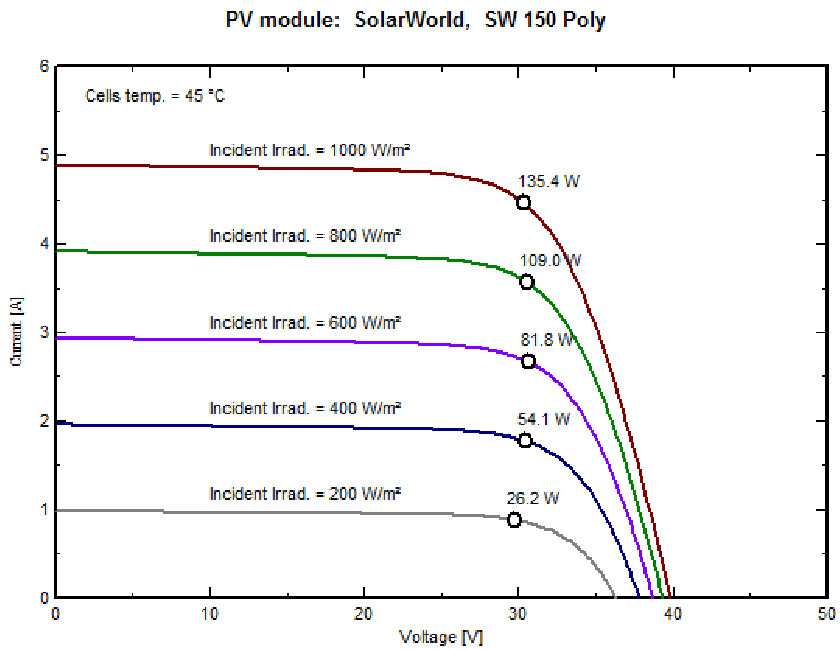


Figure 4. 12. A 150Wp SolarWorld PV module output according to incident irradiance [W/m^2]

Energy Production

An amount of radiation of about 6.191 kWh/m2 energy is received on the PV array in a year. Figure 4.13 shows this incident energy.

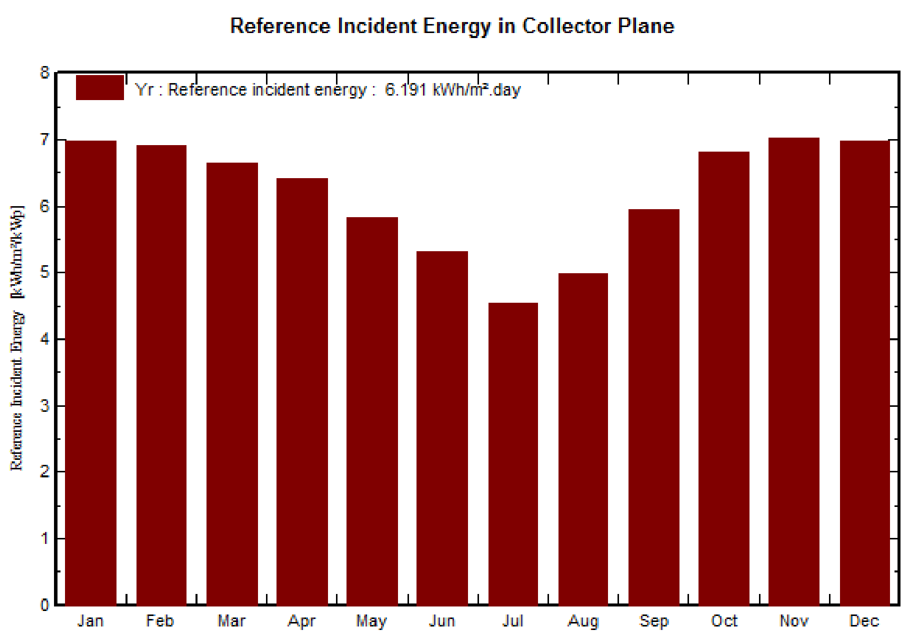


Figure 4. 13. Reference incident energy in a 1500Wp collector place

The simulation results show, 2,625.64 kW of energy will be available per year. Out of this, about 2244.25 kW of the energy will be used and 268 kW will be unused. The normalized production (per installed kWp) is show in figure 4.14.

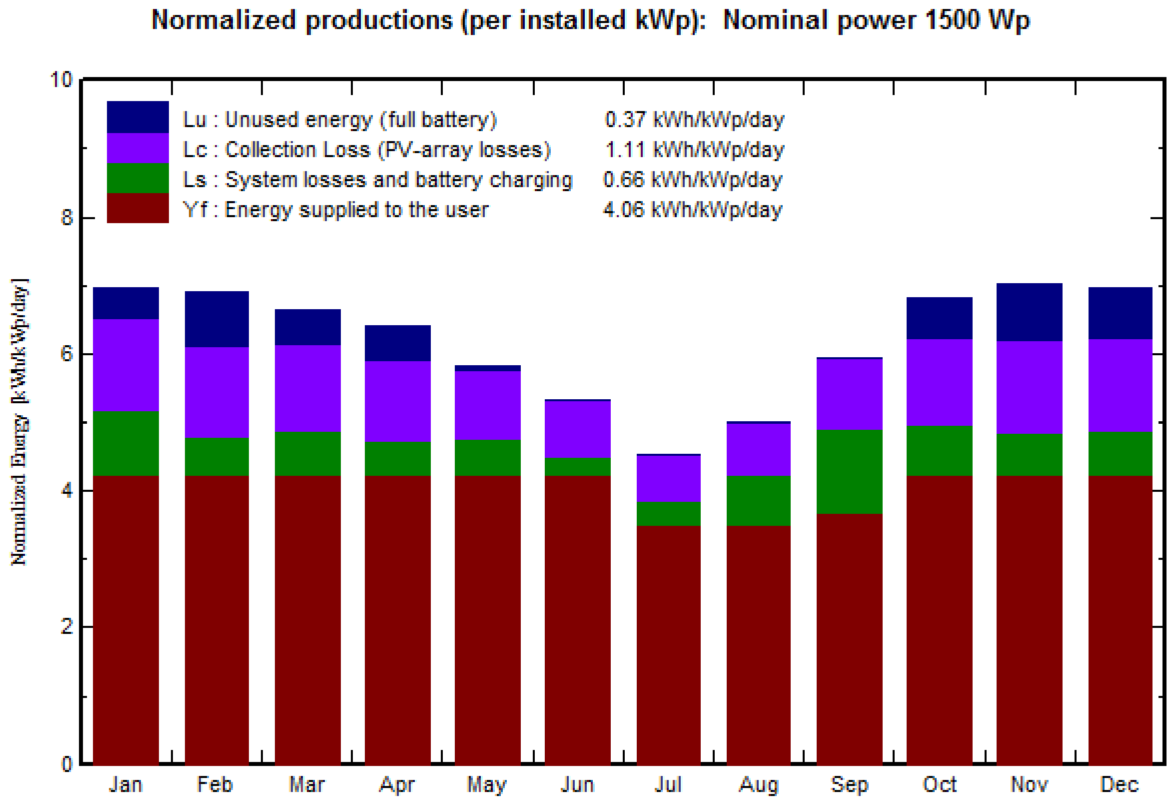


Figure 4. 14. Normalized production for a 1500Wp installation

Energy Storage

The battery storage has been simulated using different autonomy days. From the simulation, low autonomy days will increase the necessary PV power. From the analysis on different days on autonomy in Figure 4.15, for a 1 day of autonomy the battery state of charge reaches below 50% every month of the year. This will greatly affect the lifetime of the battery and will lead to a shorter life span for the battery. As the autonomy days increase, the number of times the battery going below 50% will decrease. But the capacity of the battery will be much higher which would have a negative effect on the investment cost. The battery capacity on different autonomy days has been summarized in Table 4.9.

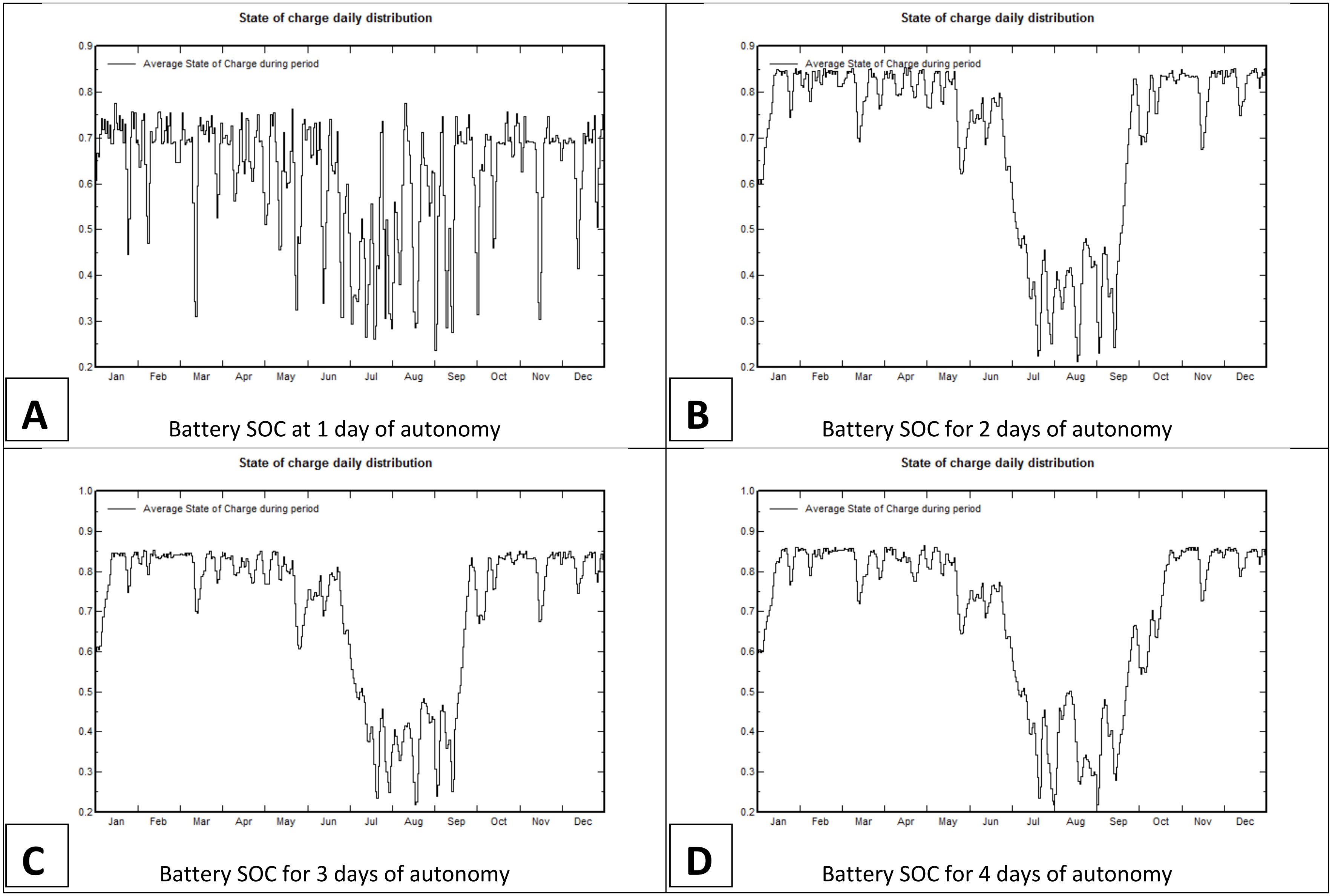


Figure 4.15. State of charge of a battery using different autonomy days

Table 4.9. Summary of the simulation results for health center

Region	Solar PV size	Battery size	System Voltage	Day of Autonomy
Amhara	1,550 Wp	257 Ah @C10	48 V	1 day
	1,500 Wp	490 Ah @C10	48 V	2 days
	1,470 Wp	729 Ah @C10	48 V	3 days
	1,440 Wp	1,030 Ah @C10	48 V	4 days
Oromia	1,440 Wp	257 Ah @C10	48 V	1 day
	1,410 Wp	490 Ah @C10	48 V	2 days
	1,410 Wp	729 Ah @C10	48 V	3 days
	1,400 Wp	1,030 Ah @C10	48 V	4 days
SNNPR	1,710 Wp	257 Ah @C10	48 V	1 day
	1,620 Wp	490 Ah @C10	48 V	2 days
	1,600 Wp	729 Ah @C10	48 V	3 days
	1,600 Wp	1,030 Ah @C10	48 V	4 days
Tigray	1,480 Wp	257 Ah @C10	48 V	1 day
	1,440 Wp	490 Ah @C10	48 V	2 days
	1,400 Wp	729 Ah @C10	48 V	3 days
	1,380 Wp	1,030 Ah @C10	48 V	4 days

The simulation results of a health center for Adama (Oromia), Hawassa (SNNP) and Mekele (Tigray) regions are presented in ANNEX-III.

From the simulation in Figure 4.15, result in Figure A shows the state of charge of the battery is kept within 30 to 80% even during the worst irradiation months of the year. But from the simulation results in B, C and D in Figure 4.15, the state of charge of the battery remains around 30% for the worst months, even down to 20% as the autonomy days increases. Hydration occurs in a lead-acid battery that is over discharged and not promptly recharged, or a battery that remains in a discharged condition for an extended time [36]. To maximize the life of a battery bank, it is best to ensure that it is regularly receiving a full charge and that its state of charge is not allowed to fall excessively [37].

The need to prevent excessive discharge leads to the need to limit the maximum depth of discharge to a certain value, which usually ranges from 0.3 to 0.6, but can approach 0.8, depending on the type of battery. The supply to the load must be cut off when this limit is reached [38]. To preserve the battery life, the recommended battery system sizing according to the simulation outputs of PVSyst is 1 day of autonomy.

Different governmental and non-governmental organizations used the same PV and battery sizes for similar institutions across the country, as opposed to the simulation results that shows different PV and battery sizes for different regions. From Table 4.9, we get a smaller PV size for Adama and Mekele areas whereas for Bahir dar and Hawassa, the PV system sizes will become larger. PV size will also increase with days of autonomy i.e. low autonomy days mean an increase in the PV size. But the battery capacity still remains the same for all the regions because of the daily load demand.

Based on the same simulation parameters used for health centers, geographical sites, region time, tilt angle and meteorological data, we get similar system design characteristics for health post.

The simulation results of the health post are summarized in Table 4.10. The simulation parameters and resulting graphs are displayed in ANNEX-III.

Table 4. 10. Summary of the simulation results for a health post

Region	Solar PV size	Battery size	System Voltage	Day of Autonomy
Amhara	465 Wp	162 Ah @C10	24 V	1 day
	450 Wp	304 Ah @C10	24 V	2 days
	440 Wp	444 Ah @C10	24 V	3 days
	440 Wp	597 Ah @C10	24 V	4 days
Oromia	430 Wp	162 Ah @C10	24 V	1 day
	420 Wp	304 Ah @C10	24 V	2 days
	420 Wp	444 Ah @C10	24 V	3 days
	410 Wp	597 Ah @C10	24 V	4 days
SNNPR	500 Wp	162 Ah @C10	24 V	1 day
	480 Wp	304 Ah @C10	24 V	2 days
	470 Wp	444 Ah @C10	24 V	3 days
	460 Wp	597 Ah @C10	24 V	4 days
Tigray	440 Wp	162 Ah @C10	24 V	1 day
	420 Wp	304 Ah @C10	24 V	2 days
	410 Wp	444 Ah @C10	24 V	3 days
	410 Wp	597 Ah @C10	24 V	4 days

There are various system sizes existing for health facilities by governmental as well as other organizations. Below is the system sizes installed across the country which were also discussed in Chapter 3.

Table 4.11. Different system sizes installed in Ethiopia

No.	System Description	PV size	Battery size	Daily Energy Demand [in Wh]
PV Systems for Health Centers and Health Posts [Ministry of Health, 2005]				
1	**Health Centers**	**2040Wp**	**640Ah@24V**	**3,886**
2	**Health Posts**	**450Wp**	**600Ah@12V**	**1,705**
PV Systems for Health Posts (345 HPs in total) [Rural Electrification Fund]				
1	**Health Posts**	**600Wp**	**880Ah@12V**	**2,865**
PV Systems for Health Posts [Rural Electrification Fund – 2015]				
1	**Health Posts**	**420Wp**	**480Ah@12V**	**1,492**
Shallo, Tediwos Amba & Telfetit health posts-Amhara region [Plan International Ethiopia]				
1	**Health Posts**	**800Wp**	**700Ah@24V**	**2,528**
5 Health Centers for-Oromia region [Doctors with Africa-CUAMM, 2016]				
1	**Health Clinics**	**1020Wp**	**400Ah@24V**	**-**
2	**Health Clinics**	**2040Wp**	**480Ah@24V**	**8,612**
PV system for 50 health centers and health posts [GIZ EnDev ET Electrification Section]				
1	**Health Centers**	**1,440Wp**	**250Ah@48V**	**-**
2	**Health Centers**	**1,700Wp**	**400Ah@24V**	**-**
3	**Health Posts**	**750Wp**	**391Ah@12V**	**1,367**
4	**Health Posts**	**1020Wp**	**400Ah@24V**	**4,972**

Table 4.11 shows the existence of different system sizes for institutions that gives similar services across the country. For health posts, four different organizations, REF, MoH, Plan International and GIZ EnDev Ethiopia supplied and installed different system sizes. The same case to systems installed for health centers. In addition, similar sized systems were supplied and installed for all regions. The simulated system using PVSyst shows, for Adama (Oromia region) and Mekele (Tigray region) smaller PV size is needed as compared with the others. Supplying the same PV size for different regions makes the system expensive resulting from selecting a bigger controlling device to control the current output from the larger PV in regions where there is a higher irradiance.

In addition, two different system versions exist in Table 4.11: DC-coupled systems and AC-coupled systems. For larger systems, AC-side coupling of PV arrays and loads offers better connectivity with the low voltage mains grid and other stand-alone systems.

Advantages of AC-coupled systems [39]

- Higher peak power output and more cost-effective components
- Expansion capability is good
- DC distribution system is avoided
- Easy coupling to additional power sources

NGO's like EECMY and CUAMM adopted this AC coupling principles by working with GIZ. But the majority of systems installed by MoWIE are DC-coupled. DC-coupled PV system is more suited to smaller installations requiring a predominately DC power with more intermittent load at night for example lighting or similar small style needs.

Simulation results for two of the different solar home systems and the schools are summarized in Table 4.12. The simulation has been done for a 1 day of battery autonomy.

Table 4.12. Summary of simulation results for SHS and schools

Location	Solar PV size	Battery size	System Voltage	Day of Autonomy
SHS Type-1				
Amhara	30 Wp	24 Ah @C10	12 V	1 day
Oromia	30 Wp	24 Ah @C10	12 V	1 day
SNNPR	30 Wp	24 Ah @C10	12 V	1 day
Tigray	30 Wp	24 Ah @C10	12 V	1 day
SHS Type-2				
Amhara	108 Wp	78 Ah @C10	12 V	1 day
Oromia	108 Wp	78 Ah @C10	12 V	1 day
SNNPR	108 Wp	78 Ah @C10	12 V	1 day
Tigray	108 Wp	78 Ah @C10	12 V	1 day
Primary School				
Amhara	784 Wp	239 Ah @C10	24 V	1 day
Oromia	720 Wp	239 Ah @C10	24 V	1 day
SNNPR	860 Wp	239 Ah @C10	24 V	1 day
Tigray	740 Wp	239 Ah @C10	24 V	1 day
Secondary School				
Amhara	11.50 kWp	1716 Ah @C10	48 V	1 day
Oromia	9.9 kWp	1716 Ah @C10	48 V	1 day
SNNPR	12.42 kWp	1716 Ah @C10	48 V	1 day
Tigray	11 kWp	1716 Ah @C10	48 V	1 day

The graphs of the simulation outputs are presented in ANNEX-III.

4. CONCLUSIONS AND RECOMMENDATIONS

Through this thesis work, some of the existing PV systems implemented by the various organizations in Amhara, Oromia, SNNPR and Tigray have been visited. The main aim of this site visit has been to check the type of systems installed, the way they have been installed considering their location, the service and maintenance that has been conducted including their current operational status. As a result, factors that affect the sustainability of solar PV systems and the best strategies for designing off-grid PV systems have been determined.

It has been identified that there is a huge gap to be filled by governmental and non-governmental organizations in coordinating when designing and implementing solar PV systems for homes as well as institutions to ensure sustainability.

A survey and follow up of the systems has revealed that system failures are mainly attributed to the following reasons:

- Lack of proper maintenance and follow up by the government: - a key to keeping a solar system sustainable is following up on its performance which should be done on a regular basis. However, many of the responsible persons at the health facilities are not aware of this need: they believe that as long as the system is working, everything is okay.
- Improper use of systems by end users: - when a solar system is designed, it is according to the electricity demands of the facilities. Although a buffer in power generation is often in the original design, due consideration should be given as to which time to use it. The over usage of the system- i.e. additional energy usage outside of the services and appliances it was designed for, results in damaging one of costly system components - the battery.
- Negligence of trained health institution operators in system supervision:- system also fails due to lack of close monitoring of the cleanliness of panels which greatly affects the power production and also close management of overall system usage.
- High turnover rates for system operators: - trained personnel often leave their position at the health institution without passing proper knowledge to their successor; hence, the systems installed will be left without an overseer, often don't last long.
- Unavailability of spare parts for replacement: - in cases where a problem is properly identified, the facilities lack spare equipment in storage or are unable to easily find the equipment available in local markets.
- Lack of an allocated budget at the health facilities for maintenance: - in a majority of cases, the health facilities neglect to incorporate a budget for maintenance in their annual planning.

In addition, the findings indicate that different organizations have installed similar sized solar PV panel for the four regions as opposed to the simulation outputs of PVSyst, which recommend varying solar PV size for the different regions. The difference in the solar PV size outputs from the PVSyst is due to the irradiance differences across the regions. The use of similar sized solar PV across the region will result in the selection of a higher controller based on the location that has the highest irradiance which will directly increase the cost of the overall system.

On the other hand, all the organizations have used three days of autonomy for battery system design, with the exception of GIZ Ethiopia that have used two days of autonomy for the systems they have implemented in 2009. The simulation results of PVSyst on battery optimization indicate that the use of less autonomy days for battery design causes the battery to receive a full charge even during the worst months of the year, which is from June through September.

The use of less autonomy days for battery sizing is supported by the findings from site visit. The majority of system failures on the visited sites were the premature death of the battery. DC to AC inverters also contributes to the premature death of the battery. The inverters are installed directly to the battery which will bring the batteries down when there is a high energy demand. Even if this is the only option, inverters have the behavior to deeply discharge the batteries than charge controllers. Since it is difficult to find a programmable inverter, which could cut-off the load at a desired battery voltage, there are solutions for monitoring the battery from deep discharge by the inverter.

Lastly, two type of system configurations has been assessed which is implemented by GOs and NGOs: AC-Coupled and DC-Coupled solar PV systems. For larger systems, AC-side coupling of PV arrays and loads offers better connectivity with the low voltage mains grid and other stand-alone systems. DC-coupled PV system is more suited to smaller installations requiring a predominately DC power with more intermittent load at night for example lighting or similar small style needs.

Recommendation

Based on the findings, the following recommendations are suggested for the way forward.

- Strict government control on the implementation of all kind of solar PV systems projects across the country. It is noted that there are government structure up to the Woreda level for monitoring the energy activities in the country but there are less control by such offices when it comes to other organizations in implementing PV projects in the regions.
- Follow up on system maintenance and control of its enforcement by different governmental and non-governmental organizations not only up to two or three years of

project implementation but until the implementing organization makes sure that the installed system is guaranteed for its sustainability after handing it over to the institution.

- Provision of training every year for systems operator in every institution where solar PV system has been installed. This will fill the gap of missing trained personnel in the institutions caused by the high turnover rates present across the institutions found in the country. A close follow up of technical capability of the institutions' staff member and their reporting of system failures and their handling of system failures should closely be followed up.
- Allocating budget for the activities mention in the recommendation above which will ensure system sustainability.
- Engaging local technicians and TVET graduates in the installation activity by all project implementers. This in the long term will create businesses for locals which in the end will ensure fast response to system failures that might occur.
- Properly design solar PV systems that could minimize the overall cost of the system by using different sized solar PV panels for the different locations.
- The use less autonomy days for battery design which will ensure its regular full charge that will maximize the batteries lifetime.
- The use AC-Coupling over DC-Coupled PV systems for institutions that have a higher load demand during the day such as health centers and secondary schools.

To avoid the deep discharge of batteries by inverters, here are the three recommendations:

1. Using the installed charge controller's Low Voltage Disconnect (LVD) function.
2. Selecting an inverter and charge controller that communicates each other.
3. The use of shunt resistor.

