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Apil Bista

A Concept: Shared Off-grid PV System

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Bachelor of Engineering

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This thesis aims at creating a concept on providing self-efficient sustainable electricity to all the people living in dark. Two case studies and their simulation were carried out in this thesis reflects the importance of the concept of Shared PV system. The rural sustainability indicators of two different solar PV systems were also compared to help answer the aim of this study. The result of this final year project was that the shared off-grid PV system can play a major role in sustainable electrification of rural areas of a developing country.

Keywords	PV, off-grid, renewable energy, Shared PV system, world energy

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List of Abbreviations

AC	Alternate Current
AMP	Amperes
AWG	American Wire Gauge
CC	Charge Controller
CFL	Compact Fluorescent Lamp
CO_2	Carbon Dioxide
DC	Direct Current
DoD	Depth of Discharge
FAQ	Frequently Asked Questions
Hrs/h	Hour
IEA	International Energy Agency
IFC	International Finance Corporation
kWh	Kilowatt hours
LED	Light Emitting Diode
NGO	Non-Governmental Organization
PV	Photovoltaic
SDG	Sustainable Development Goals
SHS	Solar Home System
V	Voltage
WB	World Bank
Wh	Watt hour
Wp	Watt-peak

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1 Introduction

A concept, or an idea, is the most vital part of any innovation. A concept leads to numerous astonishing achievements, on every socio-economic aspect. The innovation of photovoltaic (PV) effect by the French physicist Edmond Becquerel in 1839 brought a revolution in the one of the major source energy in the world [1]. When people think about reducing their dependence on fossil fuels, minimizing their carbon footprint and making a sustainable future for the sake of mankind, solar energy is often seen as a feasible alternative.

This thesis presents a template for a more convenient use of solar energy than the already existing ones. The study drafts a new kind of solar plant that can be more reliable than other forms of renewable sources, like water or wind, and beneficial to the people living in rural regions of a developing country. A shared off-grid PV system is a concept that is designed to generate enough electricity for eight to ten families with limited resources. It is different from a Single Home System (SHS) because a SHS can produce energy for one family only, and it is expensive to add another family into the system. A mini off-grid project is another project with more capacity than a shared system, but it requires a major investment. Furthermore, a mini-grid project is not suitable for far-away rural areas and even if it were possible to transmit the electricity to populated areas, the cost would be high and non-affordable to the public. Furthermore, the essence of a shared off-grid PV system is to generate small amounts of electricity to a small village or a group of people living closely, with a small investment.

This thesis discusses the world energy, the importance of renewable energy and suggests the establishment of PV system in developing countries. Further, the thesis introduces various techniques used during the design, installation, operation and simulations of a case study.

The inspiration for the concept introduced in this thesis came from the millions of people living in the dark, with no money to buy expensive electricity and no hope for the betterment of their life.

2 Theoretical Information on Energy

According to Encyclopedia Britannica, energy can be defined as capacity for doing work. Energy may exist in various forms, such as potential, kinetic, thermal, electrical, chemical, or nuclear energy, and it can be used for various purposes from lighting a bulb to running a refrigerator, from running a mechanical machine to flying out rockets and more. The modern use of energy can be divided into four categories: residential, commercial, transportation, and industrial use. Some common functions that require energy are the heating and cooling of our homes, lighting office buildings and residential areas, driving cars, construction, and manufacturing of products. [2.]

2.1 World Energy

Total energy produced and consumed throughout the world is called world energy. If the world energy produced and consumed in the past 10 years is compared to the amount produced in the next 10 years, it can be seen that the demand for energy continues to grow with the growth of population. Especially in the emerging or developing countries, the need for energy doubles every 10 years as it is vital for the economic growth and use of resources for development in these countries. [3.] No doubt, massive amounts of energy will be produced from different sources to fulfil this energy need, either with non-renewable or renewable sources, which. ultimately, effects the world climate and environment in the long run. Hence, sustainable energy production is a must in today’s world.