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ANNEX-I – Resource Assessment Results

PVSYST V6.62		05/05/17 11h43

Definition of a geographical site

Geographical Site **Bahir Dar** Country **Ethiopia**

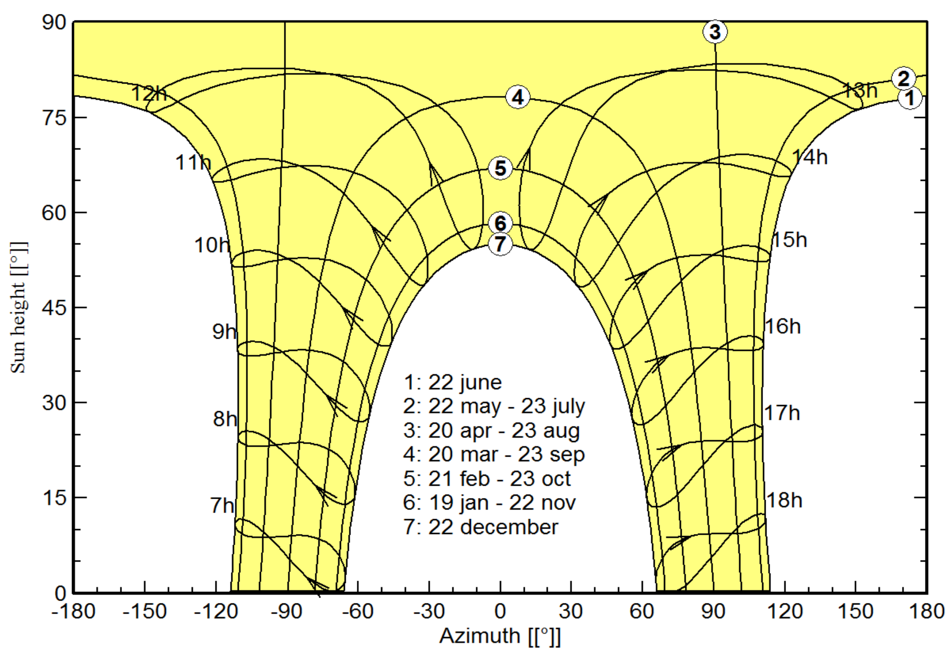
File Bahir Dar_Nasamod-Daily Irradiance.SIT of 00/00/00 00h00

Situation Latitude 11.57° N Longitude 37.37° E
Time defined as Legal Time Time zone UT+3 Altitude 1807 m

Monthly Meteo Values Source NASA-SSE satellite data, 1983-2005 (modified by user)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	6.20	6.53	6.52	6.69	6.32	5.71	5.16	5.18	5.81	5.86	6.01	5.95	5.99	kWh/m².day
Hor. diffuse	1.08	1.35	1.77	1.94	2.00	2.11	2.22	2.28	2.06	1.72	1.26	1.05	1.74	kWh/m².day
Extraterrestrial	8.70	9.50	10.18	10.55	10.52	10.40	10.41	10.47	10.28	9.70	8.90	8.43	9.84	kWh/m².day
Clearness Index	0.712	0.687	0.640	0.634	0.601	0.549	0.496	0.495	0.565	0.604	0.675	0.706	0.609	
Amb. temper.	19.5	20.9	21.6	20.8	19.9	17.6	16.3	16.4	17.3	18.0	18.4	18.7	18.8	°C

Solar paths at Bahir Dar, (Lat. 11.57° N, long. 37.37° E, alt. 1807 m) - Legal Time



PVSYST V6.62		05/05/17 11h47

Definition of a geographical site

Geographical Site **Awassa** Country **Ethiopia**

File Awassa_Nasamod-Daily Irradiance.SIT of 00/00/00 00h00

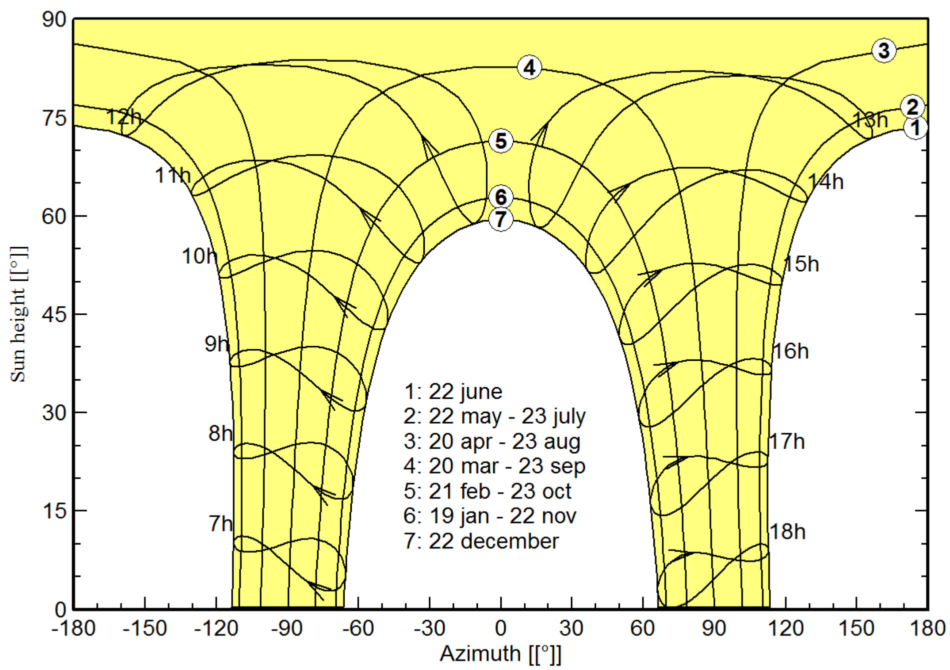
Situation Latitude 7.05° N Longitude 38.50° E

Time defined as Legal Time Time zone UT+3 Altitude 1712 m

Monthly Meteo Values Source NASA-SSE satellite data, 1983-2005 (modified by user)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	6.02	6.41	6.35	6.04	5.95	5.42	4.83	5.02	5.64	6.04	6.25	6.10	5.83	kWh/m².day
Hor. diffuse	1.43	1.57	1.92	2.11	2.00	2.04	2.16	2.23	2.14	1.80	1.40	1.26	1.84	kWh/m².day
Extraterrestrial	9.28	9.90	10.36	10.46	10.23	10.01	10.06	10.29	10.35	10.02	9.42	9.04	9.95	kWh/m².day
Clearness Index	0.649	0.647	0.613	0.577	0.582	0.541	0.480	0.488	0.545	0.603	0.663	0.674	0.586	
Amb. temper.	18.4	19.6	20.4	19.6	18.1	16.8	15.7	15.8	16.3	16.6	17.1	17.5	17.7	°C

Solar paths at Awassa, (Lat. 7.05° N, long. 38.50° E, alt. 1712 m) - Legal Time



Definition of a geographical site

Geographical Site **Mek'ele** Country **Ethiopia**

File Mek_ele_Nasa_1983 to 2005-Daily Irradiance.SIT of 00/00/00 00h00

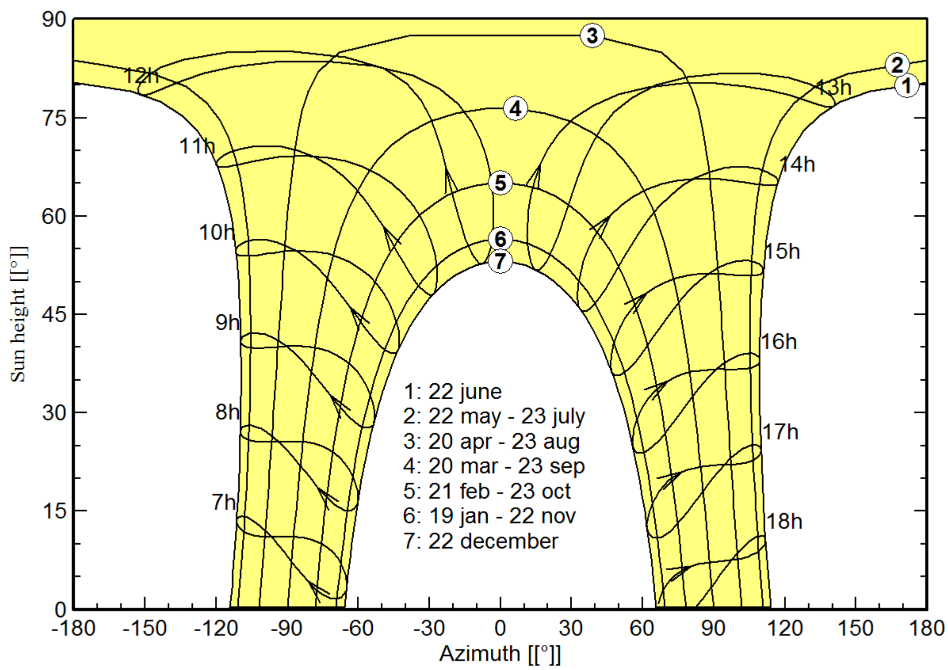
Situation Latitude 13.49° N Longitude 39.47° E

Time defined as Legal Time Time zone UT+3 Altitude 2061 m

Monthly Meteo Values Source NASA-SSE satellite data, 1983-2005

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	5.85	6.27	6.50	6.82	6.62	6.05	5.57	5.46	6.05	6.22	6.00	5.66	6.09	kWh/m².day
Hor. diffuse	1.11	1.35	1.72	1.88	1.97	2.10	2.22	2.27	1.95	1.50	1.14	1.05	1.69	kWh/m².day
Extraterrestrial	8.44	9.31	10.09	10.57	10.63	10.55	10.54	10.53	10.24	9.55	8.66	8.15	9.77	kWh/m².day
Clearness Index	0.693	0.674	0.644	0.645	0.623	0.574	0.528	0.518	0.591	0.651	0.693	0.694	0.623	
Amb. temper.	19.7	21.0	22.8	24.3	26.3	25.6	24.1	23.9	24.8	24.3	21.7	20.1	23.2	°C

Solar paths at Mek'ele, (Lat. 13.49° N, long. 39.47° E, alt. 2061 m) - Legal Time



PVSYST V6.62		11/09/17 08h47

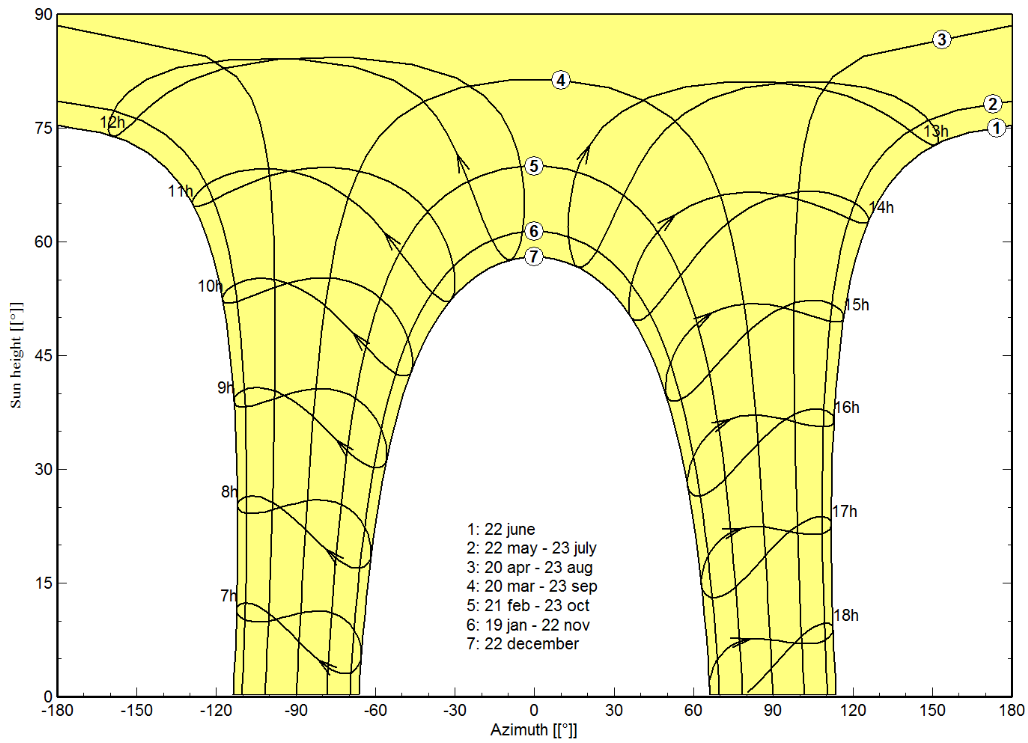
:

Definition of a geographical site

Geographical Site	**Adama**	Country	**Ethiopia**
Situation	Latitude 8.53° N	Longitude	39.26° E
Time defined as	Legal Time Time zone UT+3	Altitude	1615 m
Horizon	Average Height 0.0°		

Height [°]	0.0	0.0	0.0	0.0
Azimuth [°]	-120	-40	40	120

Definition of a geographical site



ANNEX-II - Energy Use Data

Type-1: household

Sr. No	Appliance	Qty	Wattage	Total Watt	hrs used /day	Wh/Day	DC/AC
1	Light bulbs	4	3	**12**	4	**48**	DC
2	Radio	1	10	**10**	6	**60**	DC
3	Mobile charging	2	5	**10**	2	**20**	DC
TOTAL WH needed per day						**128**	

Type-2: household

Sr. No	Appliance	Qty	Wattage	Total Watt	hrs used /day	Wh/Day	DC/AC
1	Light bulbs	4	11	**44**	4	**176**	AC
2	Radio	1	10	**10**	6	**60**	AC
3	TV	1	80	**80**	3	**240**	AC
4	Mobile charging	4	5	**20**	2	**40**	AC
Total Wattage for inverter calculation				**154**			
TOTAL WH needed per day						**516**	

PRIMARY SCHOOL

Sr. No	Appliance	Qty	Wattage	Total Watt	hrs used /day	Wh/Day	DC/AC
1	CFL Lamps (AC)	8	11	**88**	3	**264**	AC
2	CFL Lamps (AC) (outside light)	2	11	**22**	12	**264**	AC
3	Desktop Computer	1	200	**200**	8	**1,600**	AC
4	TV	-	-	**-**	-	**-**	-
5	Radio / flash player	3	10	**30**	4	**120**	AC
6	Amplifier	1	75	**75**	2	**150**	AC
7	Printer / Copy machine	1	900	**900**	0.5	**450**	AC
8	Mobile Charge	15	5	**75**	2	**150**	AC
Total Wattage for inverter calculation				**1,370**			
TOTAL WH needed per day						**2,998.00**	

SECONDARY SCHOOL

Sr. No	Appliance	Qty	Wattage	Total Watt	hrs used /day	Wh/Day	DC/AC
1	CFL Lamps (AC)	14	11	**154**	6	**924**	AC
2	CFL Lamps (AC) (outside light)	4	11	**44**	12	**528**	AC
3	Computer	21	200	**4200**	8	**33,600**	AC
4	TV & receiver (Plasma TV)	6	280	**1680**	4	**6,720**	AC

5	Radio / flash player	1	10	**10**	8	**80**	AC
6	Amplifier	1	100	**100**	4	**400**	AC
7	Printer / Copy machine	1	900	**900**	1	**900**	AC
8	Mobile Charge	10	5	**50**	2	**100**	AC
	Total Wattage for inverter calculation			**7,036**			
	TOTAL WH needed per day					**43,252.00**	

HEALTH POST (HP)

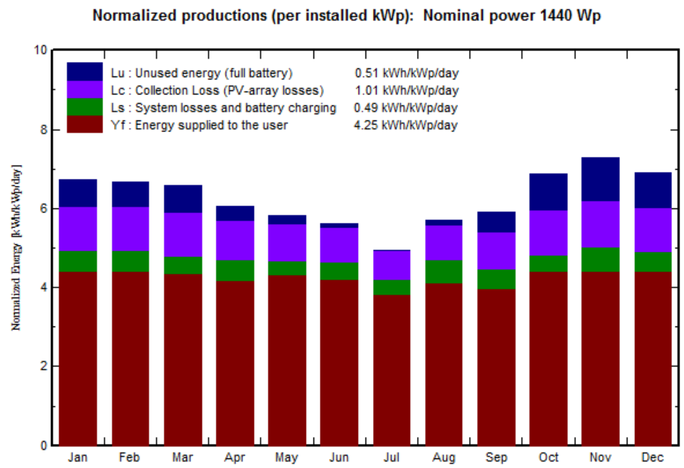
Sr. No	**Appliance**	**Qty**	**Wattage**	**Total Watt**	**Hrs used /day**	**WH/Day**	DC/AC
1	LED/CFL lamps	6	11	**66**	4	**264**	AC
2	LED/CFL lamps (outside light)	2	11	**22**	12	**264**	AC
3	Refrigerator	1	150	**150**	-	**1,200**	AC
4	Delivery lamp	1	20	**20**	2	**40**	AC
5	Cassette player/CD/Radio	1	10	**10**	8	**80**	AC
6	Mobile charge	4	5	**20**	2	**40**	AC
	Total Wattage for inverter calculation			**293**			
	TOTAL WH needed per day					**1,888.00**	

HEALTH CENTER (HC)

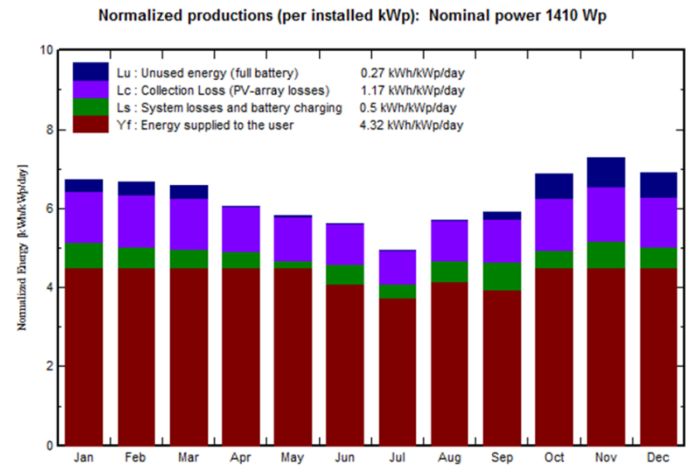
Sr. No	**Appliance**	**Wattage**	**Qty**	**Total Watt**	**Hrs used /day**	**WH/Day**	DC/AC
1	LED/CFL lamps (HC rooms)	11	30	**330**	4	**1,320**	AC
2	LED/CFL lamps (HC compound)	11	8	**88**	12	**1,056**	AC
3	LED/CFL lamps (staff residence)	11	10	**110**	4	**440**	AC
4	LED/CFL lamps (Examination)	11	1	**6**	4	**24**	AC
5	Refrigerator	150	1	**150**	-	**1200**	AC
6	Microscope	20	1	**20**	4	**80**	AC
7	Sterilizer	500	1	**500**	2	**1,000**	AC
8	Centrifuge	90	1	**90**	2	**180**	AC
9	Suction pump	150	1	**150**	2	**300**	AC
10	TV	80	1	**80**	4	**320**	AC
11	Satellite dish	30	1	**30**	4	**120**	AC
12	Radio/Tape player	20	1	**20**	8	**160**	AC
13	Mobile charger	5	15	**75**	2	**150**	AC
	Total Wattage for inverter calculation			**1,533**			
	TOTAL WH needed per day					**6,326.00**	

ANNEX-III – Simulation results

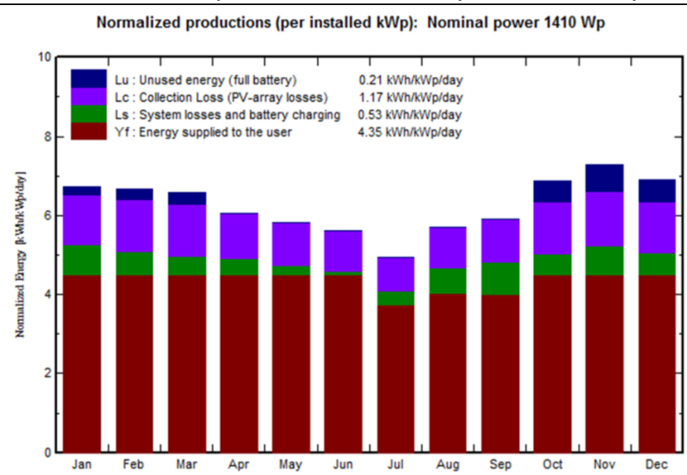
Health Center – Adama (Oromia region)



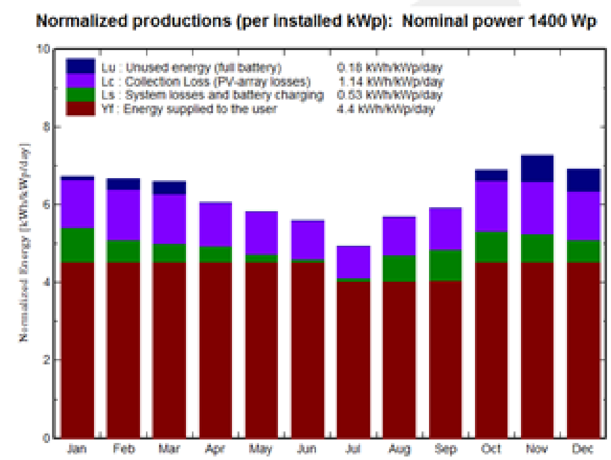
Normalized production at 1 day of autonomy



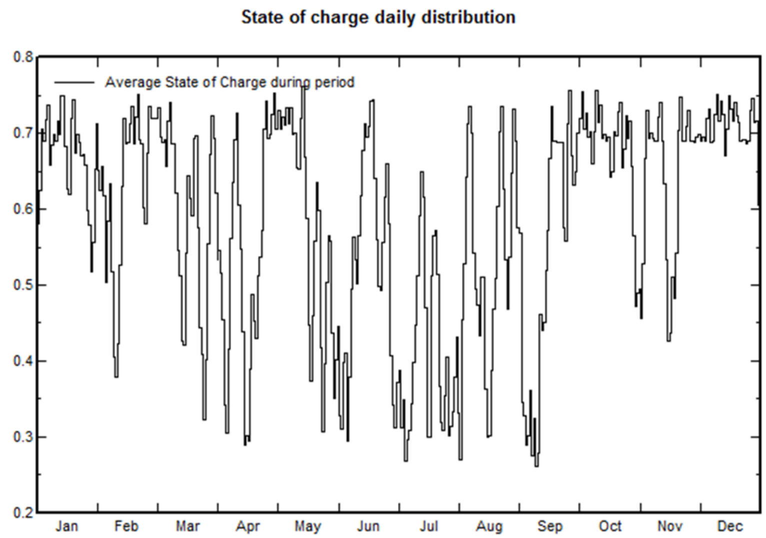
Normalized energy production at 2 days of autonomy



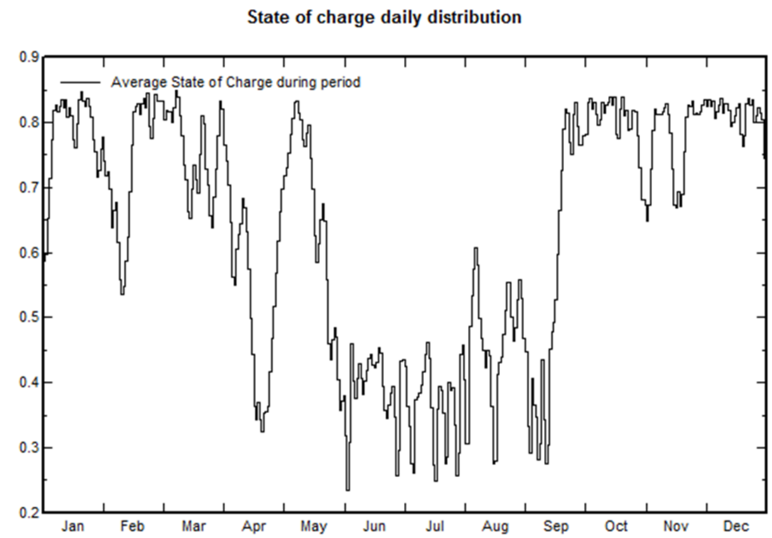
Normalized energy production at 3 days of autonomy



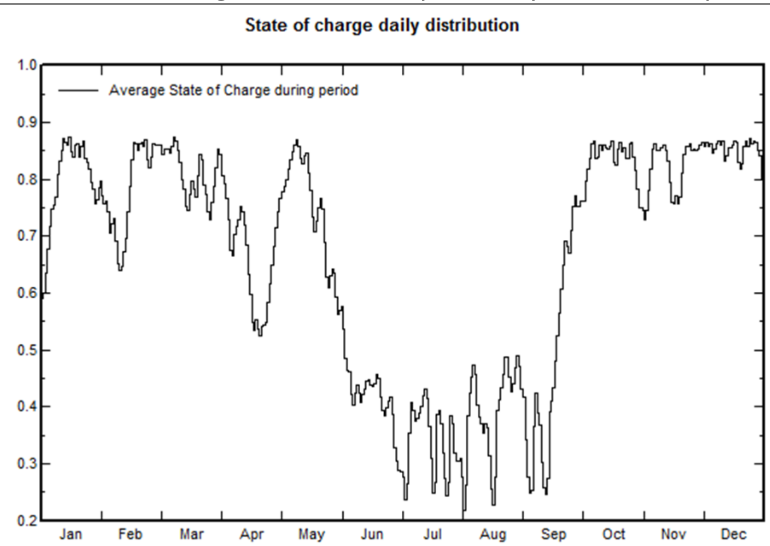
Normalized energy production at 4 days of autonomy



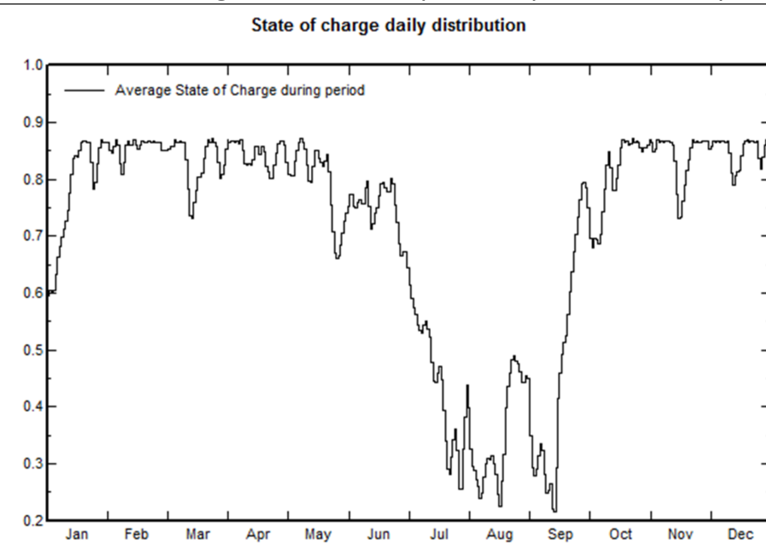
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

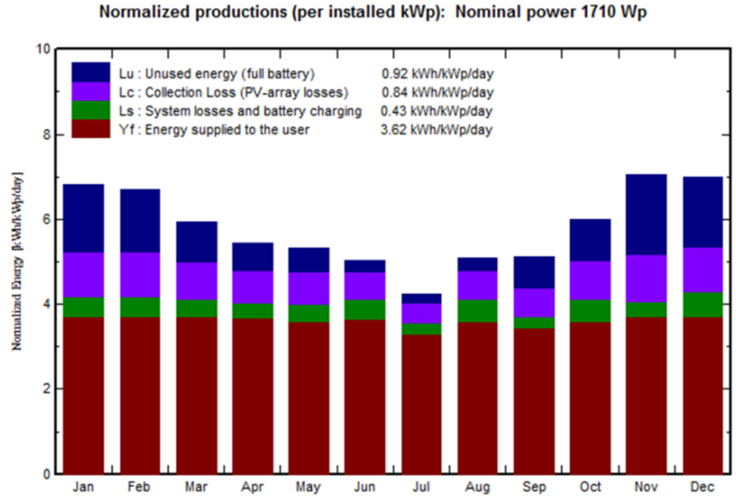


State of Charge of the battery at 3 days of autonomy

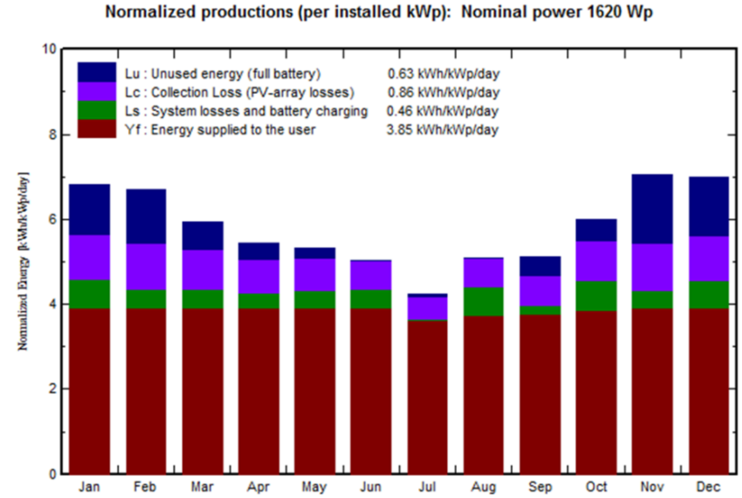


State of Charge of the battery at 4 days of autonomy

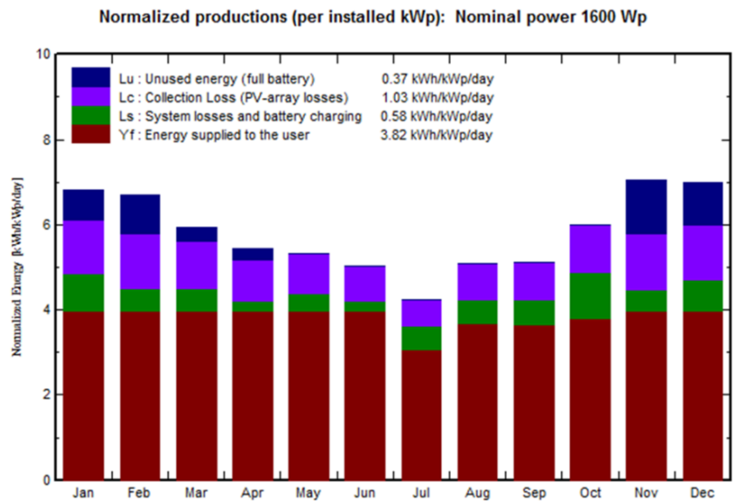
Health Center – Hawassa (SNNP region)