2.2 Source of Primary Energy Sources

The sources of primary energy vary around the world. Fossil energy sources are the main source of energy in most countries. These non-renewable energy sources are widely used. Known as unsustainable energy source for its massive carbon production and limited quantity source in earth’s surface, they make up approximately 79 % of energy sources around the world according to the 2015 data. The other sources are Renewable sources for energy production include wind, biofuels, solar and hydro. These sources of energy are considered sustainable because of their abundant availability and have positive impact on the environment and nature. Although the use of renewable energy has increased widely from past 20 years, non-renewable energy still dominates the world as main source of energy in every home. Another source of energy is Nuclear energy. Even though Nuclear energy is itself a renewable energy source, the material used in Nuclear power plant are not. For example, Uranium U-235 is a non-renewable resource. The nuclear energy sources are mainly used for generating electricity, household purposes, heating and transportation. [4.]

Electricity is the secondary source of energy because it is derived from primary energy. But similar to primary energy, electricity is not limited to generating just heat and motion but has hands in wide variety of complex appliances and products. Heating, transportation, electrical appliances, industry and machines that are run with fossil fuels can be operated by electricity. Therefore, electricity can be weighted as one of the important sources of energy used in daily life. Since it's so important, there are thousands of ways invented for electricity generation. Both renewable and non-renewable energy source can be used for electricity generation. Figure 1-3 illustrates the conversion of both perpetual and ephemeral energy sources into electricity in two different continents and worldwide. [4.]

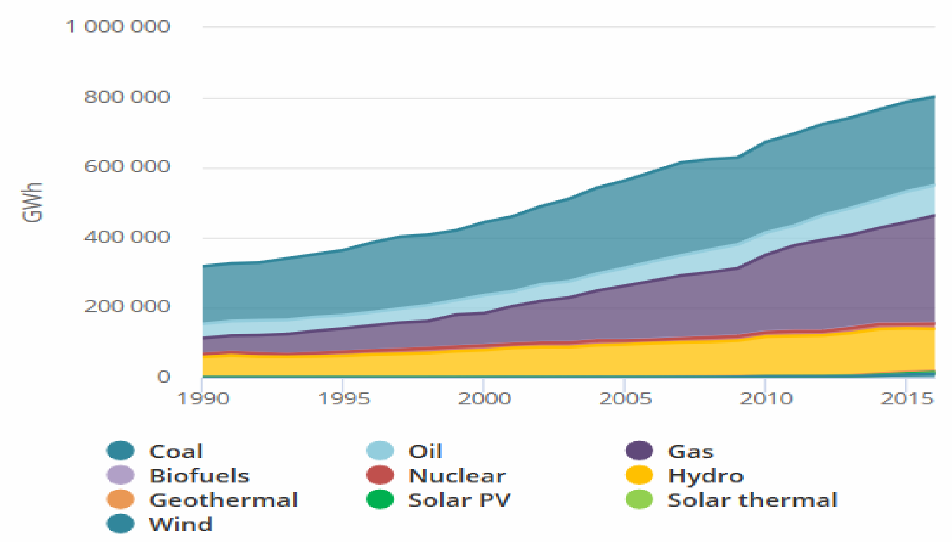

Figure 1. Electricity generation by fuel in Africa 1990-2016 [4].

According to the IEA electricity information, 80.6 % of the total energy produced in Africa was produced by non-renewable sources in 2016. Although the total energy production of the continent has increased during the past 20 years, renewable energy production is still in its in its infancy, as seen in figure 1.

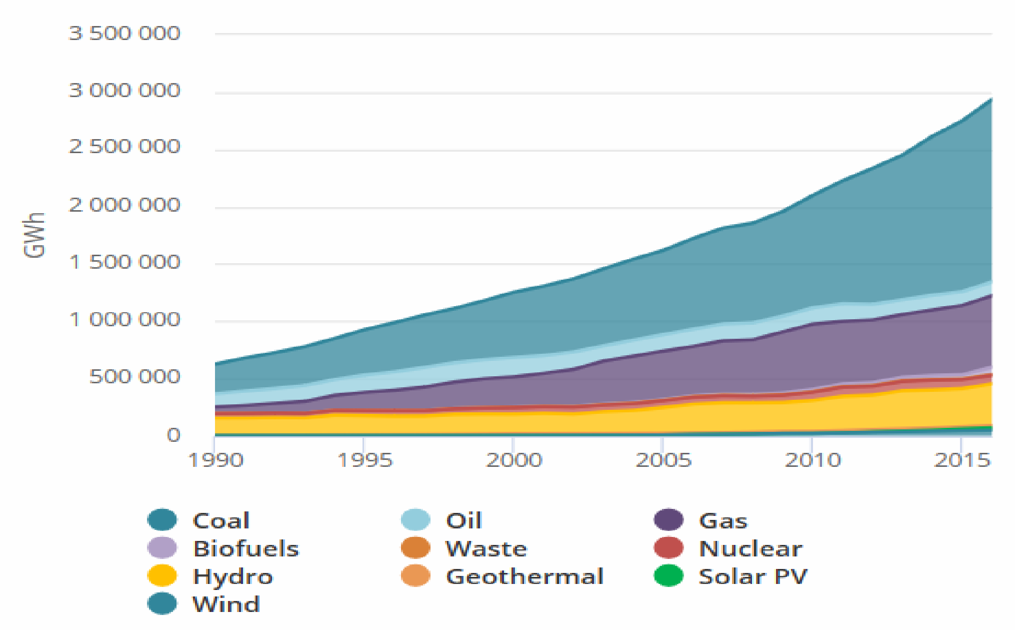

Figure 1. Electricity generation by fuel in Asia excluding China, IEA 1990-2015 [5].

In Asia (excluding China), 79.7 % of electricity is produced with non-renewable sources. Even though the use of renewable energy sources has increased from previous years, the use of non-renewable sources, especially coal, has increased significantly as seen in figure 2. [5.]

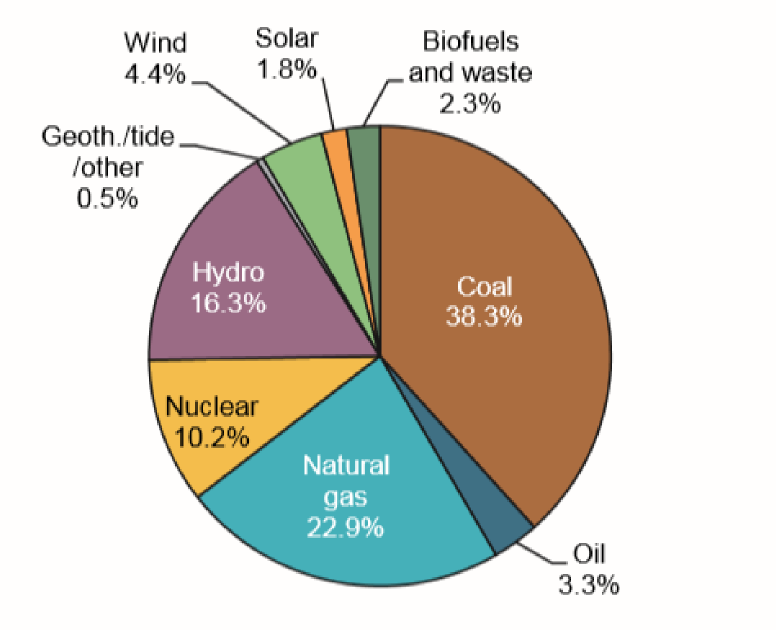

Figure 2. World gross electricity production by source 2017 by IEA [6].

According to the latest data provided by the IEA, the world still produces 66.8 % of its electricity with non-renewable fuels. However, the growth of electricity generation with renewable sources, such as wind (7 %) and solar (19.9 %) energy has grown substantially in the recent years. [6.]

2.3 Sustainable Energy Sources

With the increasing world population, the rate of energy production has increased. From a financial point of view, using non-renewable energy sources can be economical on some level for a short period of time, but it will surely affect the natural habitat in the long run. The figures above in chapter 2.2 clearly describe the types and share of unsustainable sources of energy used. The total share of renewable energy sources in the world energy is very small, about 18 % in 2017, compared to non-renewable sources. This means that the way to transform fossil fuel energy production to low-carbon or renewable energy production is still long. [6.]