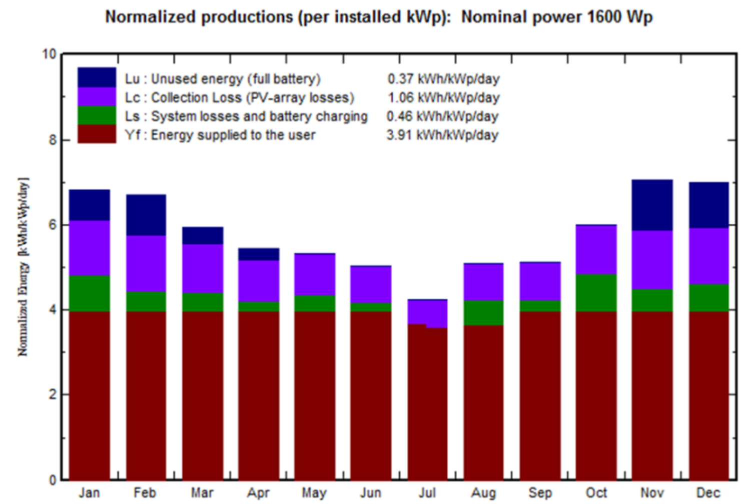
Normalized production at 1 day of autonomy



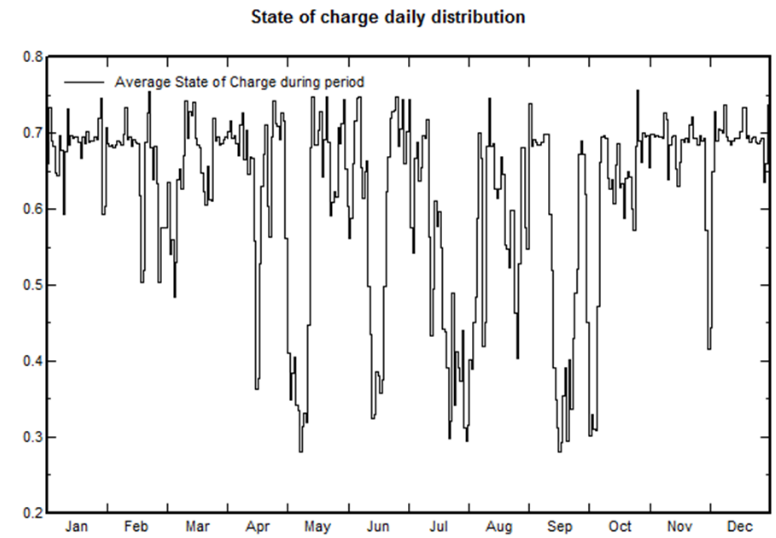
Normalized production at 2 days of autonomy



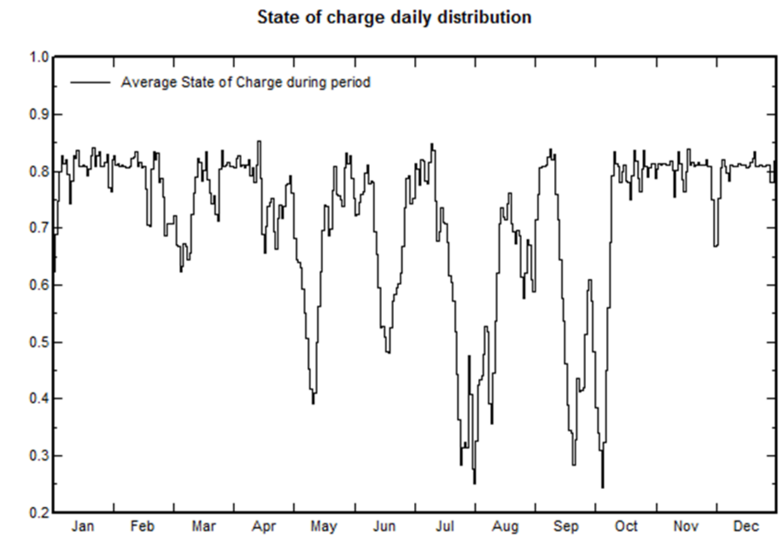
Normalized production at 3 days of autonomy



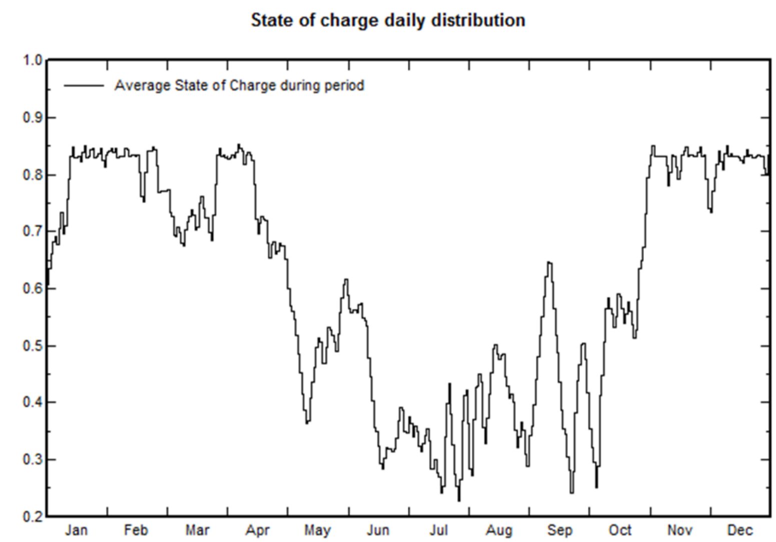
Normalized production at 4 days of autonomy



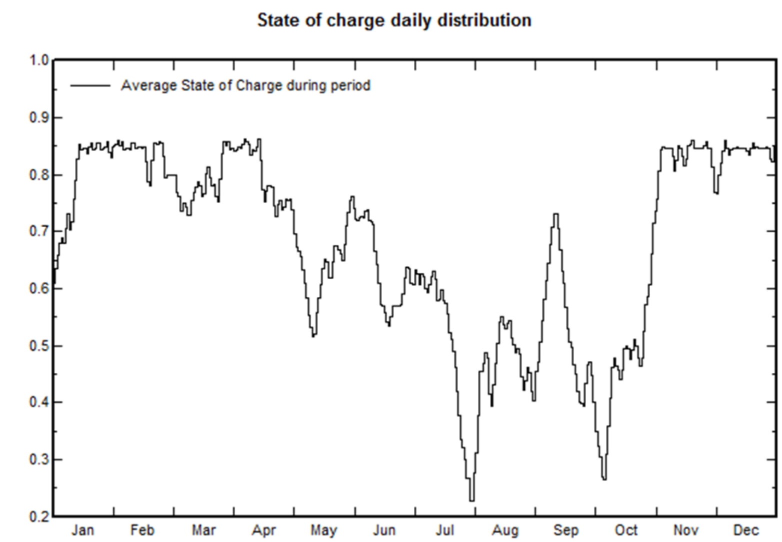
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

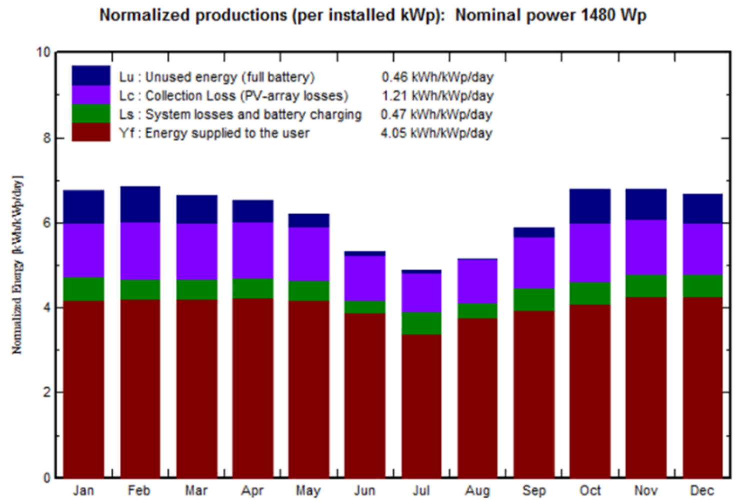


State of Charge of the battery at 3 days of autonomy

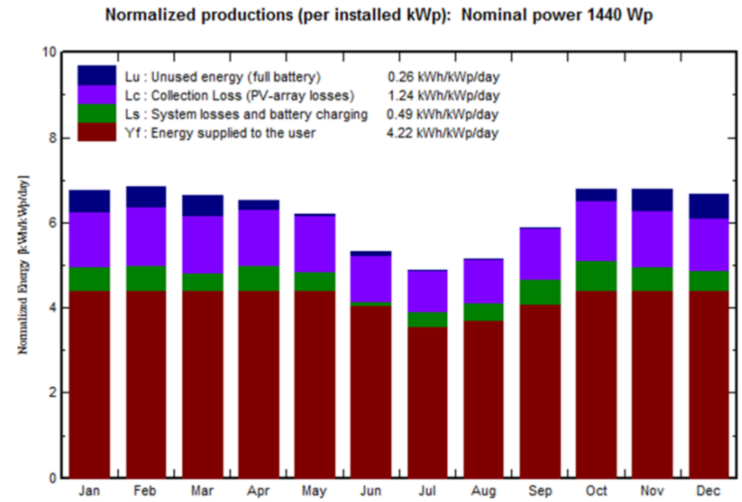


State of Charge of the battery at 4 days of autonomy

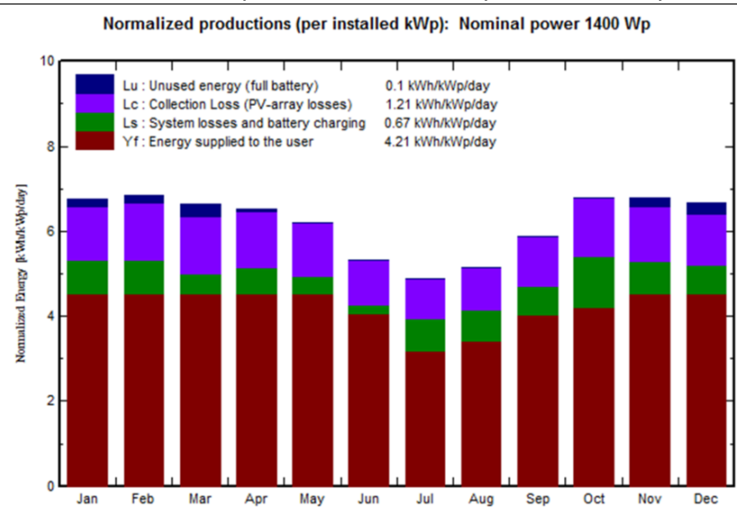
Health Center – Mekele (Tigray region)



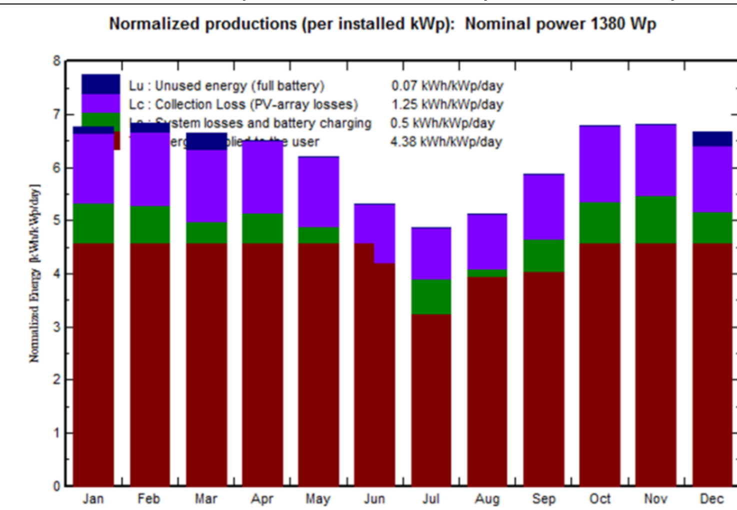
Normalized production at 1 day of autonomy



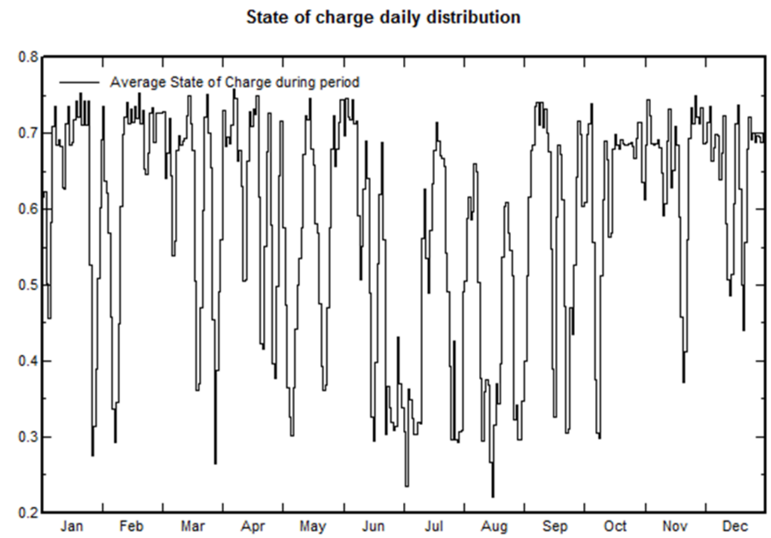
Normalized production at 2 days of autonomy



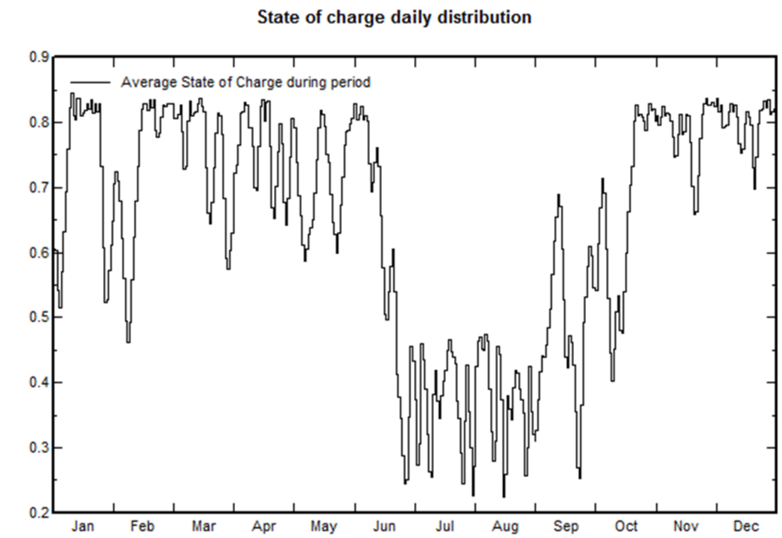
Normalized production at 3 days of autonomy



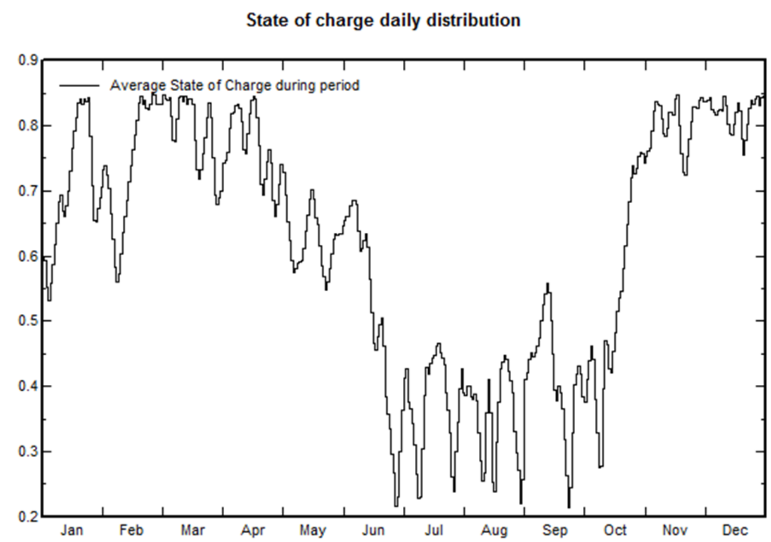
Normalized production at 4 days of autonomy



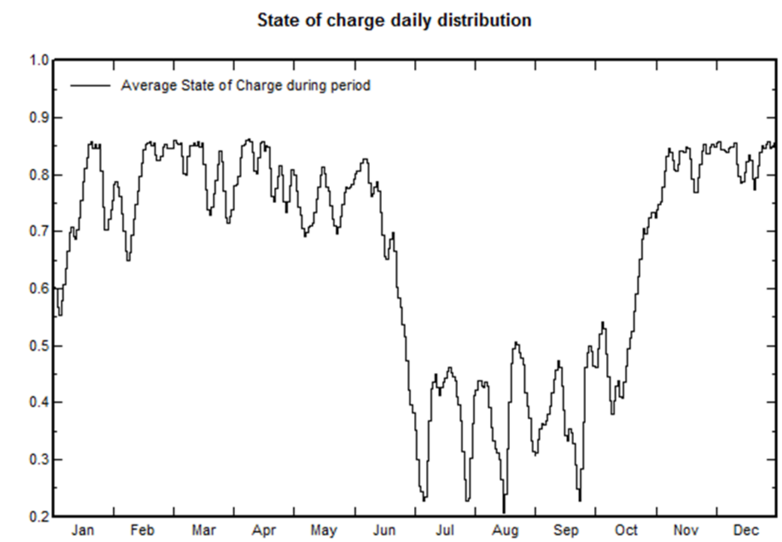
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

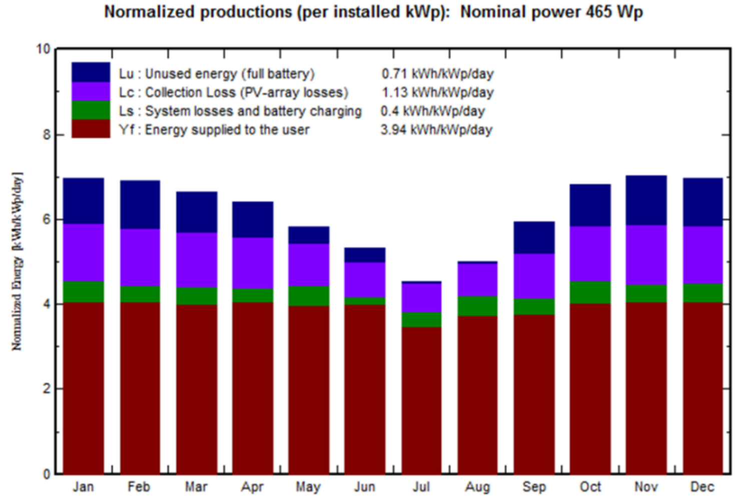


State of Charge of the battery at 3 days of autonomy

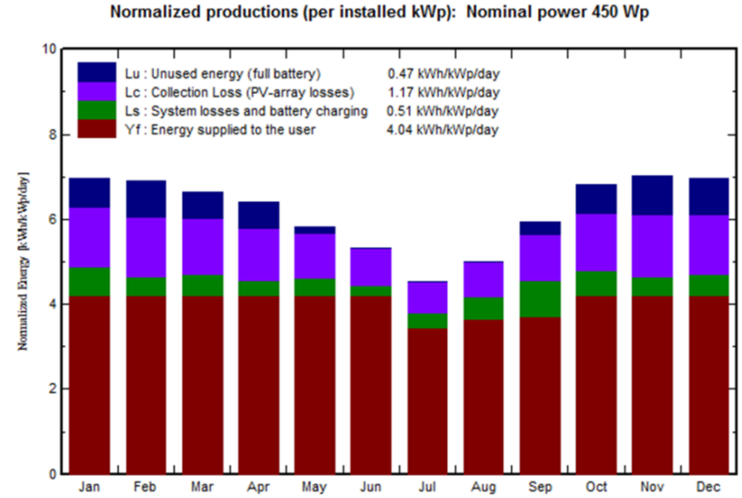


State of Charge of the battery at 4 days of autonomy

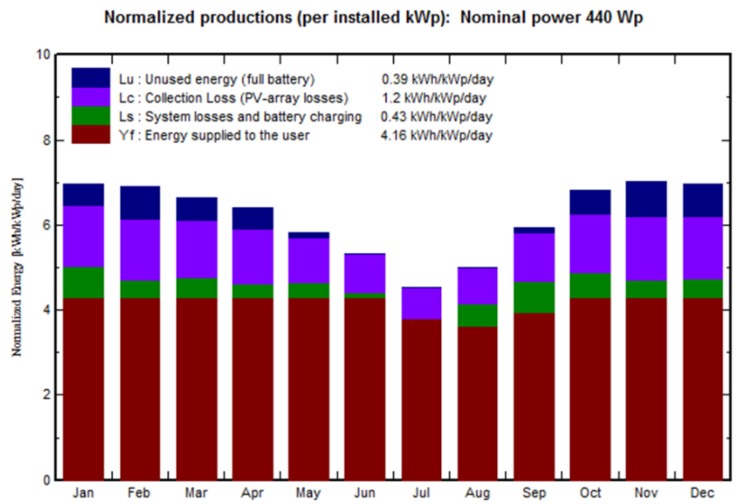
Health Post – Bahir dar (Amhara region)



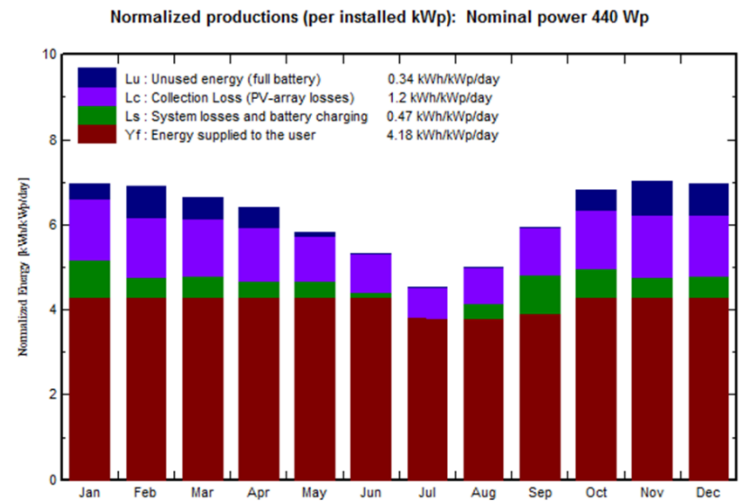
Normalized production at 1 day of autonomy



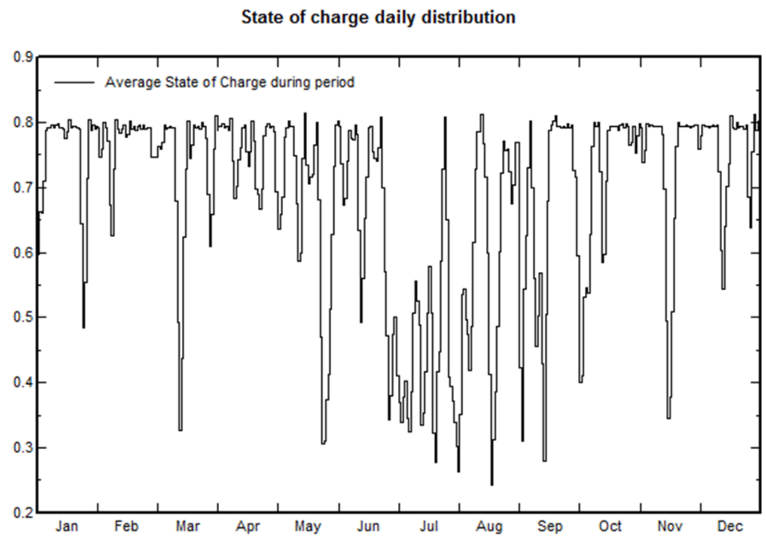
Normalized production at 2 days of autonomy



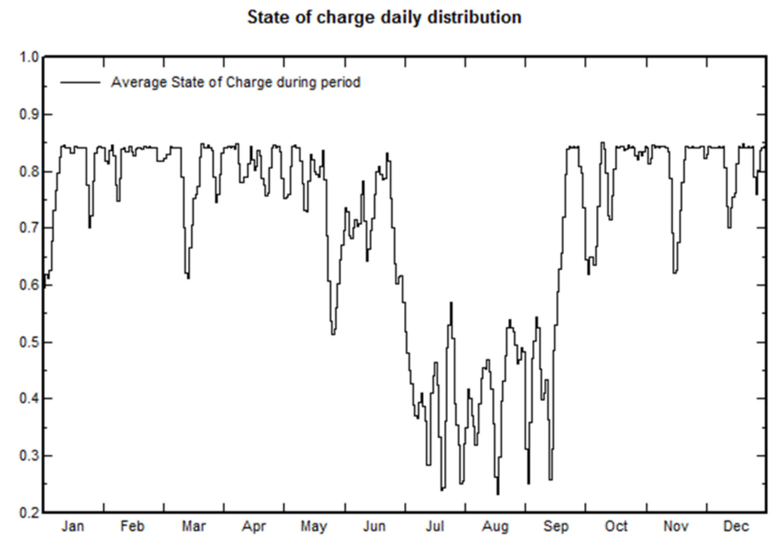
Normalized production at 3 days of autonomy



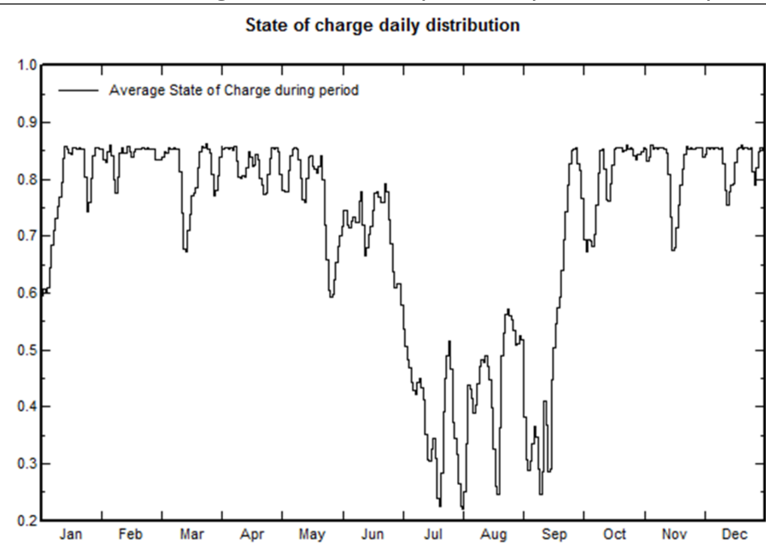
Normalized production at 4 days of autonomy



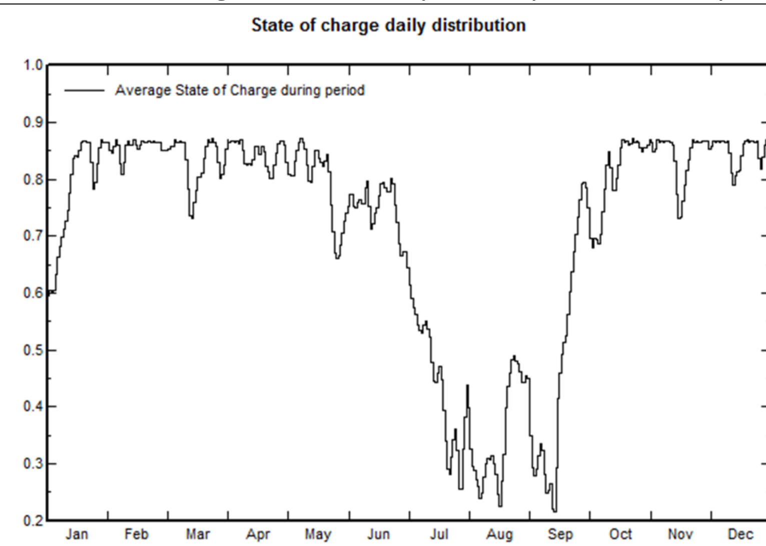
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

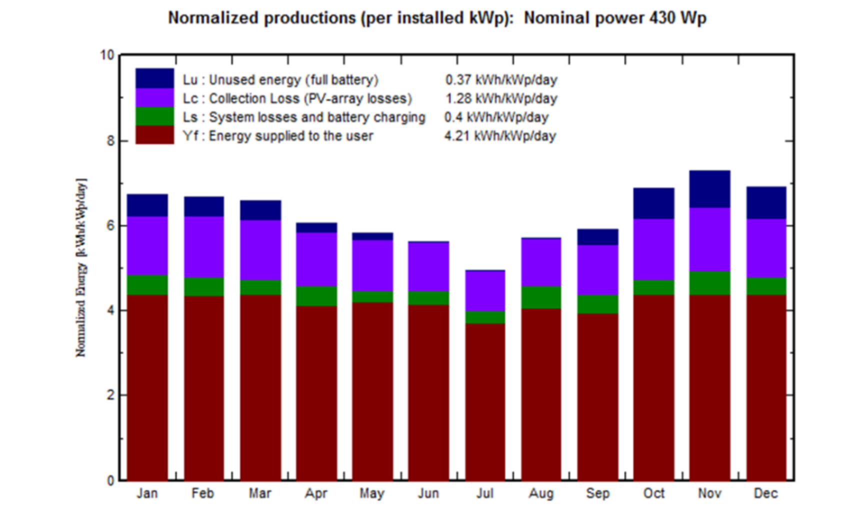


State of Charge of the battery at 3 days of autonomy

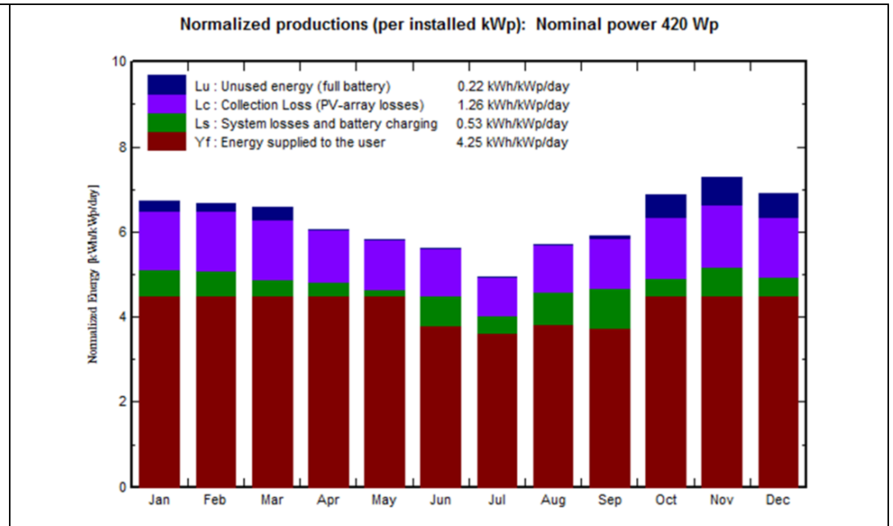


State of Charge of the battery at 4 days of autonomy

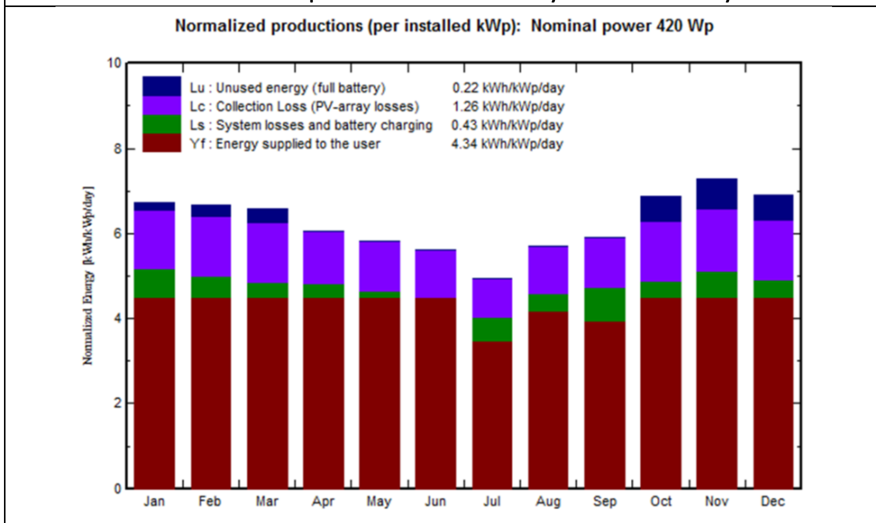
Health Post – Adama (Oromia region)



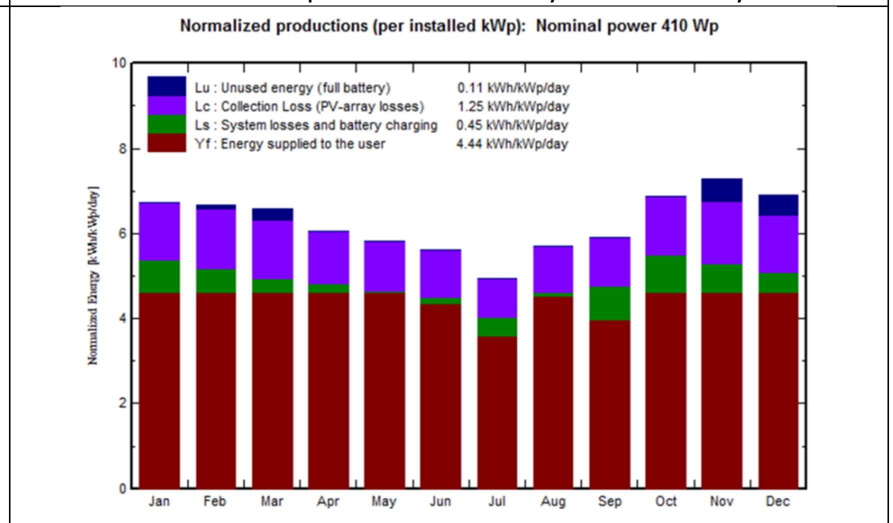
Normalized production at 1 day of autonomy



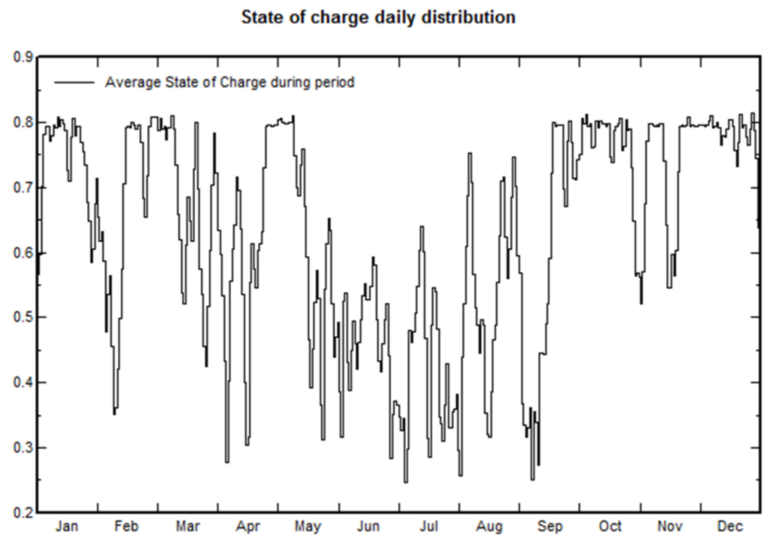
Normalized production at 2 days of autonomy



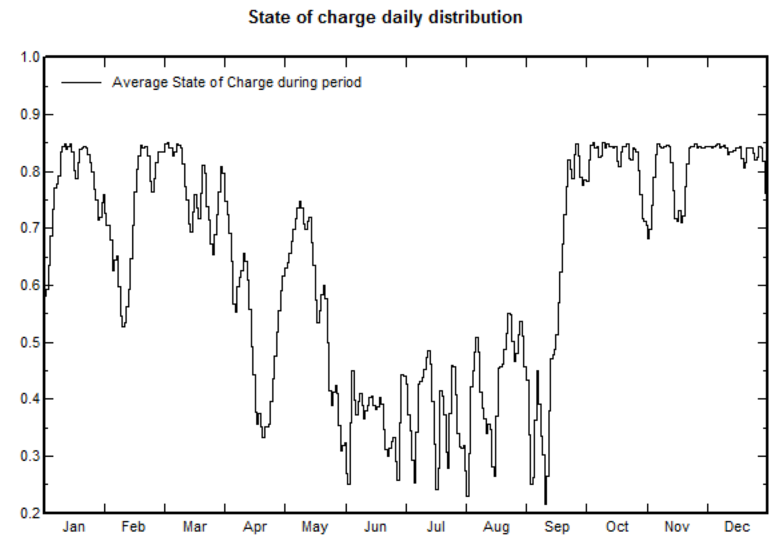
Normalized production at 3 days of autonomy



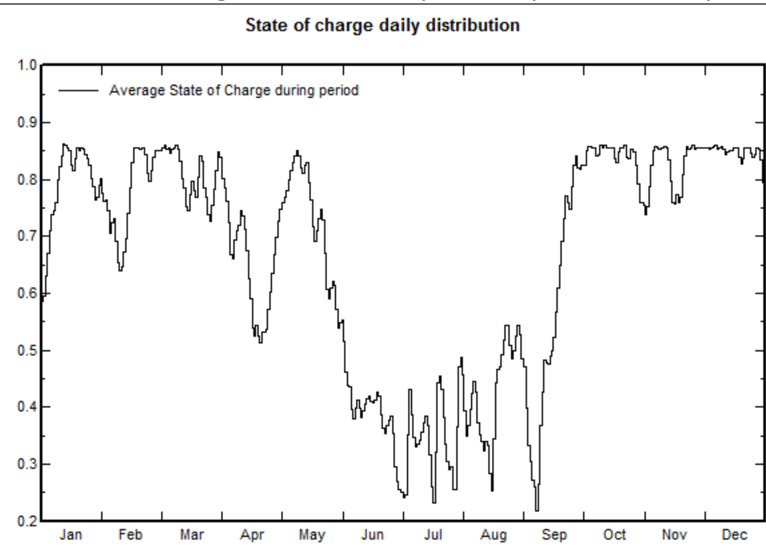
Normalized production at 4 days of autonomy



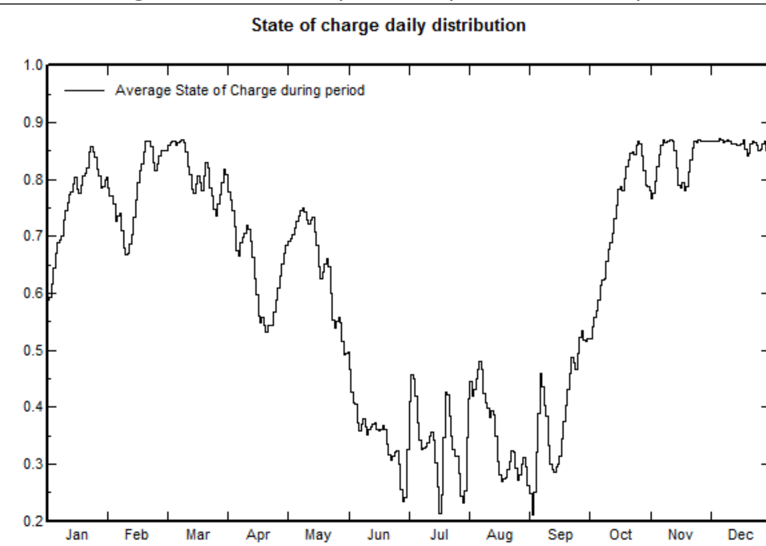
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

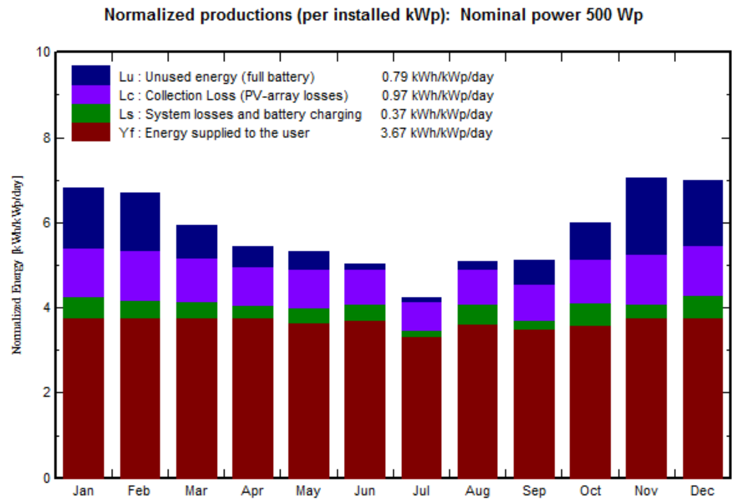


State of Charge of the battery at 3 days of autonomy

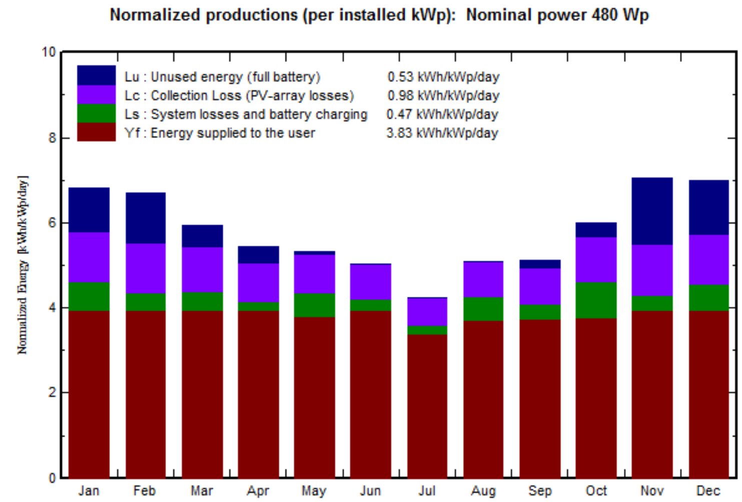


State of Charge of the battery at 4 days of autonomy

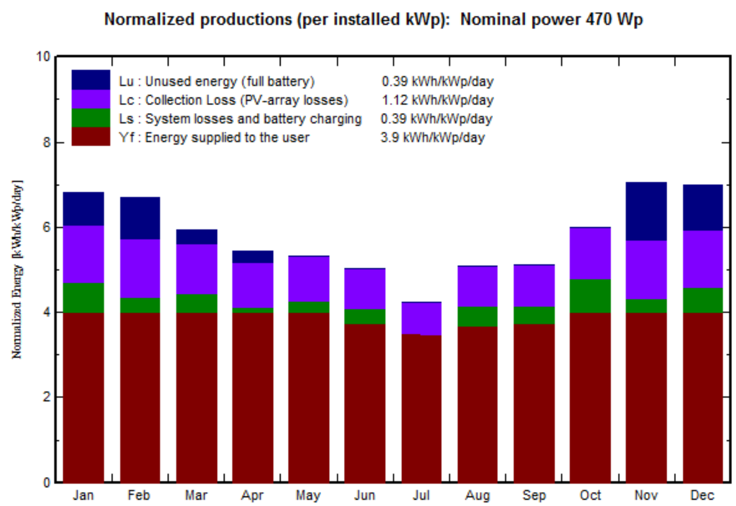
Health Post – Hawassa (SNNP region)



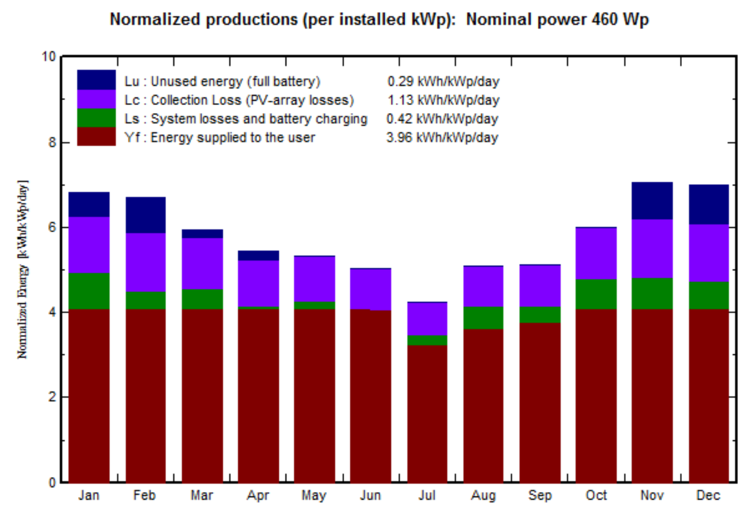
Normalized production at 1 day of autonomy



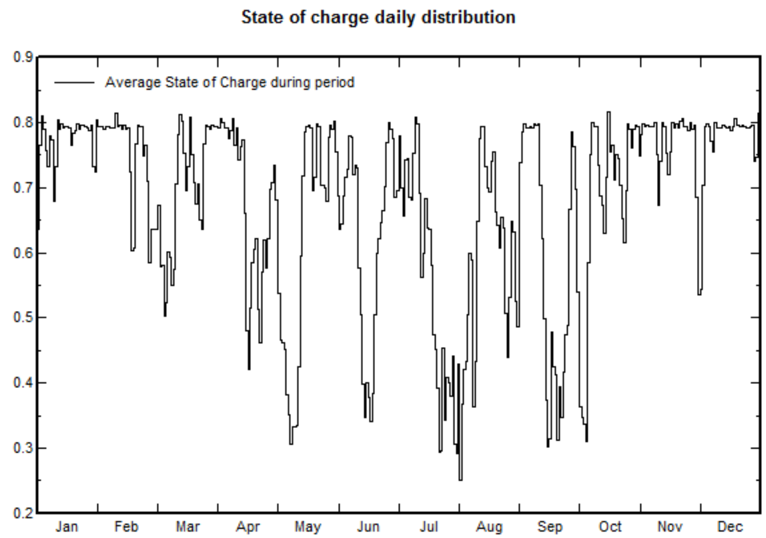
Normalized production at 2 days of autonomy



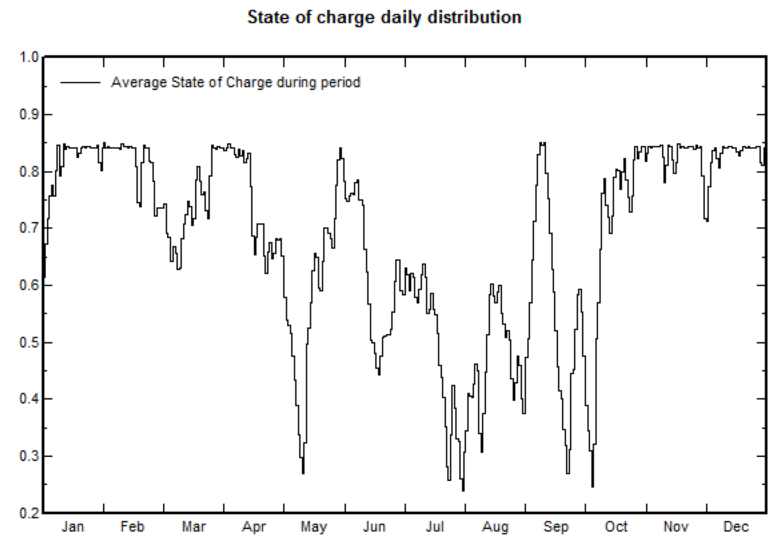
Normalized production at 3 days of autonomy



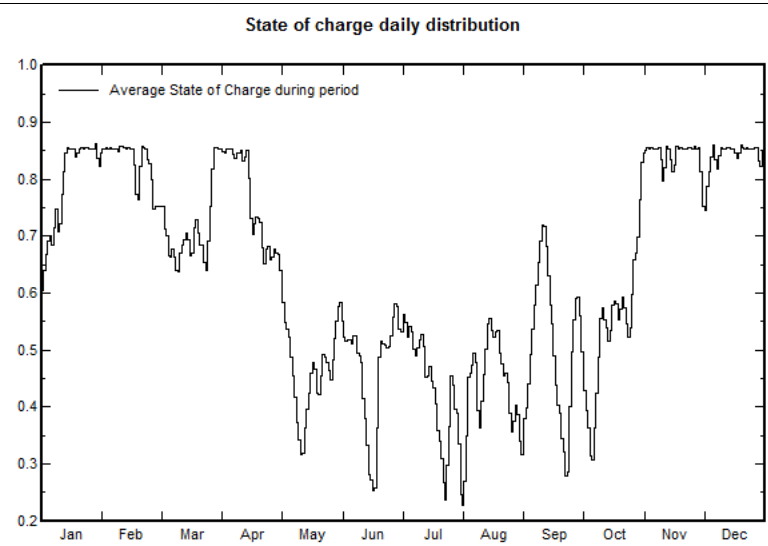
Normalized production at 4 days of autonomy



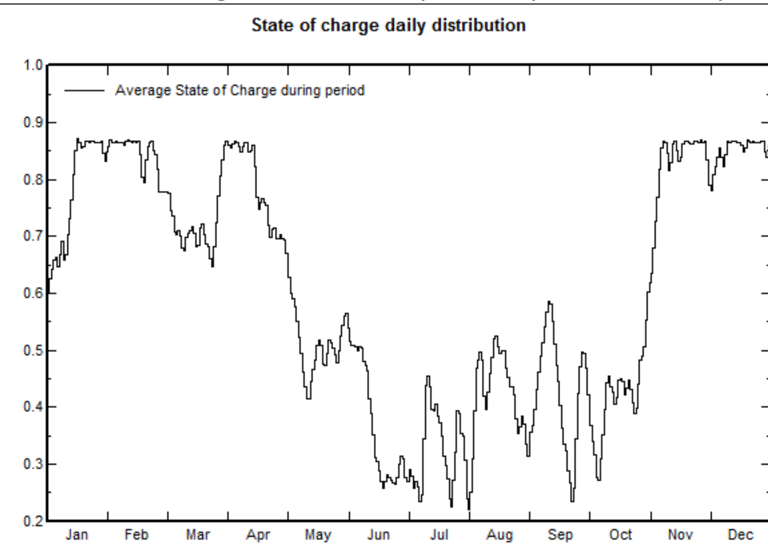
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

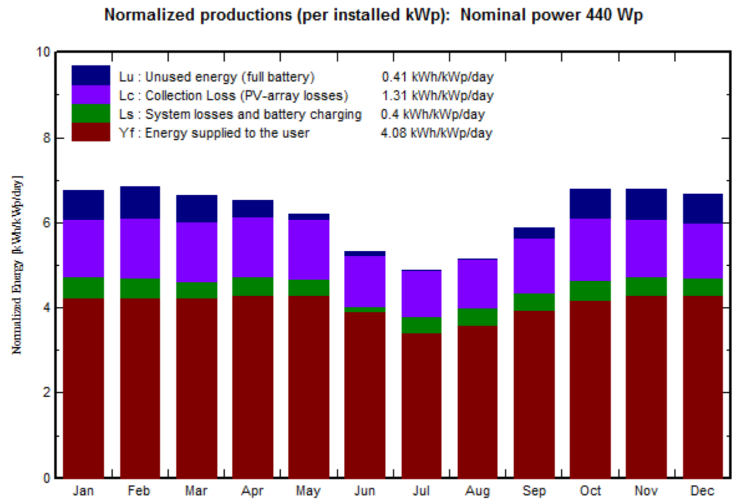


State of Charge of the battery at 3 days of autonomy

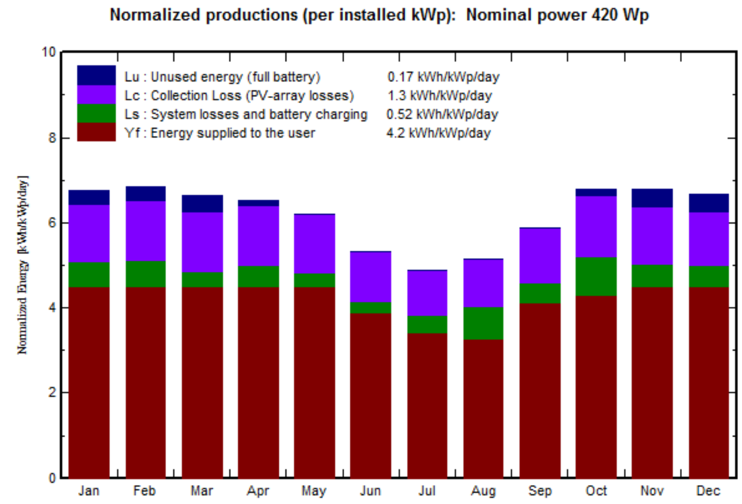


State of Charge of the battery at 4 days of autonomy

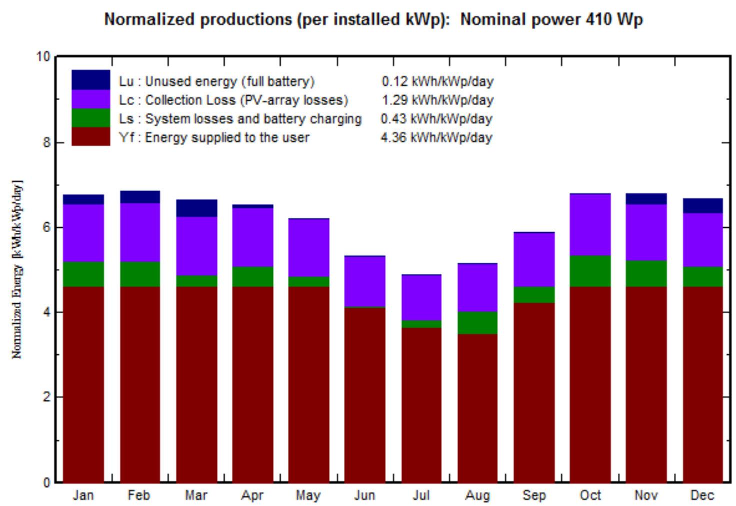
Health Post – Mekele (Tigray region)



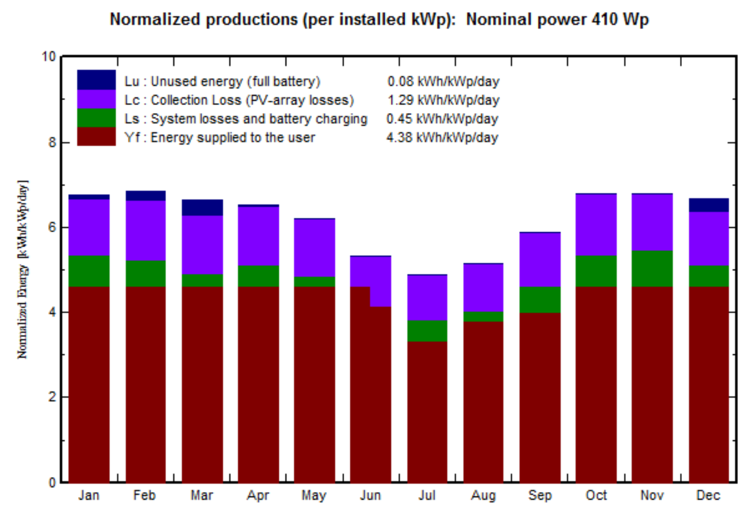
Normalized production at 1 day of autonomy