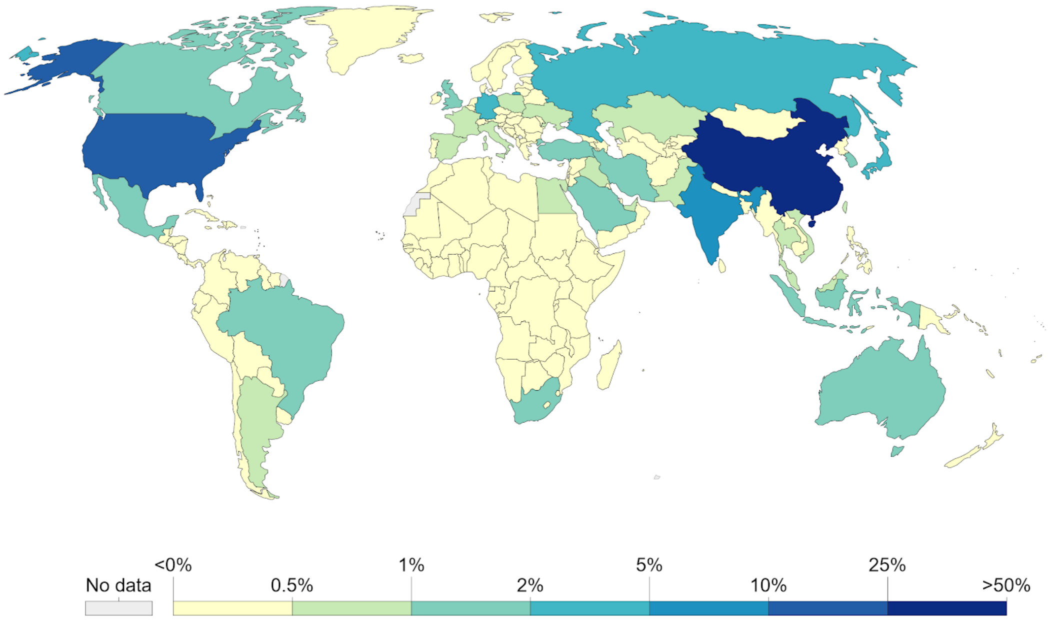

Figure 3. Annual share of global CO2 emissions in percentage 2017 [7].

The global map in figure 4 indicates each country's share of global CO_2 emissions in 2017. The USA, China and India are the leading carbon emitters with 14,58 %, 27,21% and 6,82 % respectively. Global carbon emissions reached their highest point in 2018 with the release of 37.1 billion tonnes CO_2 with countries like the USA, India and China contributing with a growth of 2.5 %, 6.3% and 4.7 %. respectively. Even though these three countries are heavily responsible and criticized for their disinterest in solving the greenhouse problem, there are no reports on their contributions or concerns against climate change. Due to the significant energy demand for more population and the use of more fossil fuels to cover that demand, carbon emissions are likely to increase in 2019. [7; 8.]

Another adverse effect of using unsustainable sources of energy is the long-term rise in the global average temperatures. The phenomenon is known as global warming. The average global temperature on Earth has increased every year since the 1880´s and the latest annual average anomaly is 0.8°C. The graph in figure 5 illustrates the change in the global surface temperature with the average temperatures, the average between 1951 and 1980 as the zero level. [9.]