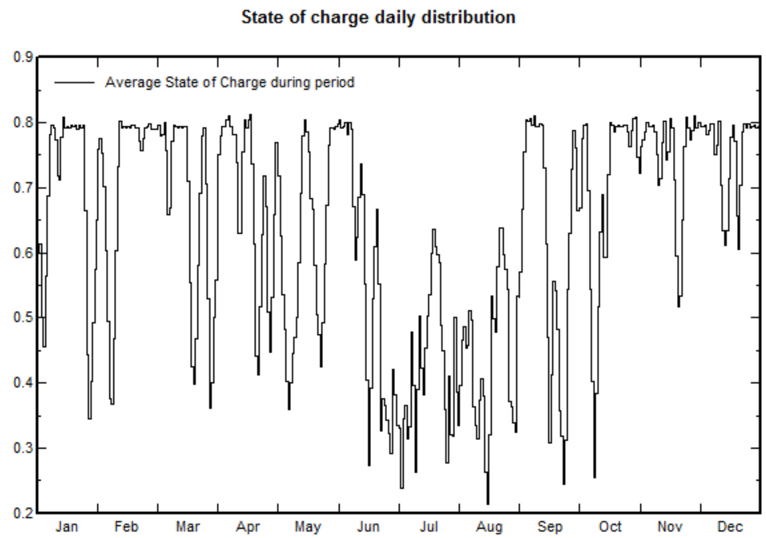
Normalized production at 2 days of autonomy



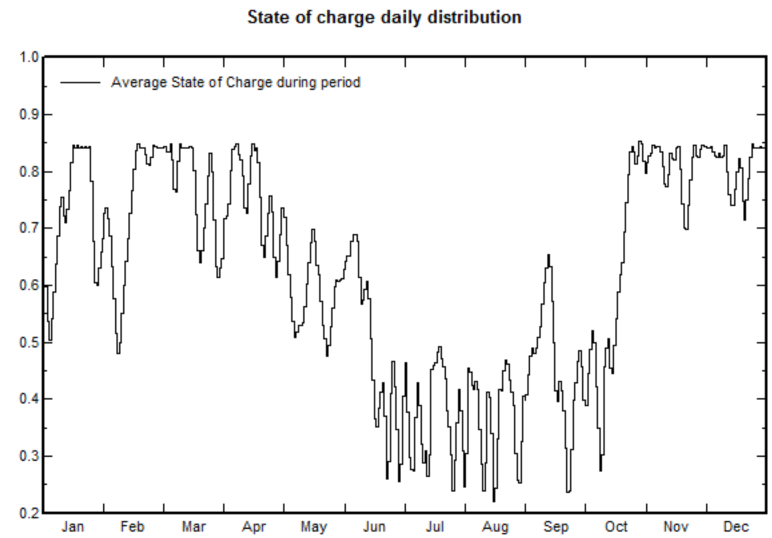
Normalized production at 3 days of autonomy



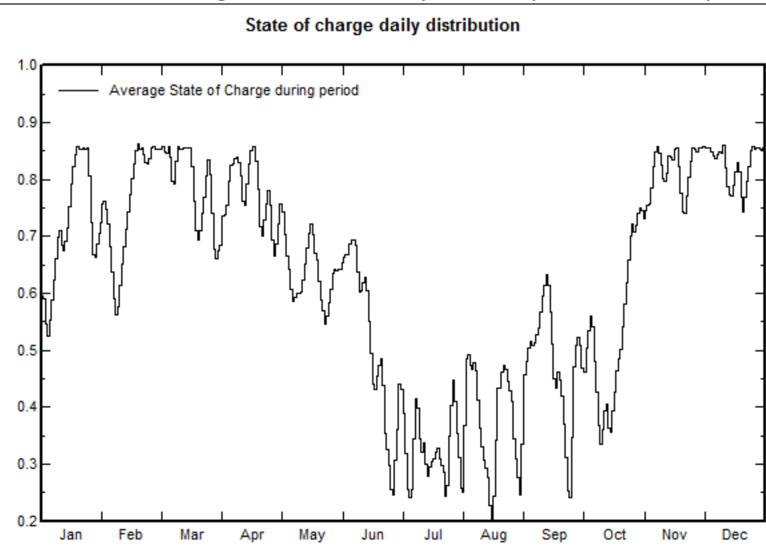
Normalized production at 4 days of autonomy



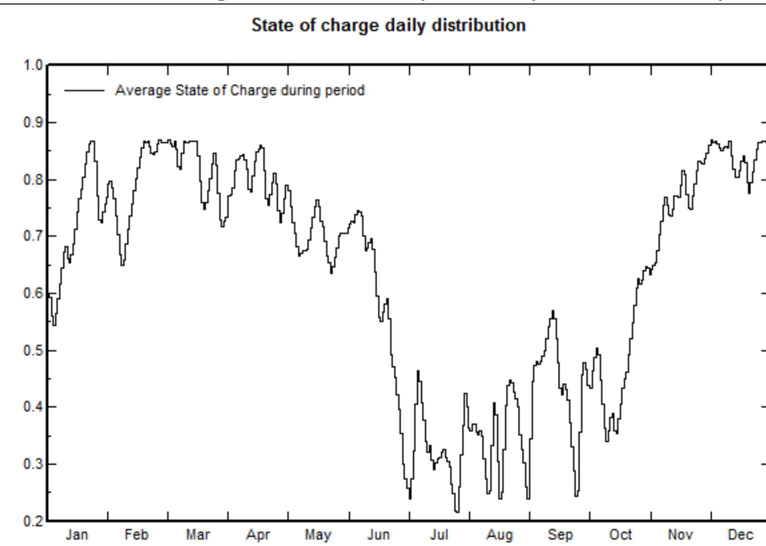
State of Charge of the battery at 1 day of autonomy



State of Charge of the battery at 2 days of autonomy

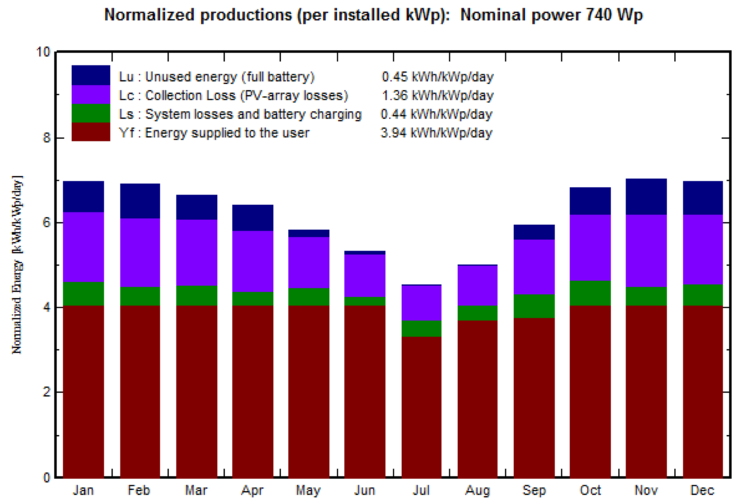


State of Charge of the battery at 3 days of autonomy

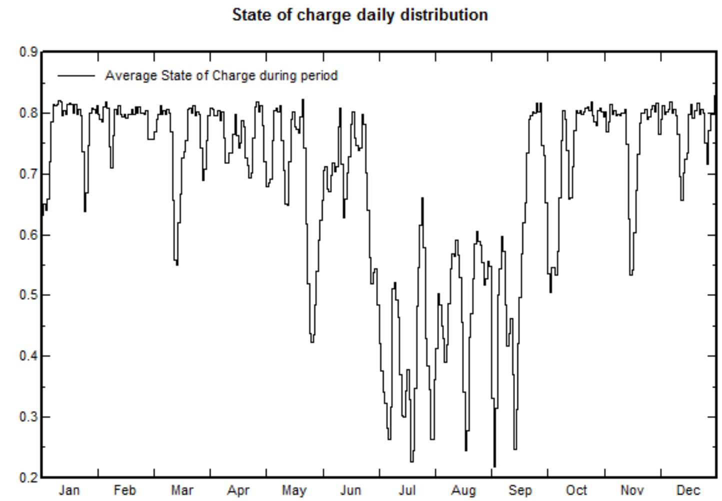


State of Charge of the battery at 4 days of autonomy

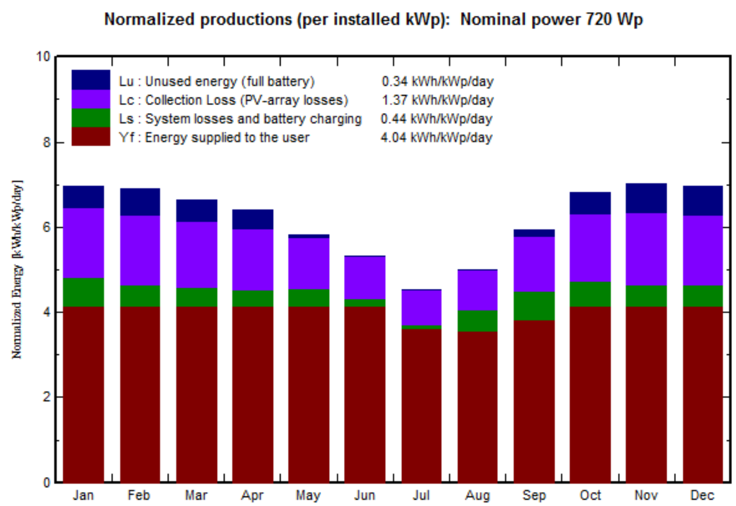
Primary School – Bahir dar (Amhara region)



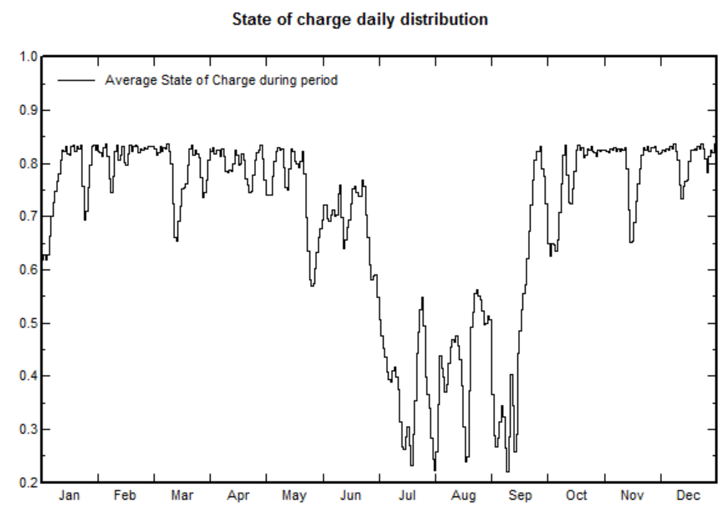
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

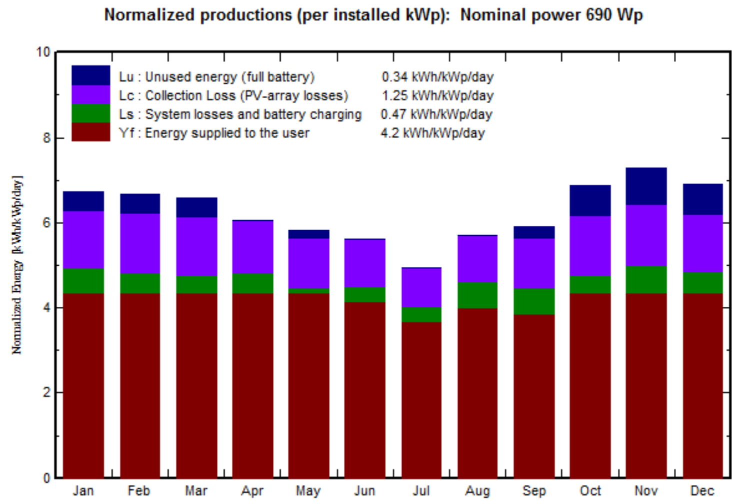


Normalized production at 3 days of autonomy

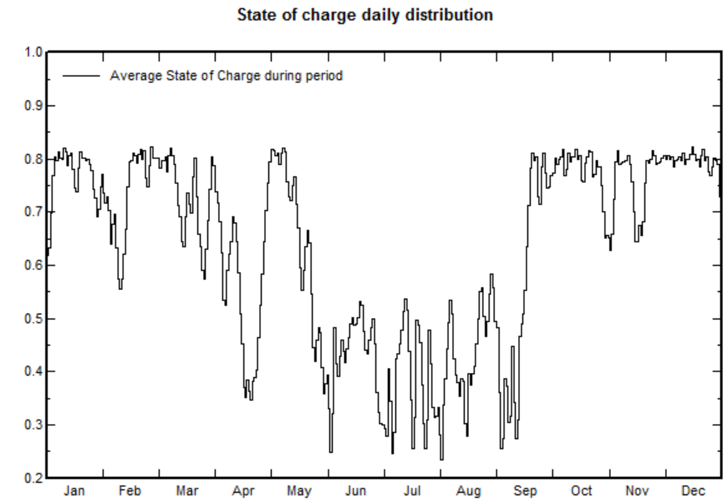


State of Charge of the battery at 3 days of autonomy

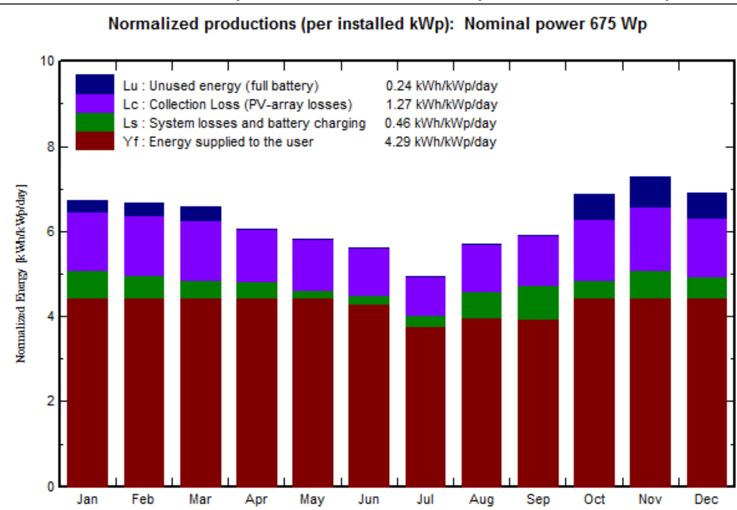
Primary School – Adama (Oromia region)



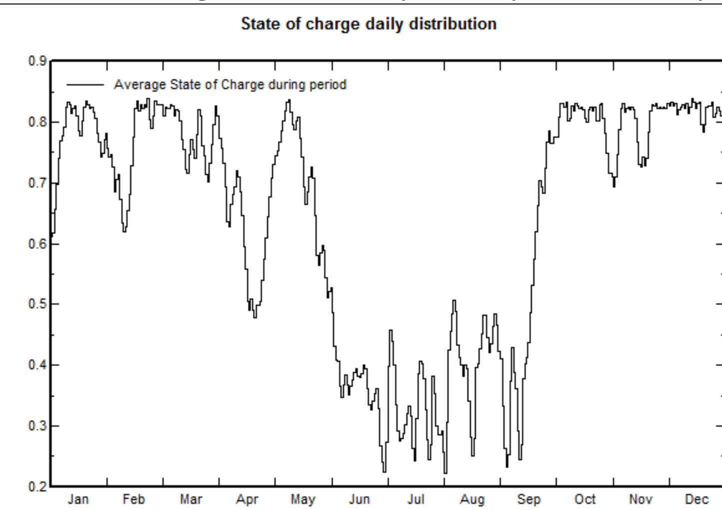
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

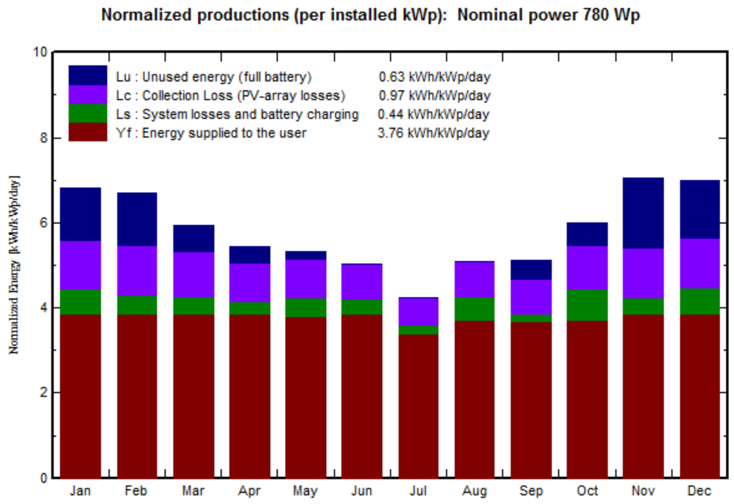


Normalized production at 3 days of autonomy

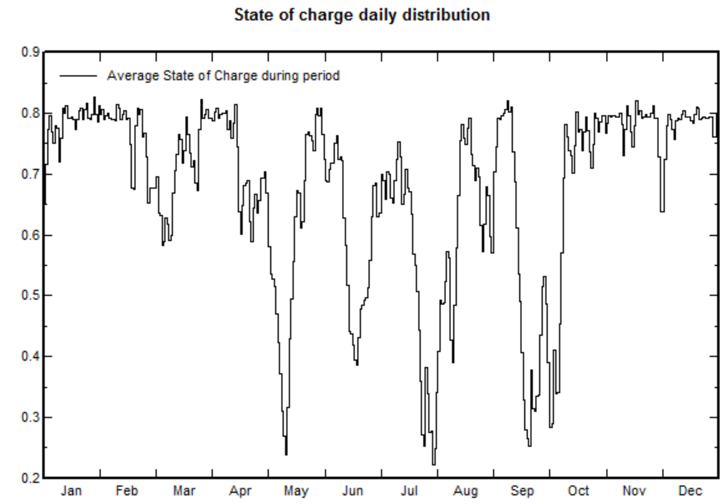


State of Charge of the battery at 3 days of autonomy

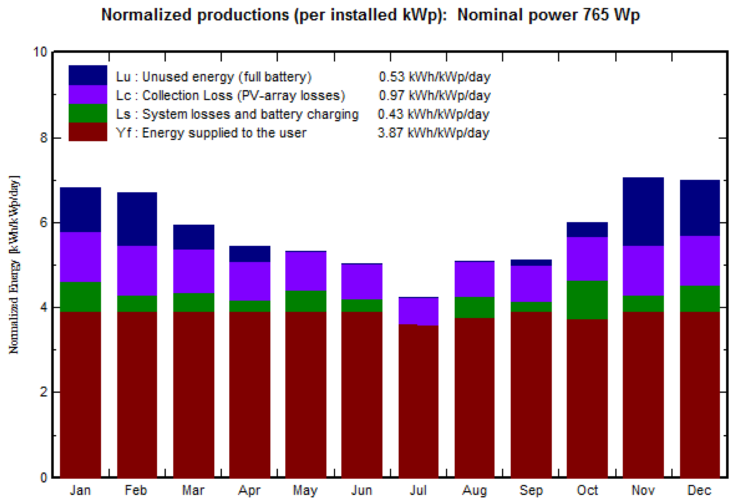
Primary School – Hawassa (SNNP region)



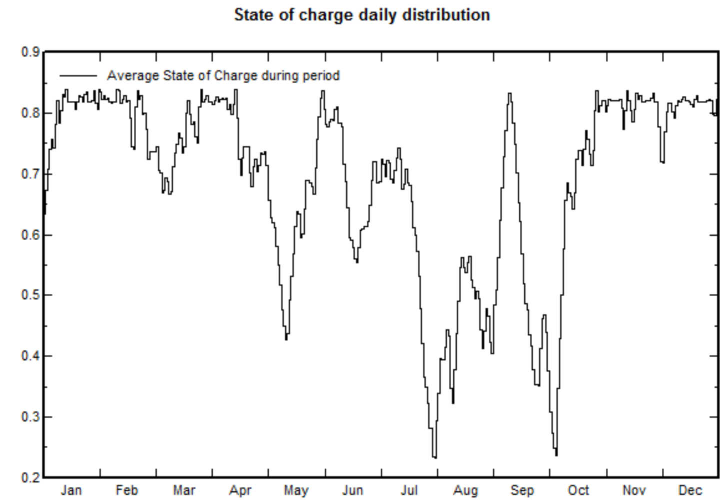
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

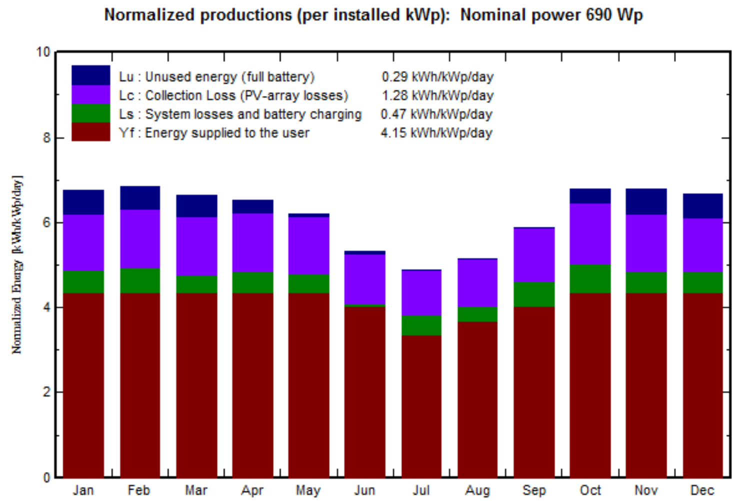


Normalized production at 3 days of autonomy

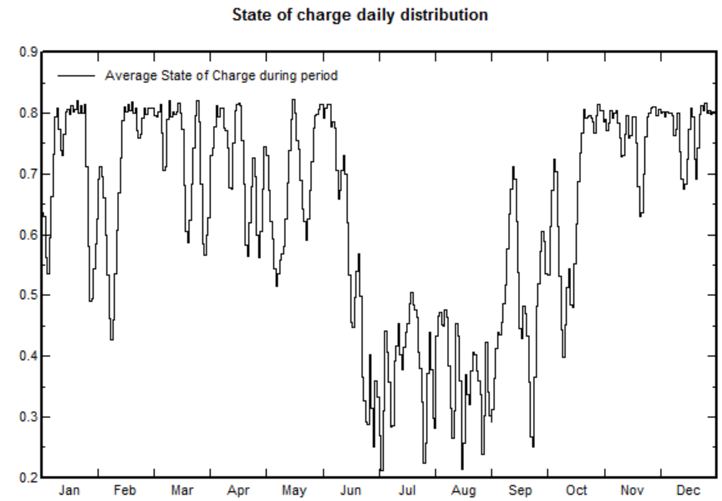


State of Charge of the battery at 3 days of autonomy

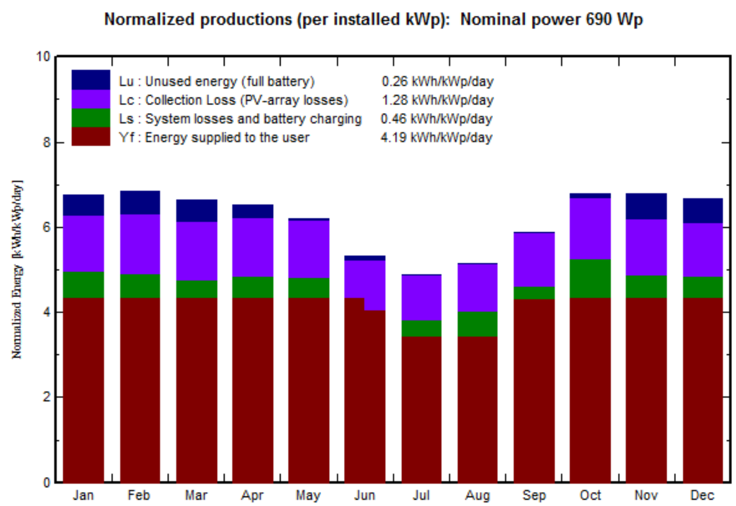
Primary School – Mekele (Tigray region)



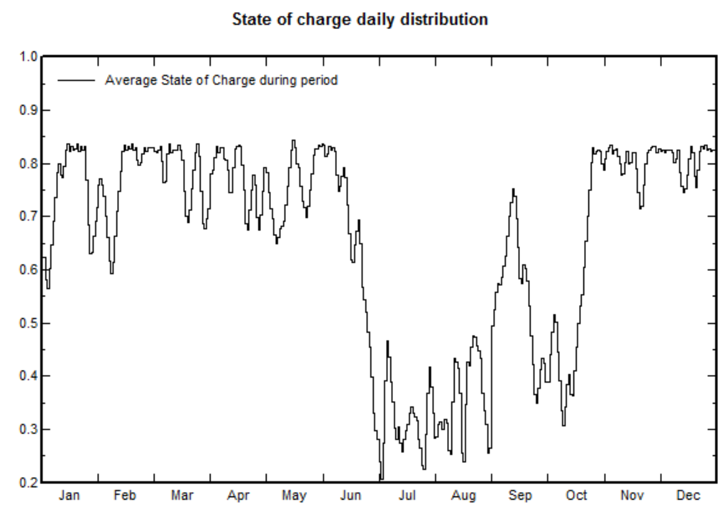
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

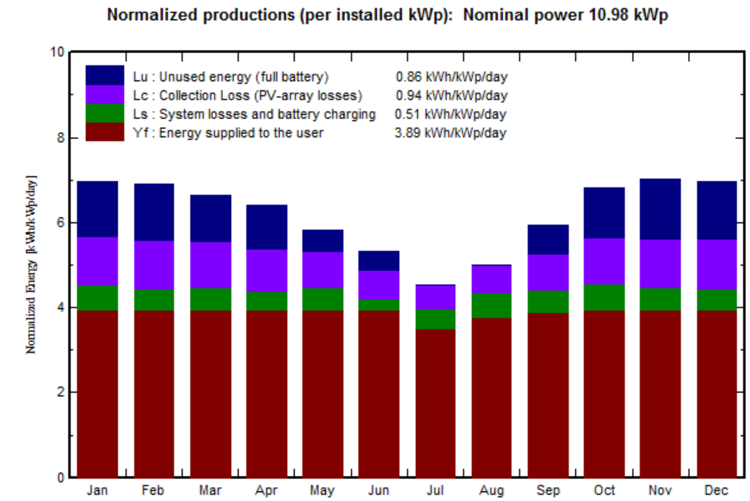


Normalized production at 3 days of autonomy

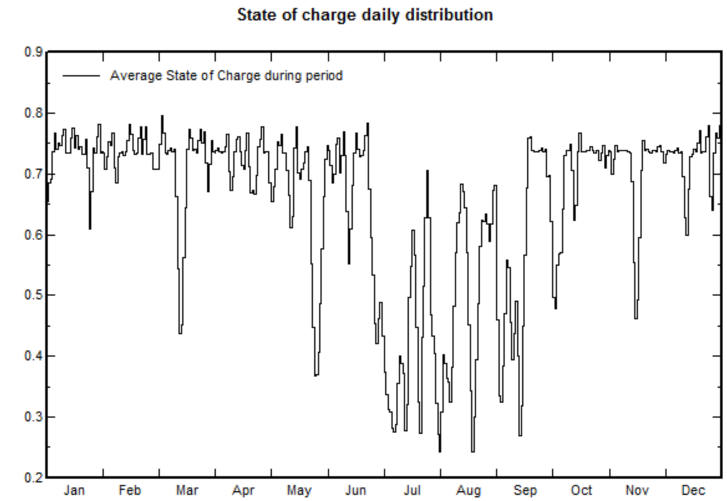


State of Charge of the battery at 3 days of autonomy

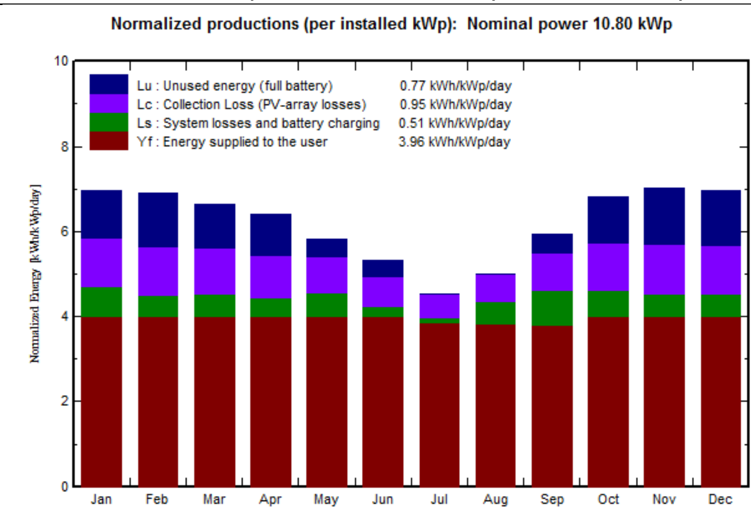
Secondary School – Bahir dar (Amhara region)



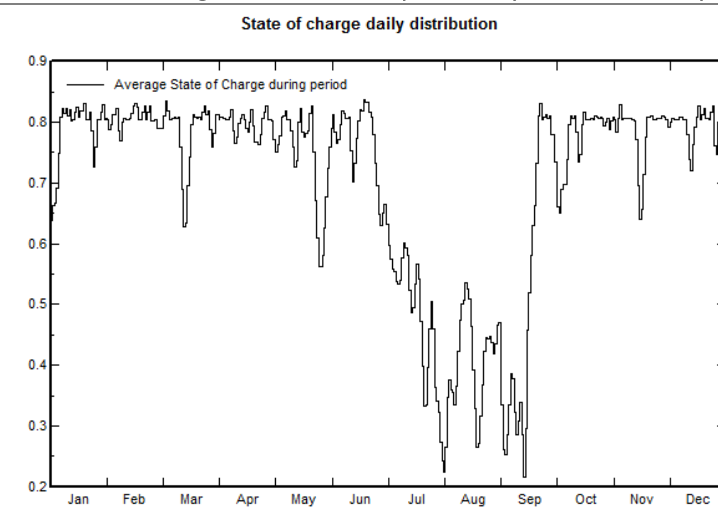
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

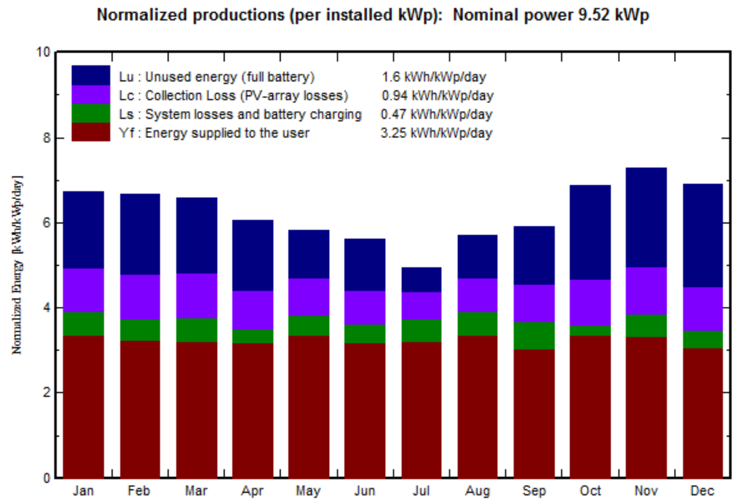


Normalized production at 3 days of autonomy



State of Charge of the battery at 3 days of autonomy

Secondary School – Adama (Oromia region)



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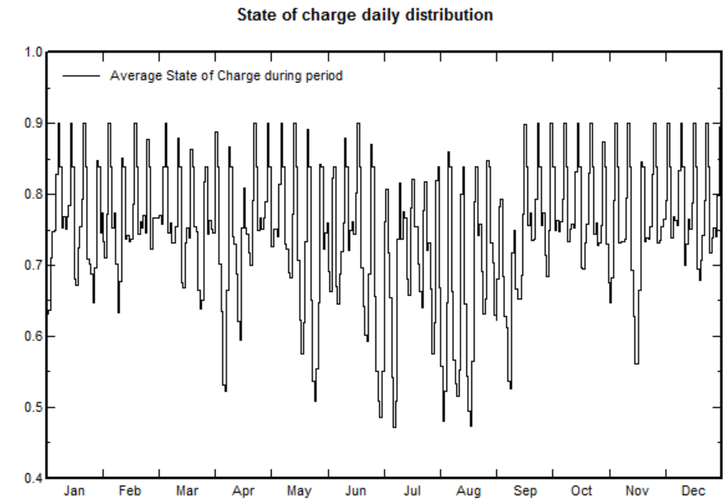
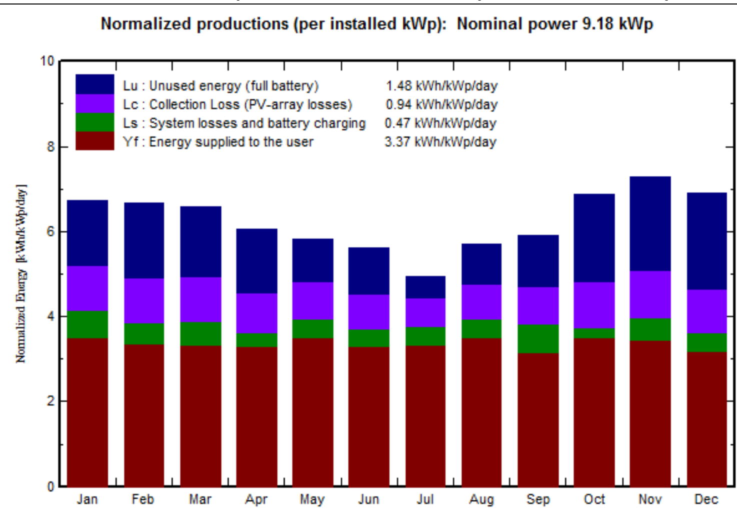
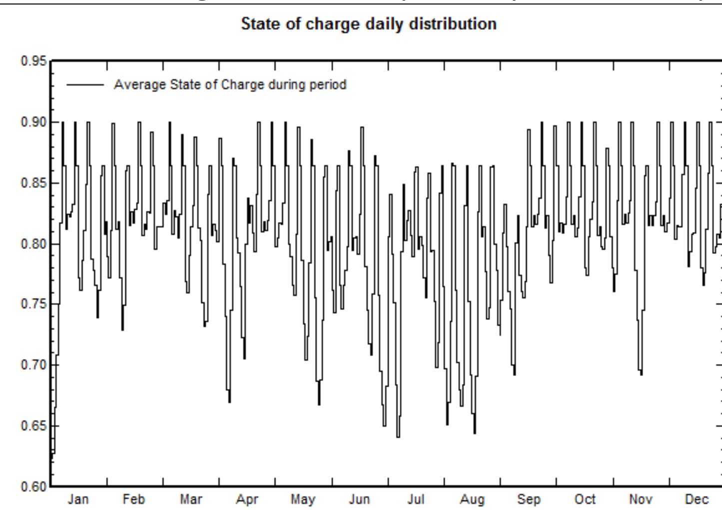


State of Charge of the battery at 2 days of autonomy

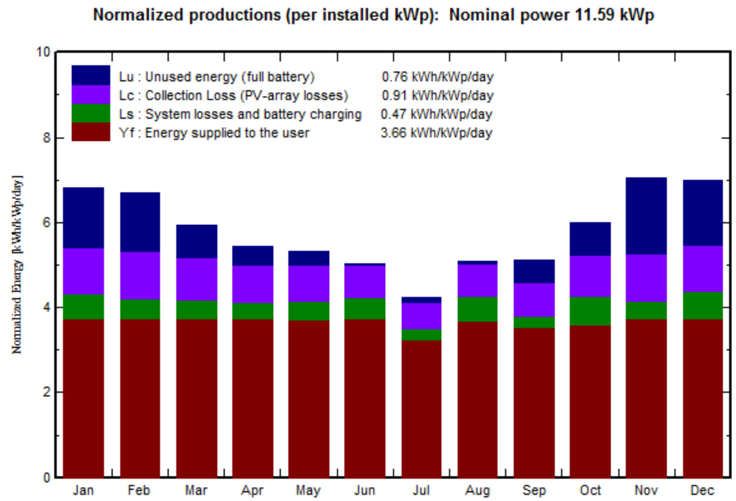


Normalized production at 3 days of autonomy



State of Charge of the battery at 3 days of autonomy

Secondary School – Hawassa (SNNP region)



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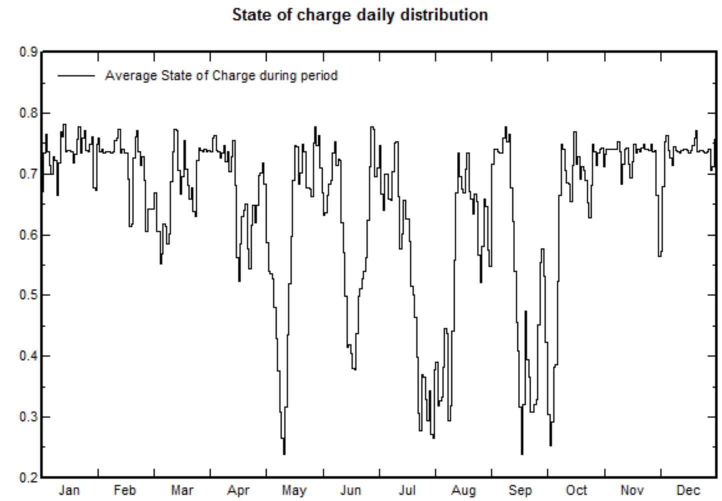
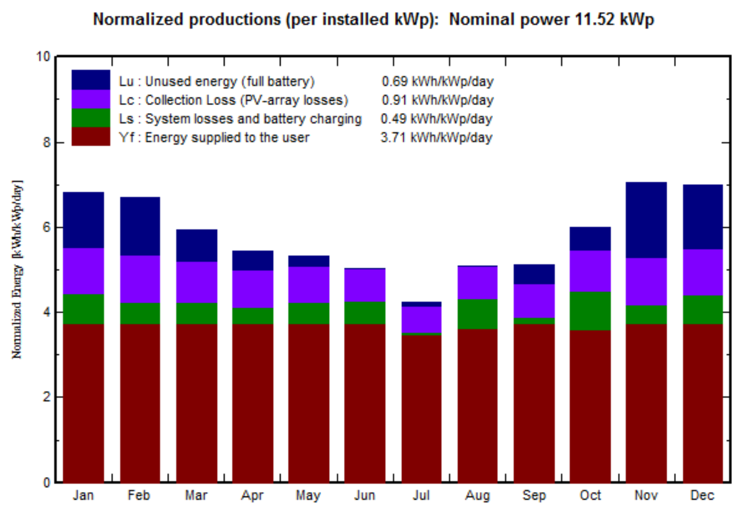
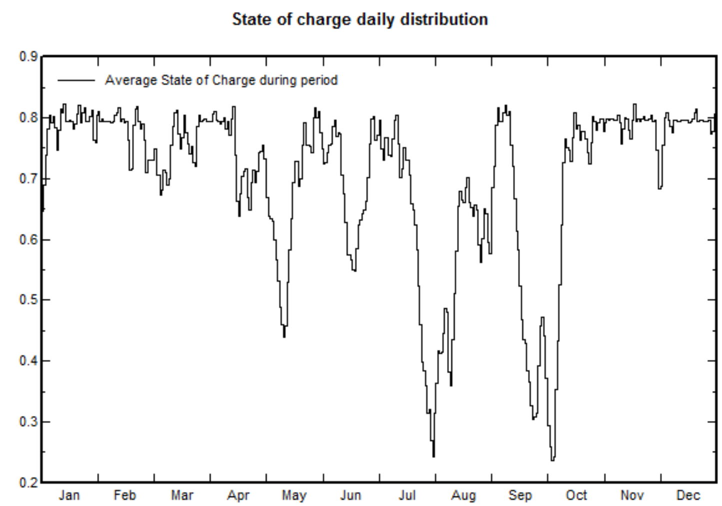


State of Charge of the battery at 2 days of autonomy

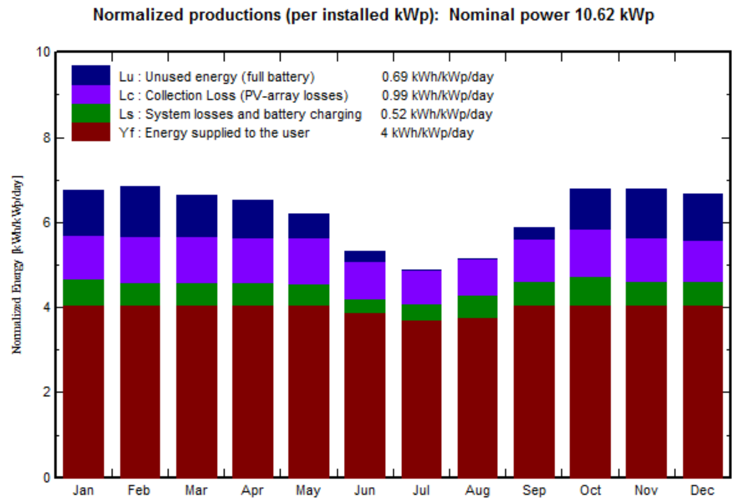


Normalized production at 3 days of autonomy

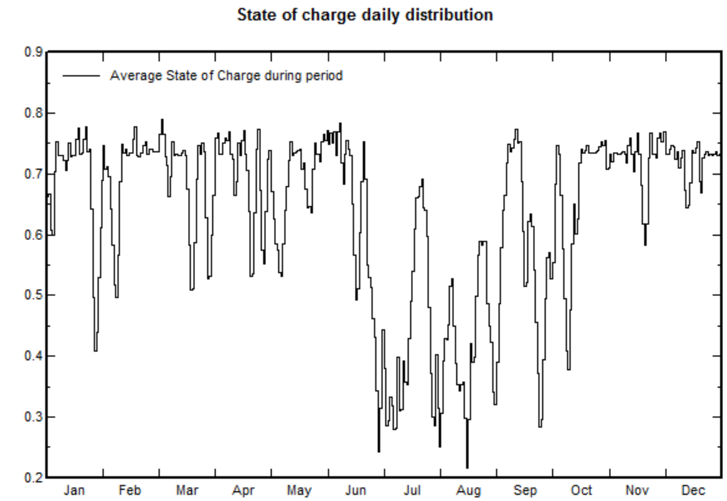


State of Charge of the battery at 3 days of autonomy

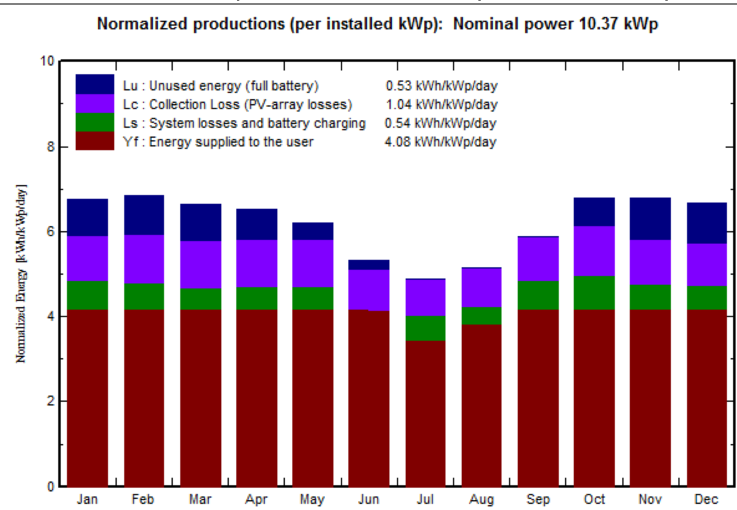
Secondary School – Mekele (Tigray region)



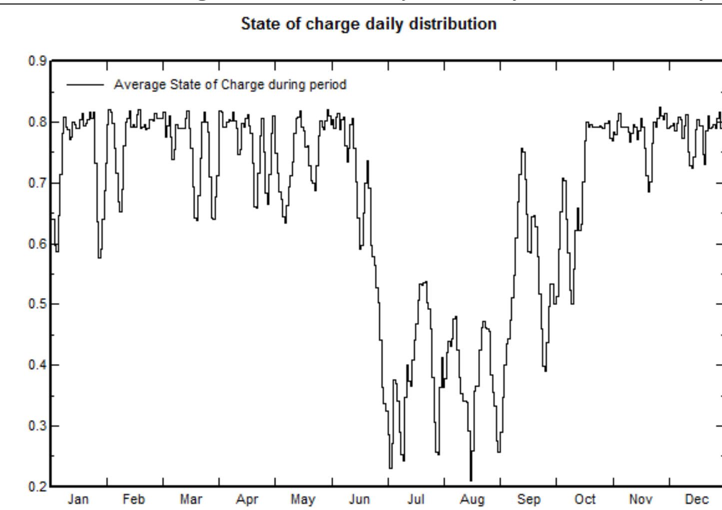
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

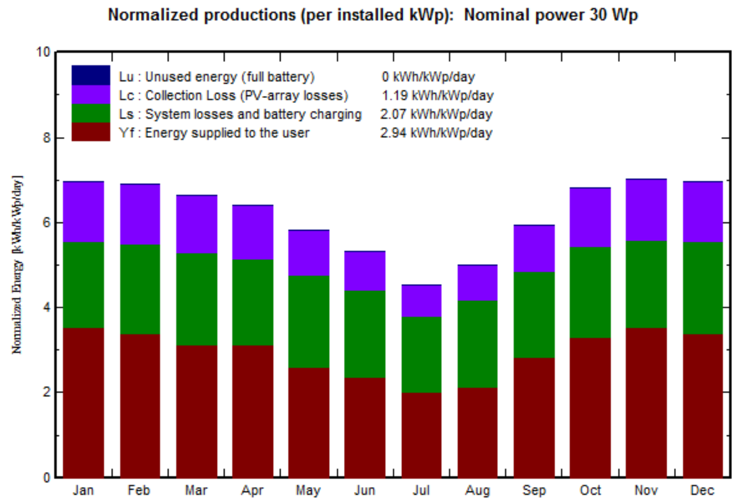


Normalized production at 3 days of autonomy

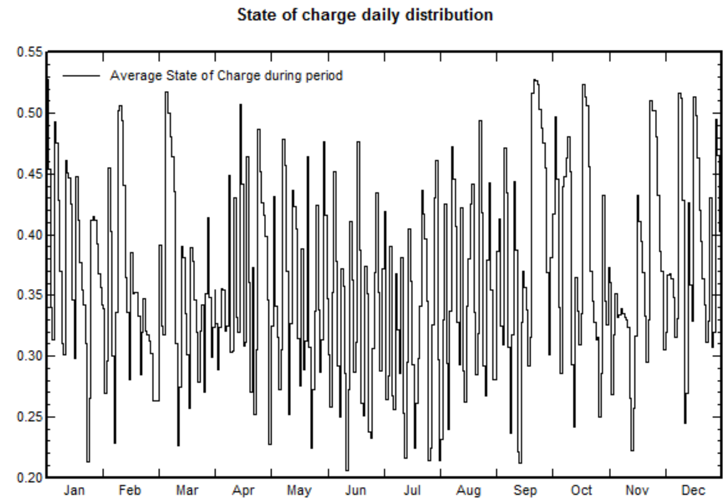


State of Charge of the battery at 3 days of autonomy

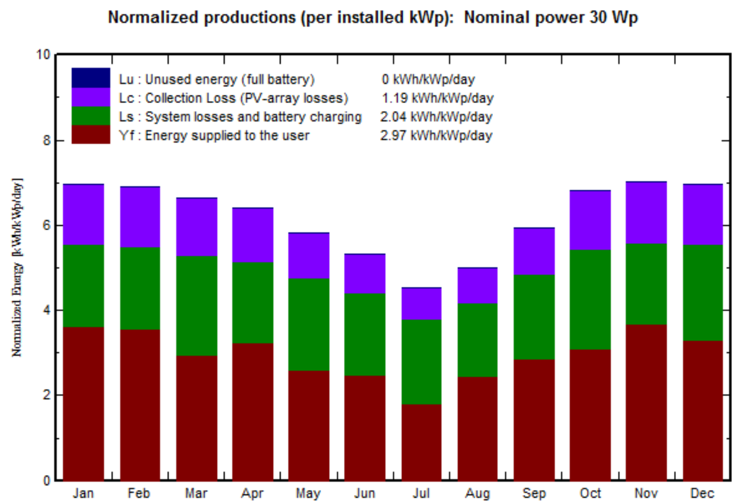
SHS Type 1 – Bahir dar (Amhara region)



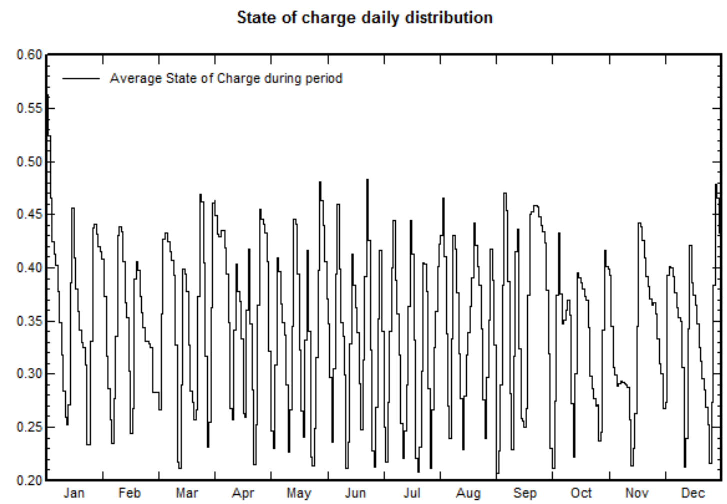
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

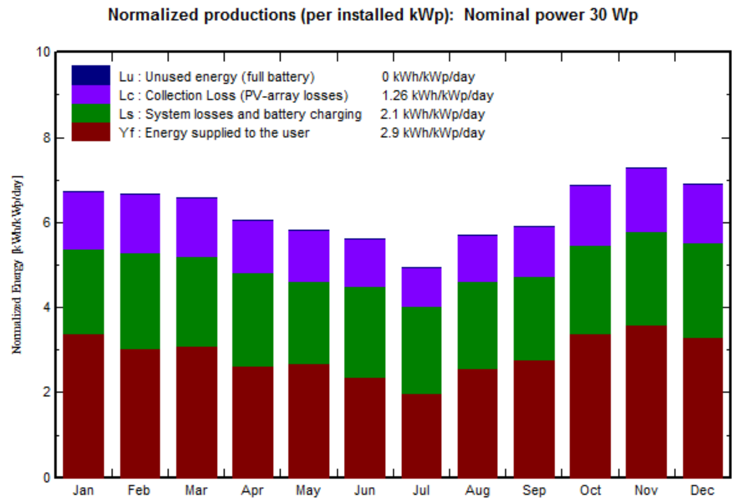


Normalized production at 3 days of autonomy

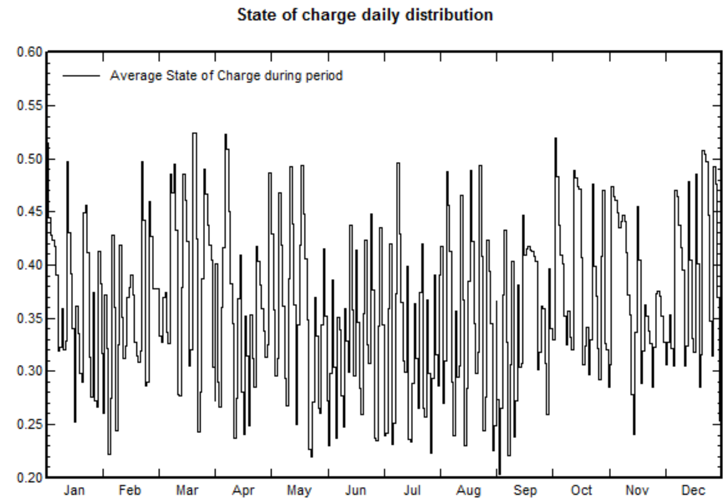


State of Charge of the battery at 3 days of autonomy

SHS Type 1 – Adama (Oromia region)



Normalized production at 2 days of autonomy



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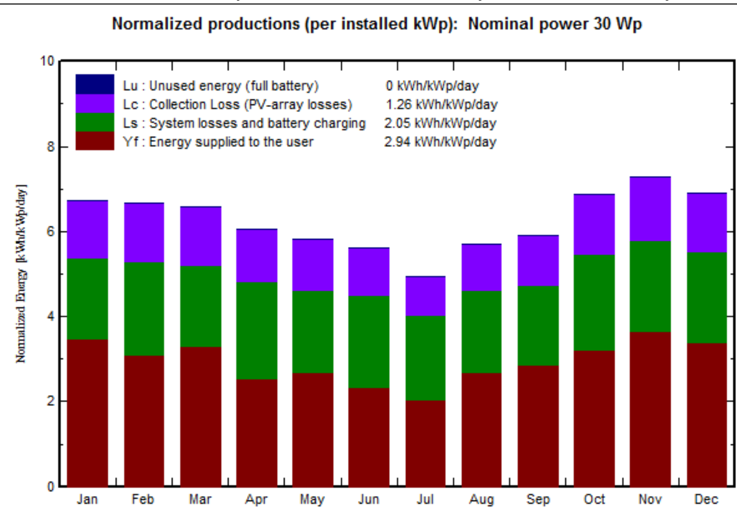
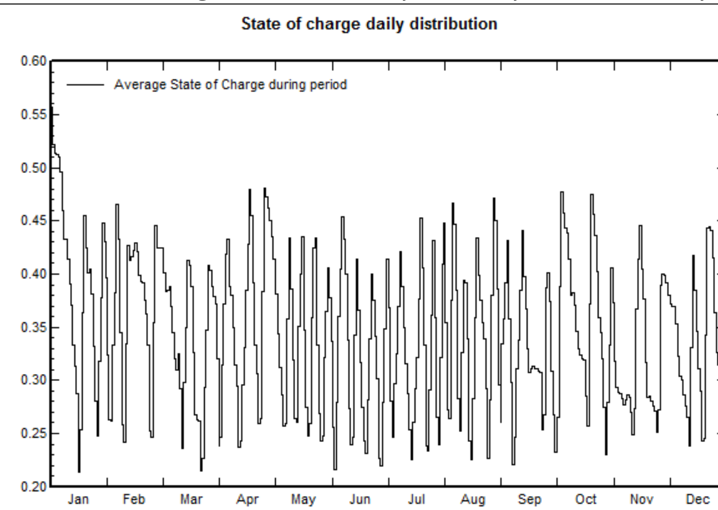
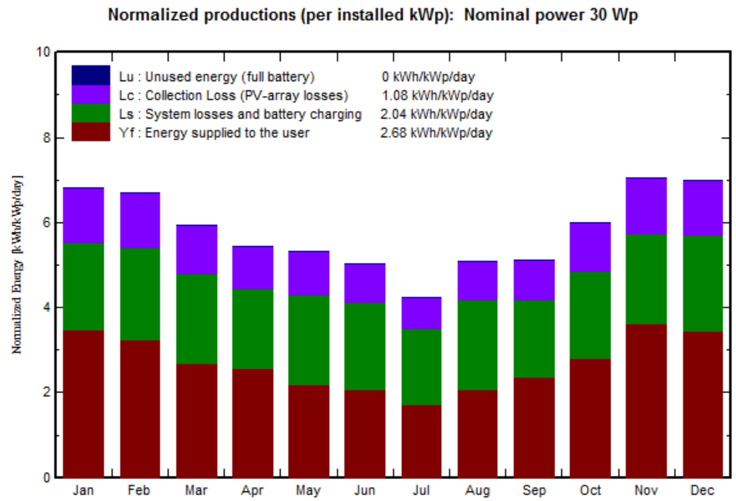


Normalized production at 3 days of autonomy

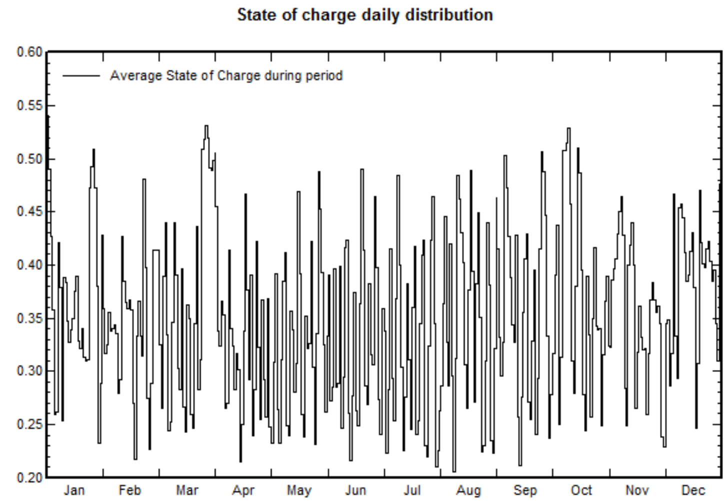


State of Charge of the battery at 3 days of autonomy

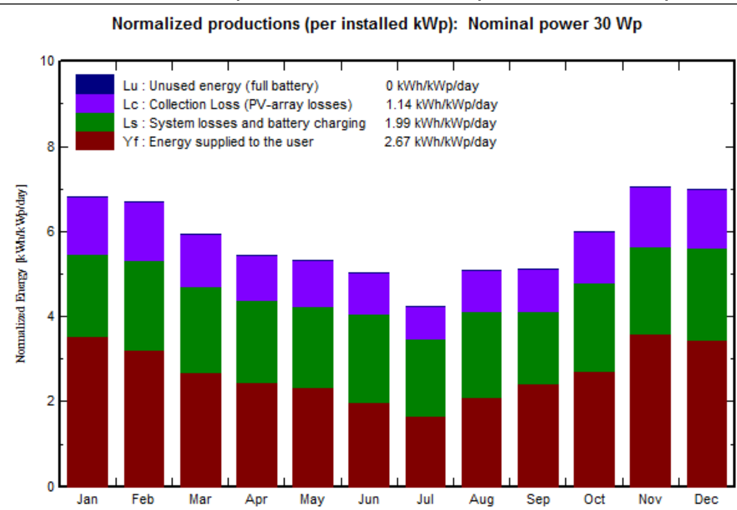
SHS Type 1 – Hawassa (SNNP region)



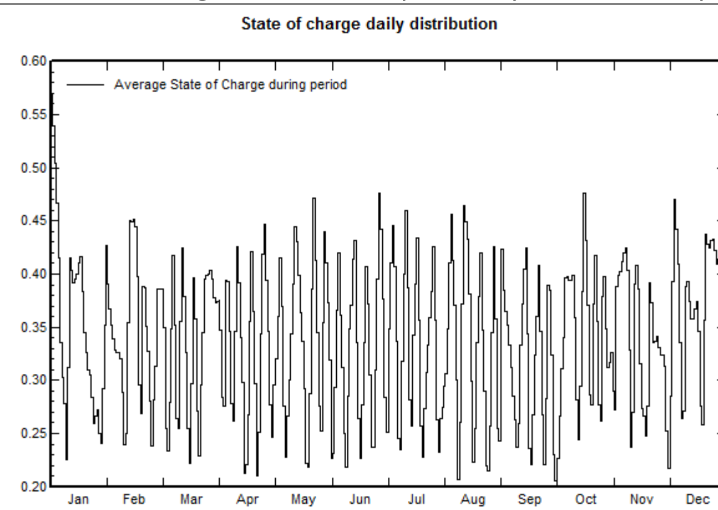
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

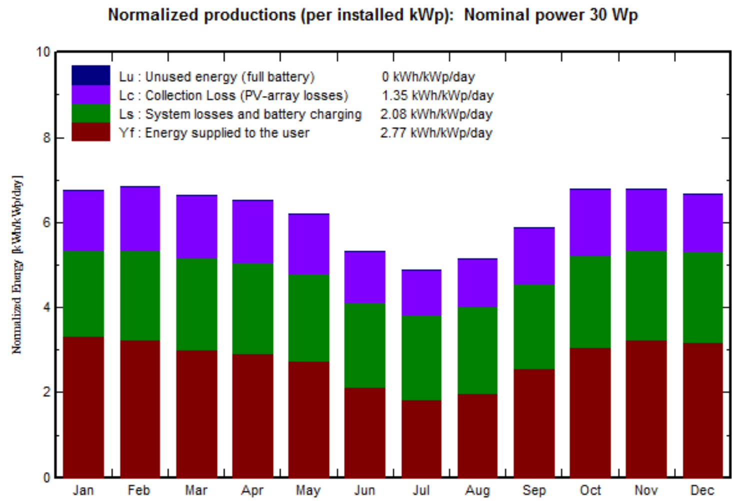


Normalized production at 3 days of autonomy

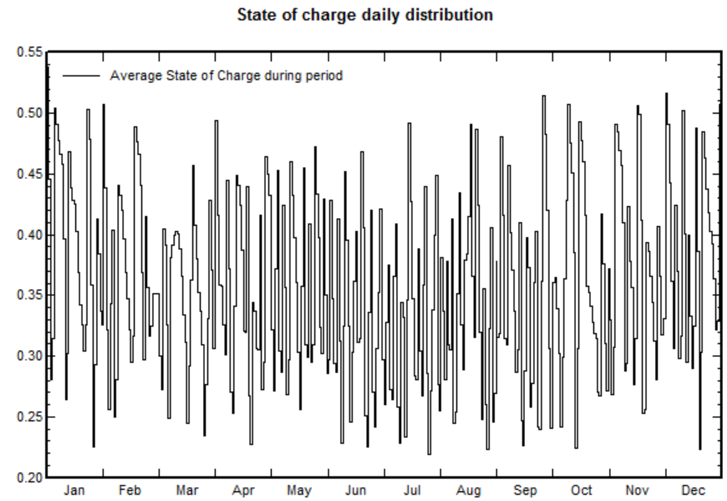


State of Charge of the battery at 3 days of autonomy

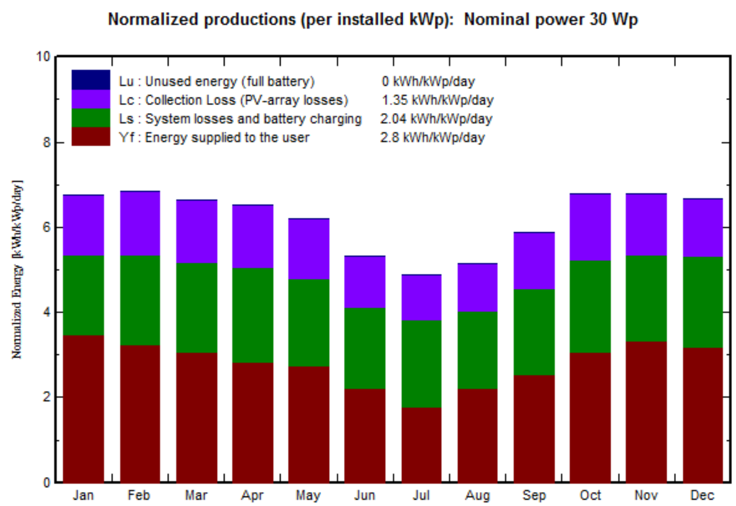
SHS Type 1 – Mekele (Tigray region)



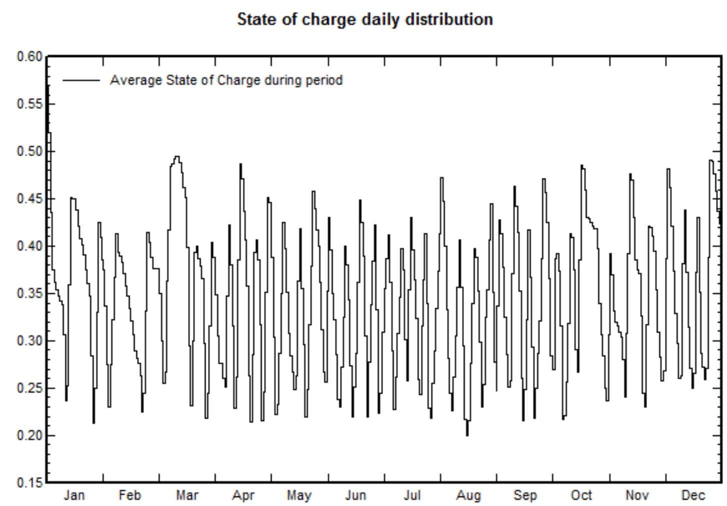
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

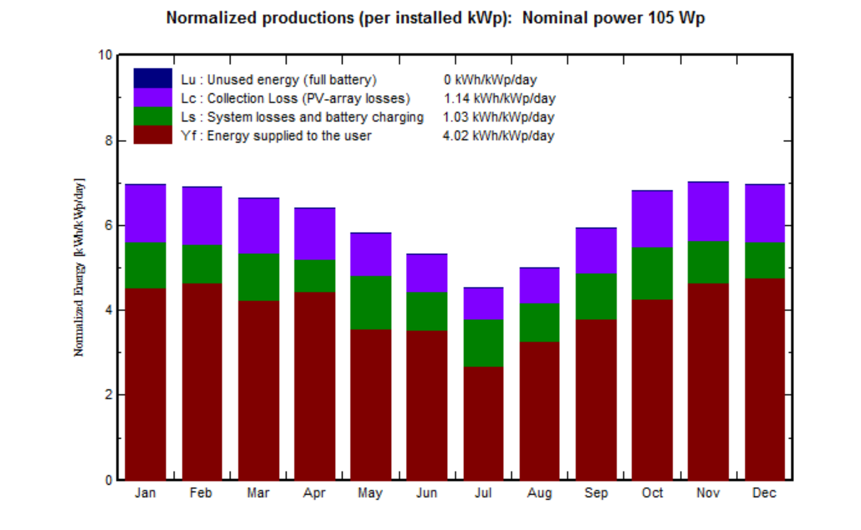


Normalized production at 3 days of autonomy

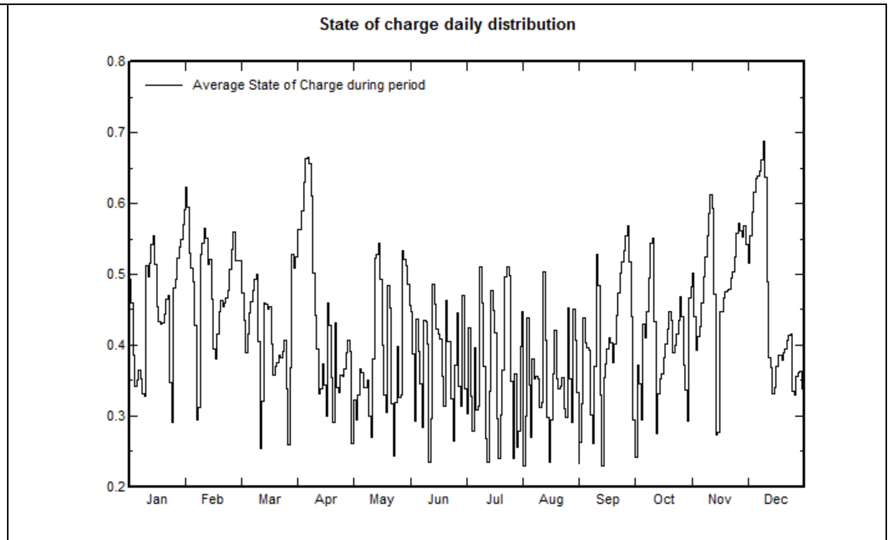


State of Charge of the battery at 3 days of autonomy

SHS Type 2 – Bahir dar (Amhara region)



Normalized production at 2 days of autonomy



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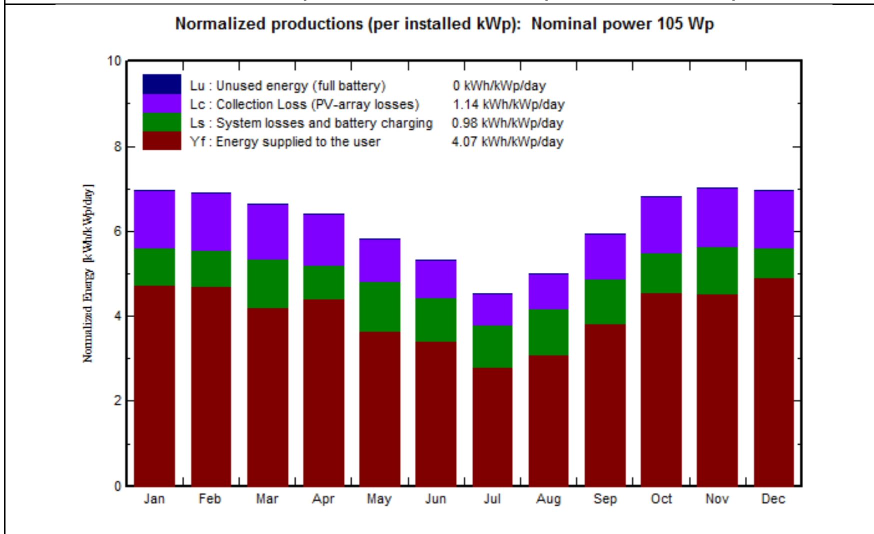
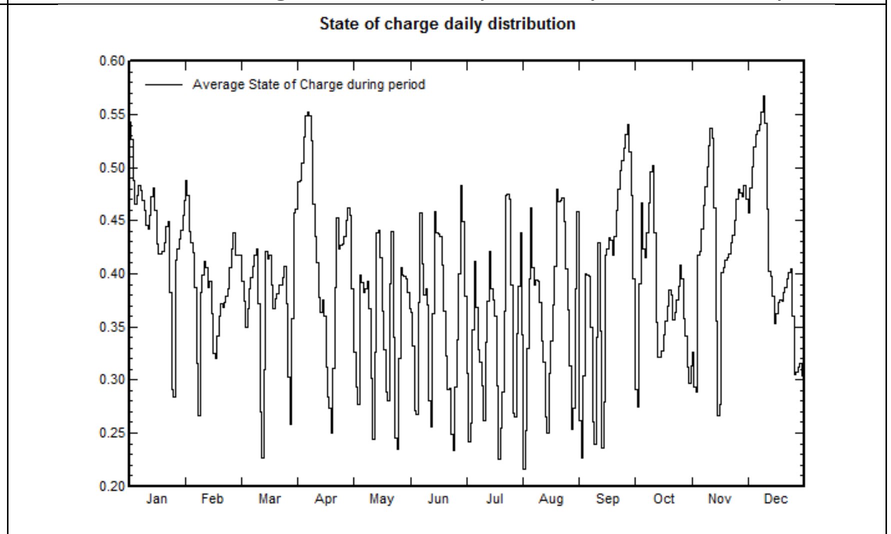
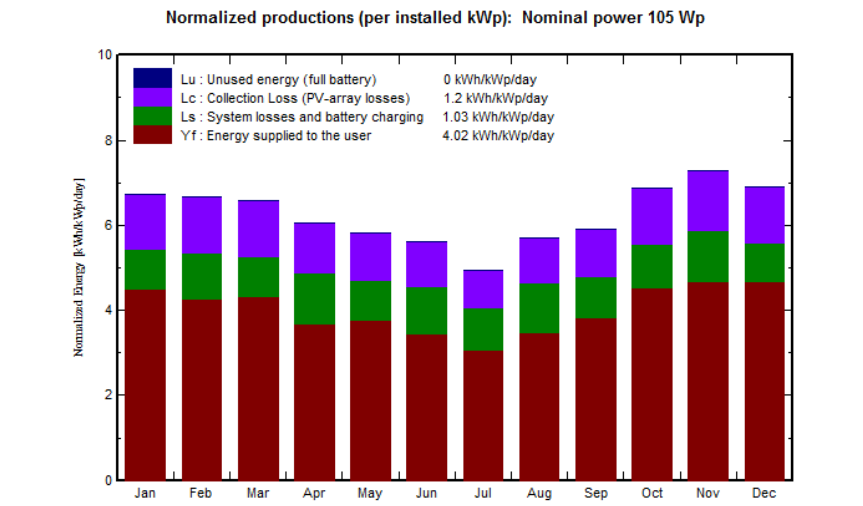


Normalized production at 3 days of autonomy



State of Charge of the battery at 3 days of autonomy

SHS Type 2 –Adama (Oromia region)



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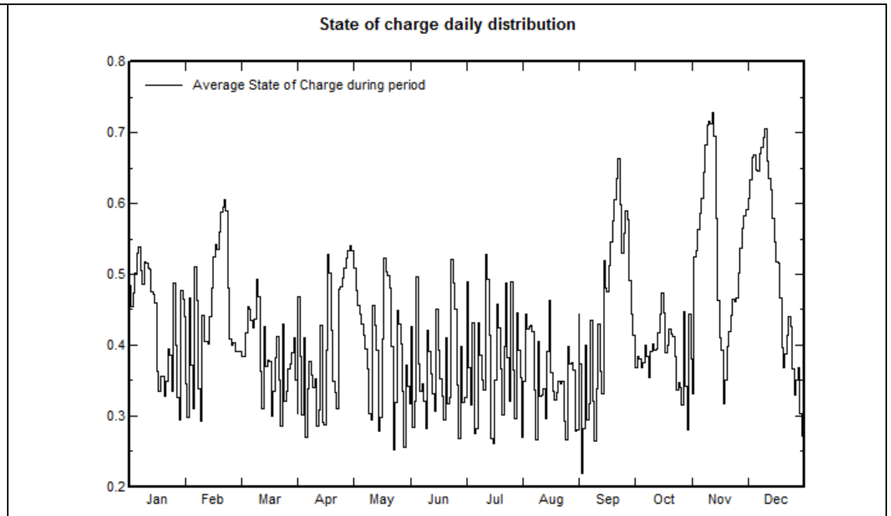

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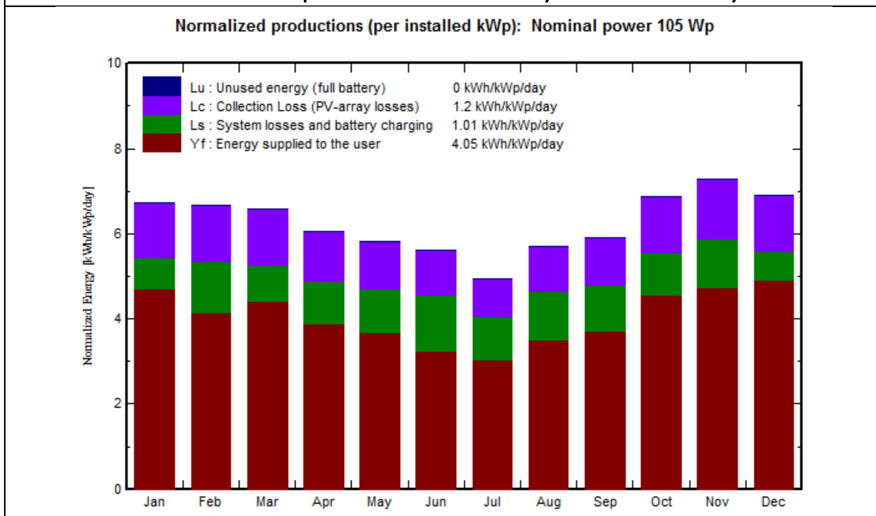
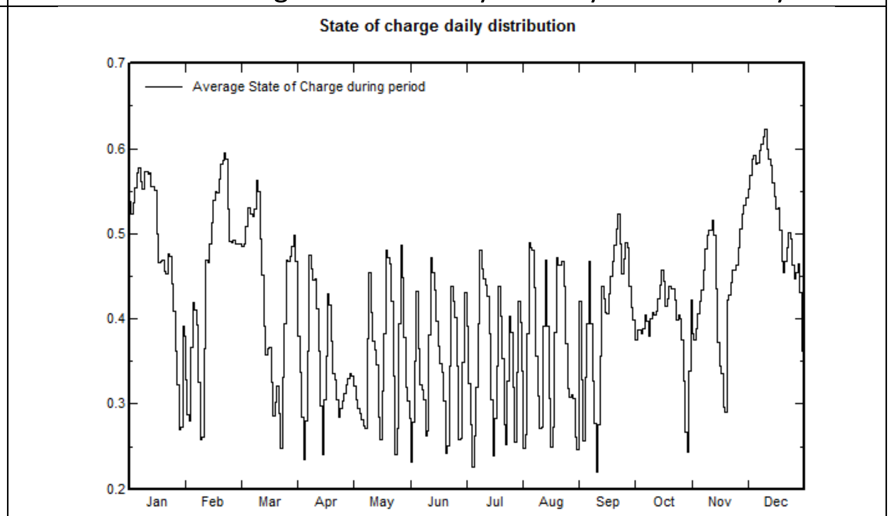
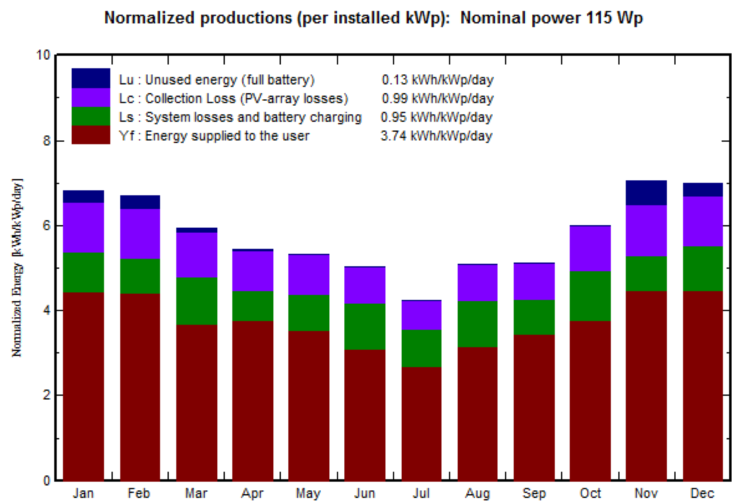


Normalized production at 3 days of autonomy



State of Charge of the battery at 3 days of autonomy

SHS Type 2 –Hawassa (SNNP region)



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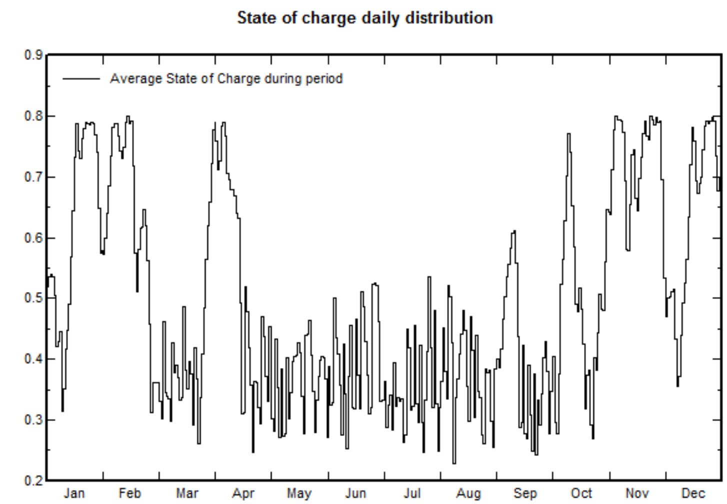
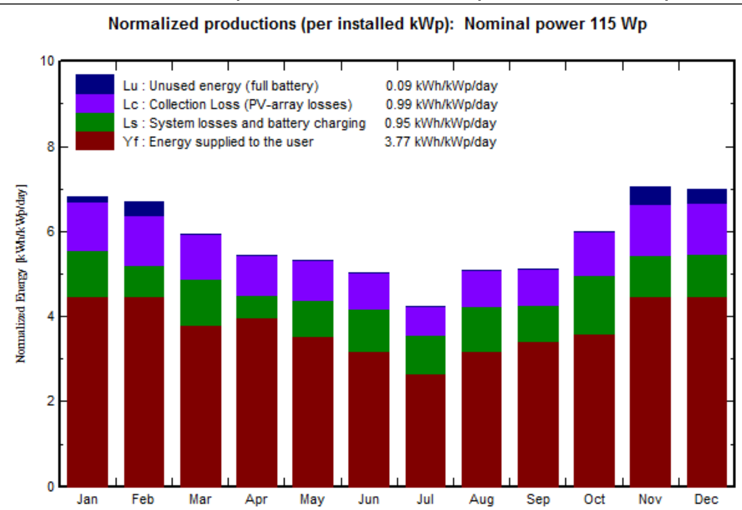
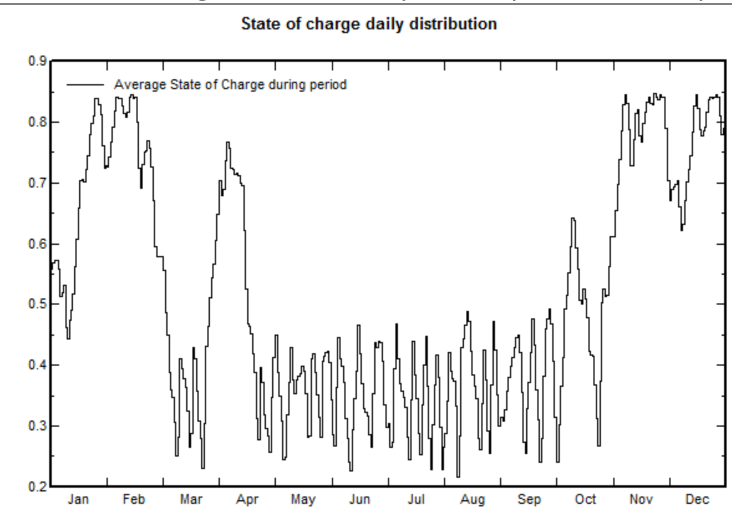


State of Charge of the battery at 2 days of autonomy

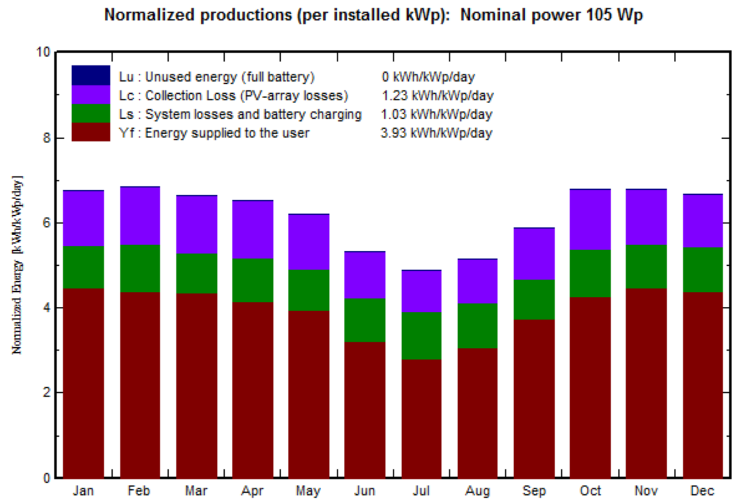


Normalized production at 3 days of autonomy

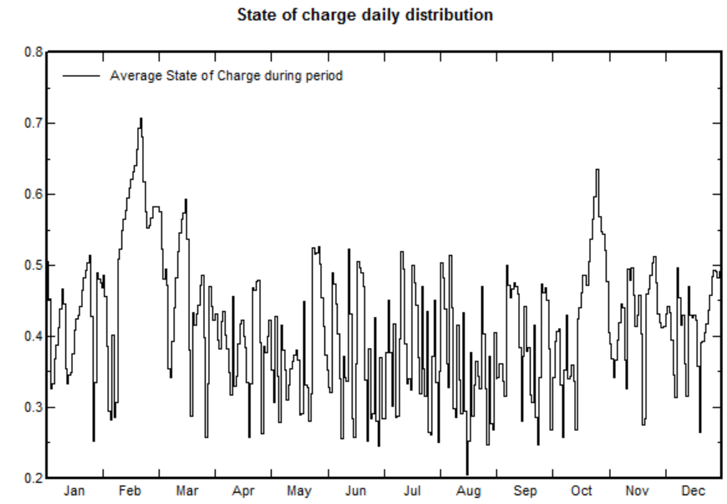


State of Charge of the battery at 3 days of autonomy

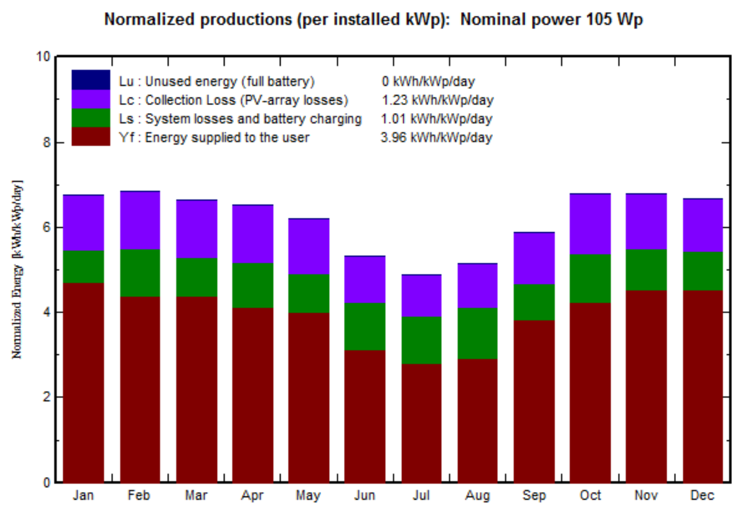
SHS Type 2 – Mekele (Tigray region)



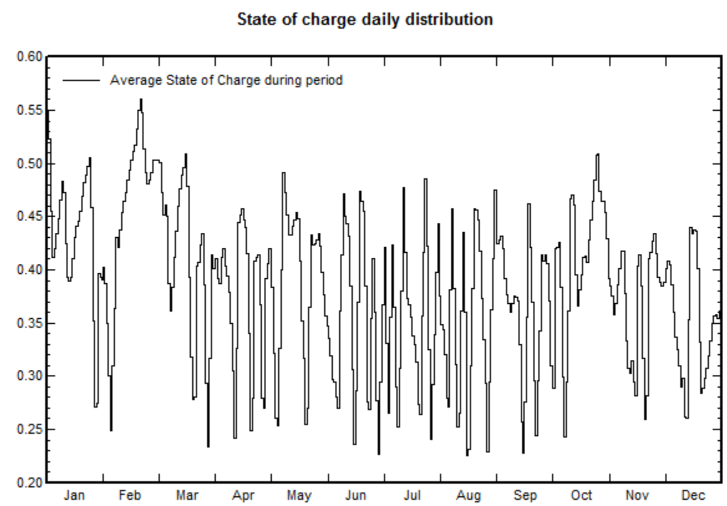
Normalized production at 2 days of autonomy



State of Charge of the battery at 2 days of autonomy

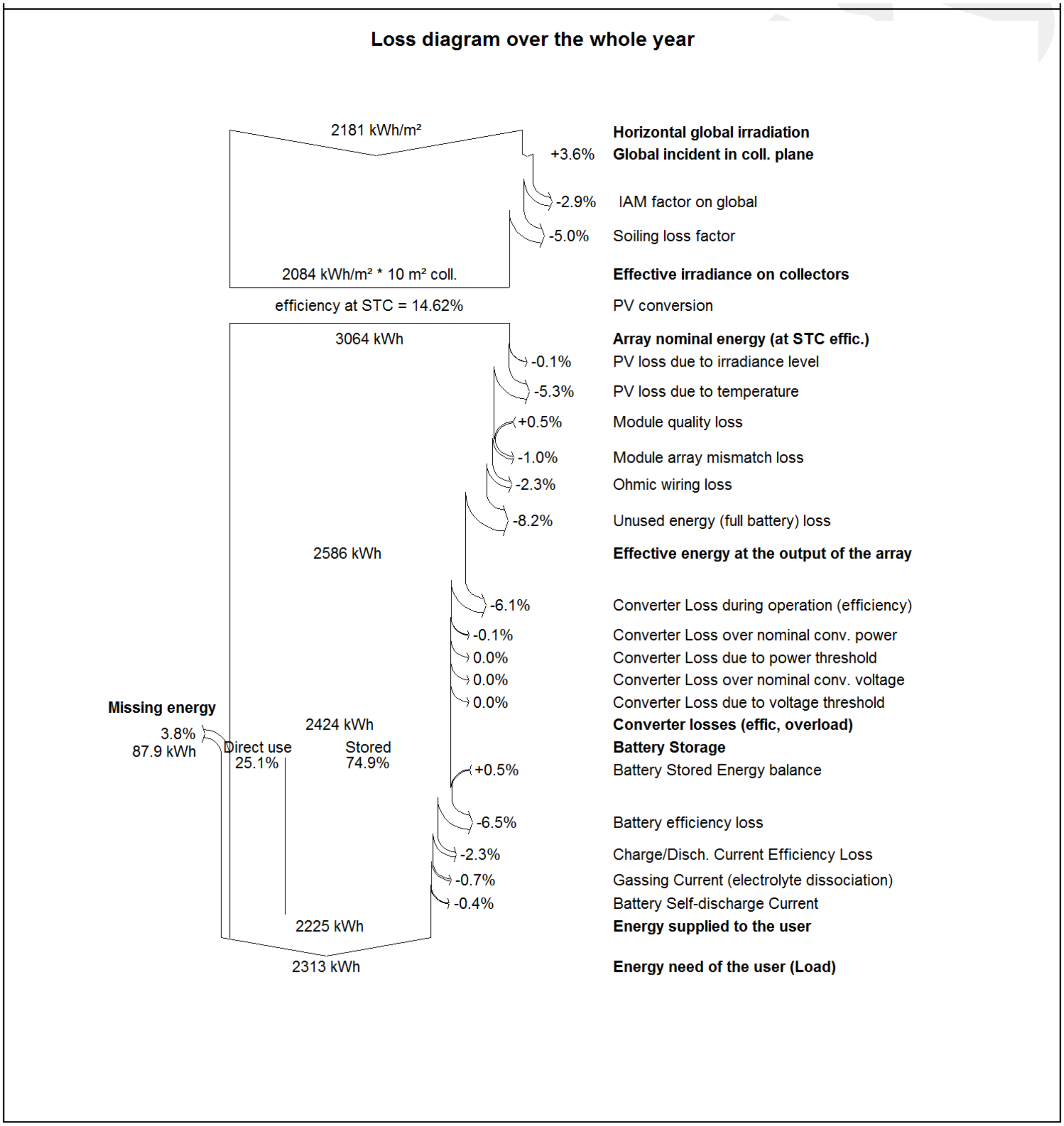


Normalized production at 3 days of autonomy



State of Charge of the battery at 3 days of autonomy

Detailed System Losses



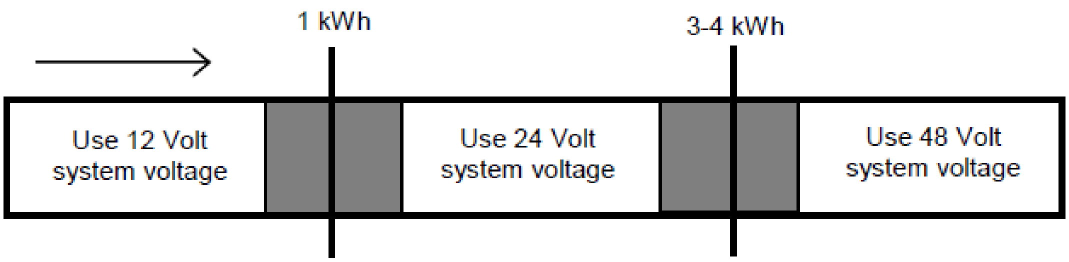
ANNEX-IV – Assumptions Used for the Design

Appliance	Primary school	Secondary school	Health post
Lamps	director room (1), library/teachers room (3), 1 classroom (4), outside light (2)	director room (1), library (5), classroom (8), outside light (2)	3 rooms (each 2 lights), outside light (2) and for delivery (1)
TV	For primary schools, TV is not assumed. For secondary schools, TV (Plasma) is definitely needed. The assumption is every classroom will get one and a minimum of 6 classrooms exist. ***Danger***: the schools could use for more number of hours than it is assumed for the design. The batteries will then down. ***Solution***: good follow up by project implementers.		Because health extension worker travels a lot, no TV necessary.
Radio / flash player	1 radio for staff (4h/d)	1 radio for staff (4h/d)	1 radio for HP staff
Computer	All cluster schools (primary) will get one. For secondary schools; 1 for the director room and 20 for computer labs. A minimum of 1 computer labs are assumed.		
Copy machine	For primary schools, the assumptions are if cluster schools will be delivered a copy machine. All secondary schools definitely need them. ***Danger***: the schools still used them for longer duration than thought and the battery is empty too much. ***Solution***: good follow up service by project implementers and give manuals & good instruction to the right personnel (e.g.: cleaning staff, guards-people that stay there for many years (teachers often only stay for a few years)		
Refrigerator			Fridges given out from government are TCW 3000 (1.32 kwh/24hr), RCW 50 EK (2.46 kwh/24h)and SIBIR (6.3kwh/24h). *TCW 3000 has been assumed for the design.*

Input Parameters for Battery Sizing

Description	Symbol	SHS	School		Health Facilities	
			Primary	Secondary	HC	HP
Operating Voltage	V	12	12	48	24	48
Days of Autonomy	day	2	2	2	3	3

Range of KWh for system voltage selection [39]



ANNEX-V – Questionnaire Used for the Survey

Different sets of questionnaires were developed for gathering the necessary information from off-grid rural households and institutional facilities such as schools, health centers and health posts. The questionnaires were designed to collect the following information:

- Gather the general information about the respondent, SHS user/institutional PV system operator,
- Geographical information about the site,
- General information about the household/institution,
- Technical data about the installed solar PV system,
- Usage of the solar system,
- General information about system performance and basic energy services,
- Advantages and disadvantages of the installed system,
- The loads currently used in the household and institutions
- The loads expected by the household when the solar PV comes

There were open ended questions for the PV system user that were designed to gather information on:

- The impact the solar PV system on
    - Access to information
    - Income generation
    - Education for the students
    - Time availability to work, security from thief and gender levels
- Satisfaction level
    - Expectation from the PV system before its arrival
    - Did it the expectations met?
    - System failures in the past
- Possible end use
    - Other expectation from the solar system, such as additional appliance
    - Ability to upgrade the system to use electrical equipment's

After the questionnaire has been drafted, it was applied in the different regions described in the introduction. The field visit has been conducted using two teams under different circumstances.

ANNEX -VI –Data and Pictures Collected During the Survey

- SHS users including system performance details from different Woredas

Data collected from Minjar and Shenkor Woreda energy bureau

No.	Name of SHS user	Cooperative Name	Kebele	PV capacity	Problem identified
1	Ato Ketema Goshime	Adama Berhan	Adama	10Wp	Lamp failure and panel problem
2	Ato Fikre Mogese	Adama Berhan	Adama	10Wp	Battery problem
3	Ato Adugnaw Kebede	Adama Berhan	Adama	8Wp	Battery problem
4	Ato Tedila Terefe	Adama Berhan	Adama	130Wp	Inverter problem
5	Ato Minda Lema	Adama Berhan	Adama	130Wp	Inverter problem
6	W/ro Sisay Abebe	Adama Berhan	Adama	10Wp	Battery exchanged but has failed again
7	Ato Gebeyehu Negash	Addis Alem	Dire	60Wp	Battery charge problem
8	Ato Abeb Yismu	Addis Alem	Dire	10Wp	Battery problem
9	Ato Dereje Sisay	Addis Alem	Dire	10Wp	Battery charge problem
10	Ato Misrat Kifle	Addis Alem	Dire	10Wp	Battery problem
11	Ato Tafese Kidane	Addis Alem	Dire	10Wp	Problem unknown
12	Ato Abera Getachew	Addis Alem	Dire	8Wp	Battery problem
13	Ato Aweke Habte	Enideg	Kiticha	10Wp	Lamp problem
14	Ato Mamush Tsegaye	Enideg	Kiticha	130Wp	Switch problem
15	Ato Endeshaw Tesfaye	Enideg	Kiticha	10Wp	Battery problem
16	Ato Denbelash Belete	Chele	Chele	10Wp	Lamp problem
17	Ato Weyfene Yeshaw	Chele	Chele	10Wp	Battery exchanged but has failed again
18	Ato Gebeyehu Getachew	Chele	Chele	10Wp	Battery problem
19	W/ro Emiyenesh Gormu	Chele	Chele	10Wp	Battery exchanged but has failed again
20	Ato Engidaw	Chele	Chele	10Wp	Lamp problem

	Amide				
21	Ato Bekele Feru	Chele	Chele	10Wp	Battery problem
22	Ato Zena W/Mariam	Chele	Chele	10Wp	Battery problem
23	Ato Alemayehu Zeleke	Chele	Chele	10Wp	Lamp problem
24	Ato Asfaw Amene	Addis Alem	Dire	10Wp	Battery exchanged but has failed again
25	Ato Girma Dessalegn	Addis Alem	Dire	8Wp	Battery exchanged but has failed again
26	Ato Deboch Zergaw	Chereka Gibat	Choba	8Wp	Problem unknown
27	Ato Asimamaw Sisay	Chereka Gibat	Choba	60Wp	Lamp not installed, due to cable shortage during installation
28	Ato Asegid Sisay	Chereka Gibat	Choba	60Wp	Problem unknown
29	Ato Anbes Zebene	Enideg	Kiticha	10Wp	Lamp problem
30	Ato Minda Emishaw	Enideg	Kiticha	10Wp	Lamp problem
31	Ato Adinew Getachew	Enideg	Kiticha	10Wp	Problem unknown
32	Ato Kebede Mekasha	Adama Berhan	Adama	8Wp	Problem unknown
33	Ato Asaminew Siyoum	Chele	Chele	10Wp	Battery problem
34	Ato Mulugeta Abera	Chele	Chele	10Wp	Battery problem
35	Ato Begashaw Tilahun	Chele	Chele	10Wp	Mobile charging problem
36	Ato Nigat Kebede	Chele	Chele	10Wp	Mobile charging problem
37	Ato Taye Feru	Chele	Chele	8Wp	Battery problem
38	Ato Tarekegn Ejigu	Chele	Chele	10Wp	Battery problem
39	Ato Kabtamu Takele	Chele	Chele	10Wp	Lamp problem
40	Ato Haile Tsega	Chele	Chele	8Wp	Battery problem
41	Ato Bilew Dirib	Chele	Chele	10Wp	Lamp problem
42	Ato Adinew Wendiyifra	Enideg	Kiticha	10Wp	Mobile charging problem

43	Ato Lishanu Fetene	Enideg	Kiticha	10Wp	Battery problem
44	Ato Gizaw Deneke	Enideg	Kiticha	10Wp	Battery problem
45	Ato Demewez Dessalegn	Enideg	Kiticha	8Wp	Battery problem
46	Ato Adinew Getachew	Enideg	Kiticha	10Wp	Mobile charging problem
47	Ato Ayitenfisu Tadele	Adama Berhan	Adama	10Wp	Battery problem
48	W/ro Almaz Birhane	Adama Berhan	Adama	10Wp	Battery problem
49	Ato Ahmed Nur Suhali	Chereka Gibat	Choba	8Wp	Mobile charging problem

Data collected from Mukiye Haro cooperative

No.	Name of SHS user	Cooperatives Name	PV capacity	Problem identified
1	Abachere Mengesha	Mukiye Haro	40Wp	Mobile charging problem
2	Tadesse Mengesha	Mukiye Haro	40Wp	Mobile charging problem
3	Rugle Belayneh	Mukiye Haro	40Wp	Mobile charging problem
4	Birke Bedada	Mukiye Haro	40Wp	Mobile charger and lamp failure
5	Shito Girma	Mukiye Haro	40Wp	Lamp problem
6	Mulat Moges	Mukiye Haro	20Wp	Lamp problem
7	Fagule	Mukiye Haro	40Wp	Battery problem
8	Kebebu Ameha	Mukiye Haro	40Wp	Lamp problem
9	Mekonen Sera	Mukiye Haro	40Wp	Battery problem
10	Dexe	Mukiye Haro	40Wp	Lamp problem
11	Shimelis Leta	Mukiye Haro	20Wp	Battery problem
12	Yifira Gezahegn	Mukiye Haro	20Wp	Mobile charger and lamp failure
13	Negussie Tiruneh	Mukiye Haro	40Wp	Lamp problem
14	Abi Fagule	Mukiye Haro	40Wp	Battery problem
15	Kasa Bedada	Mukiye Haro	40Wp	Lamp problem
16	Gizaw Mekonen	Mukiye Haro	40Wp	Battery problem
17	Eshet Wude	Mukiye Haro	40Wp	Battery problem
18	Belay Tilahun	Mukiye Haro	60Wp	Battery charger problem
19	Jema Telila	Mukiye Haro	40Wp	Battery problem
20	Tegenu Regassa	Mukiye Haro	10Wp	Battery and lamp problem
21	Fekadu Gebru	Mukiye Haro	20Wp	Battery problem
22	Aselefu Geremew	Mukiye Haro	20Wp	Battery problem

23	Gessese Demessie	Mukiye Haro	10Wp	Battery problem
24	Bekele Abebe	Mukiye Haro	40Wp	Charger problem
25	Gizaw Abebe	Mukiye Haro	40Wp	Charger problem
26	Kebede Roresa	Mukiye Haro	20Wp	Lamp problem
27	Demeke Tezera	Mukiye Haro	20Wp	Battery problem
28	Lema Debebe	Mukiye Haro	40Wp	Lamp problem
29	Shemu Mekonen	Mukiye Haro	40Wp	Battery charger
30	Mesfin Mekonen	Mukiye Haro	40Wp	Lamp problem
31	Agezew Kebede	Mukiye Haro	40Wp	Lamp problem
32	Mestawet Demessie	Mukiye Haro	10Wp	Charger problem
33	Tadesse Tamiru	Mukiye Haro	40Wp	Battery problem
34	Tilahun Wude	Mukiye Haro	40Wp	Battery problem
35	Gezahegn Asfaw	Mukiye Haro	40Wp	Battery problem
36	Zewedu Wel.N.	Mukiye Haro	40Wp	Battery problem
37	Tamiru Teli	Mukiye Haro	40Wp	Battery problem
38	Tilahun Dadi	Mukiye Haro	40Wp	Battery problem
39	Dechew Leta	Mukiye Haro	40Wp	Battery problem
40	Sisay Bekele	Mukiye Haro	40Wp	Battery problem
41	Tadesse Kassa	Mukiye Haro	20Wp	Battery problem
42	Shimelis Seyoum	Mukiye Haro	40Wp	Battery problem
43	Taye Abebe	Mukiye Haro	40Wp	Battery problem
44	Bekele Teka	Mukiye Haro	20Wp	Battery problem
45	Tilahun Abebe	Mukiye Haro	40Wp	Battery problem
46	Sahilu Eshete	Mukiye Haro	40Wp	Battery problem
47	Lakew Haile	Mukiye Haro	40Wp	Battery problem
48	Girma Awosa	Mukiye Haro	40Wp	Battery problem
49	Haro Giorgis	Mukiye Haro	40Wp	Battery problem
50	Keme Ero	Mukiye Haro	40Wp	Battery problem
51	Tefu Haile	Mukiye Haro	40Wp	Lamp problem
52	Debebe Zewde	Mukiye Haro	40Wp	Lamp problem

Inspected schools in SNNPR [MoWIE 2012]

S/N	**Zone**	**Woreda**	**Name of primary school**	**Summary of observed problems**
1	Amaro special	Amaro special	Amaro Medyne	- Grounding system is not proper (not covered with cement at the level it runs on the ground to connect it to the earthing rod).
2	Burji special	Burji special	Halame	
3	South omo	South Ari	Shepi	
4	South omo	Bena Tsemay	Mukecha	
5	Konso special	Konso	Messoya	

6	Dereshe special	Dereshe special	Kola mashile	- PV array tilt angle is not correct. - Poor installation(cable run diagonal and cable clamps are not at regular intervals) - Lanterns are not working properly (Their brightness decrease with charge discharge cycles and some are totally not functional). - No conduits are used in some installations. - DB and Battery Box are not grounded. - PV array support structure is not tightly fixed to the roof beam.
7	Gamo Gofa	Kucha	Sochora	
8	Gamo Gofa	Dermalo	Menena Abaya	
9	Gamo Gofa	Oyda	Ubadama	
10	Wolayita	Duguna Fango	Fango sore Dega	
11	Dawaro	Tocha	Ganidenefa	
12	Dawaro	Essera	Shada Tela	
13	Kembata Tembaro	Angacha	kuyea	
14	Halaba special	Halaba special	Mito Dubela	
15	Silte	Sankura	Deneba	
16	Silte	Sankura	Woteta	
17	Silte	East Azernet	Goda	
18	Hadiya	Gibe	Keseda kodada	
19	Hadiya	Soro	Kecha	
20	Hadiya	Soro	Denetora	
21	Hadiya	Shashago	Jora	
22	Hadiya	Dawacho	1st kotto	
23	Gurage	Kebbena	Wetign	
24	Gurage	Ezzia	Yegobet	
25	Gurage	Ezzia	Wort	
26	Gurage	Gutazer Welene	Huter	
27	Gurage	Enemor Ener	Kanas	

Inspection area, component voltage output and System status for health post [30]

No.	Region	Zone	Woreda	Name of health post	Batt. Voltage output	Charge controller voltage output	Inverter voltage output	PV voltage output	System status
1	SNNPR	Sidama	Arbegona	Charicho	4.9V	0V	0v	19.2V	Non Functional
2	SNNPR	Sidama	Arbegona	Arbegona Shashoncho	4.51V	0V	0V	19.2V	Non Functional
3	SNNPR	Sidama	Laka Abeya	Abeya Zuria	0v	0v	Inverter burnt	Wires are disconnected	Non Functional

4	SNNPR	Sidama	Aleta Wondo	Kila Hikicha	0v	0v	0v	19.3V	Non function
5	SNNPR	Sidama	Hawasa Zuria	Jara Hinesa	0v	0v	0v	19.5V	Functional
6	SNNPR	Sidama	Chuko	Gambella	0v	0v	0v	19.5V	Not functional
7	SNNPR	Sidama	Bensa	Osole	3.75V	0V	0V	0v	Not functional
8	SNNPR	Sidama	Hula	Hula Bochesa	4.67V	4.67V	0V	19.5V	Not functional
9	SNNPR	Hadiya	West Badewacho	Hawora health center	11.26V	11.5 V	235V,	Not measur ed	Functional
10	SNNPR	Hadiya	East Badewacho	Tikareqoqor e	13.9V	11.4V	232V	19.2V	Functional
11	Tigrai	central	Mereb leke	Adifetaw	13.55V	11.6V	0V(fuse burnt)	19.96V	Not Functional
12	Tigrai	central	Ahferom	Mayi Hamato	13.53V	11.2V	231V	19.08V	Functional
13	Tigrai	central	Wereileke	Golagule	13.72V	11.5V	229V	19.68V	Functional
14	Tigrai	central	Mereb leke	Tarewer	13.76V	11.7V	222V	19.85V	Functional
15	Tigrai	central	Naideradiat	Teregegn	13.73V	11.3V	235V	19.28V	Functional
16	Tigrai	central	Kolla Temben	Dedere	13.53V	11.6V	231V	19.08V	Functional
17	Tigrai	North west	Lalay Adiabo	Adimillion	12.23V	11.6V	242V	16.12V	Functional
18	Tigrai	North west	Lalay Adiab	Adi Nigisti	13.12V	11.6V	201V	18.5V	Functional
19	Tigrai	North west	Asgede Tsembela	Maebele	13.79V	11.2V	242V	19.41V	Functional
20	Tigrai	North west	Tatayadiab o	Lese	12.89V	11.5V	223V	19.08V	Functional
21	Tigrai	North west	Tselemti	Chachare	12.03V	11.7V	223V	19.07V	Functional
22	Tigrai	North west	Tselemti	Fiyelwuha	13.75V	11.3V	229V	18.82V	Functional

SHS installed in Oromia Region.As can be seen, it is sealed by the installer using red plasters not to be opened.

Photo taken by Lemu Kebede, June 2016

The figure below shows a grid installation in a village where lots of houses own an SHS.

Photo taken by Lemu Kebede, June 2016

An SHS from Amhara region that was installed by an NGO called Solar Energy Foundation.

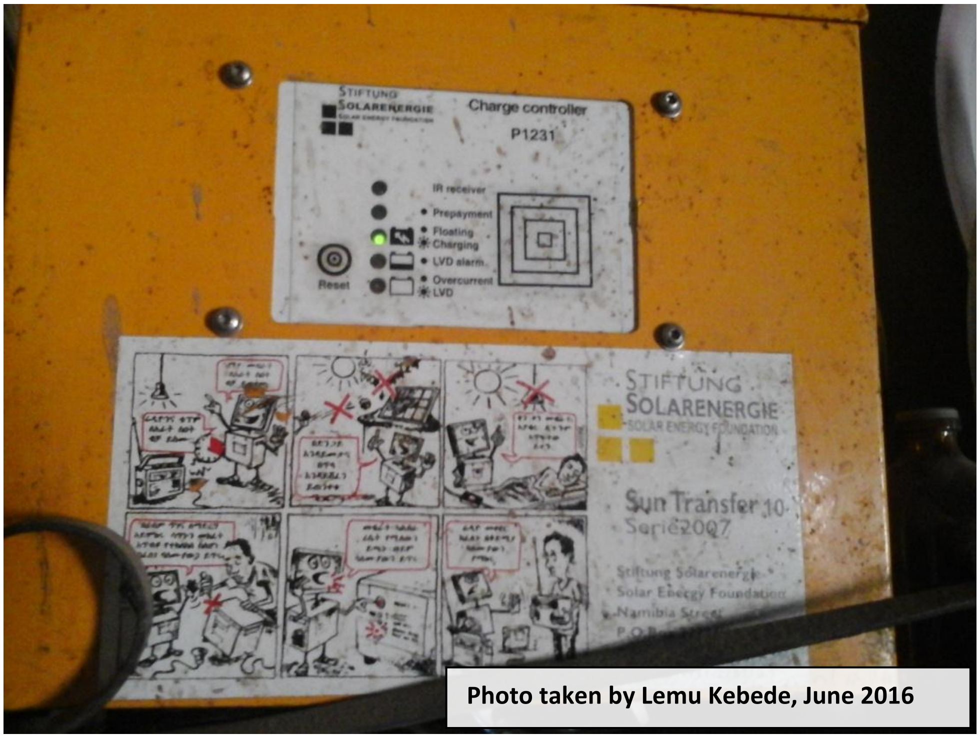


Photo taken by Lemu Kebede, June 2016

Another SHS in Amhara region which is managed by REF

Photo taken by Lemu Kebede, June 2016