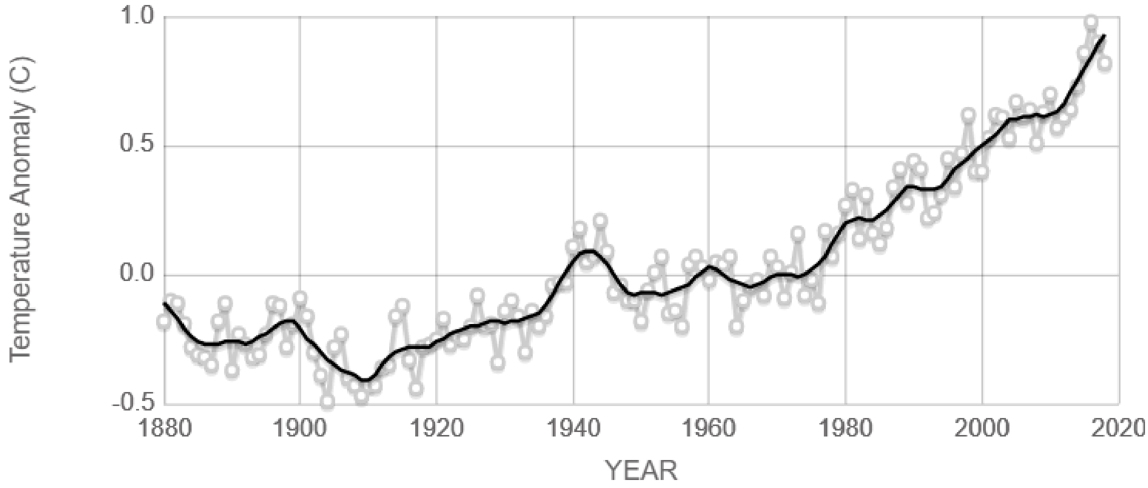

Figure 4. Global Land-Ocean temperature index, NASA/GISS 2018 [9].

The graph in figure 5 demonstrates that the rate of temperature rise has nearly doubled in the last 50 years.

Climate Change

A massive use of fossil fuels indicates higher CO_2 emissions, worldwide pollution and an increase in non-decomposable waste, which does not just lower our standard of living, but also affects the condition of the environment in every aspect, making the world toxic for future generations. Carbon dioxide emissions from factories and vehicles together with other greenhouse gases cause global warming, which in turn leads to climate change and ozone layer depletion. Climate change has a massive negative effect on agriculture, fresh water, biodiversity and global climate. The increase in global heat is melting glaciers and sea ice causing a shift in precipitation patterns, the rise in the sea level and unexpected natural disasters. If the sea level keeps on rising every year, coastal countries like the Maldives will soon be seen submerged into seas and oceans. In addition to human life, the climate change affects wildlife and habitats. If no actions are taken right now, as the time passes by, we, the humans, will face the greatest environmental challenges. The world now needs sustainable energy more than ever.

3 Electricity in Developing Countries

All over the world, electricity is most likely the most common form of energy used. People use electricity to do various everyday activities like using mobile phones, computers, travelling on the metro and trains, as well as in all forms of industrial tasks. Even though the importance of electricity is significant, especially developing countries still face shortages of electricity. [6]

Developing countries face several challenges on giving all their population a fair access to electricity. There are shortages of electricity in different parts of the world because of an imbalance between electricity production and consumption. The foremost reason is poverty and lack of skilled manpower. When a country lies on the poverty line, it has consequences on its infrastructure. The country has a hard time to produce skilled manpower due to scarce resources to produce them. Even when some electricity is generated, it cannot be transmitted to all people because of its expensiveness. People living in rural areas cannot afford the electricity at the same rates as the city dwellers or factory holders pay. When electricity planners of a country fail to recognise the needs of different kinds of customers, living in different parts of the country, it results in some localities without any electricity and some localities with a full 24 hours of electricity. Furthermore, the government of a country may fail to generate affordable, reliable and good quality electricity and invest in the maintenance of the production facilities and the grid for long term use. In countries like Bangladesh, Uganda and Nigeria, frequent power fluctuations hamper the productivity and create technical problems for small business and household equipment by damaging electrical equipment and affecting the quality of all business outcomes. [10.]

3.1 Electricity Usage Statistics

According to the World Bank, the global electrification rate has reached 89 % across the globe. However, there are still 573 million people only in Africa and 350 million in Asia who do not have electricity. According to a 2017 study, the total final electricity consumption of the world reached 21.372 TWh, but still millions of people are without electricity. These problems are seen in all cities of underdeveloped countries and rural parts of developed countries. Some of the main reasons for the lack of widespread access to electricity are extreme poverty, lack of skilful manpower and lack of resources. [11; 12; 13.]

3.2 Solar Energy as Solution

Solar energy is the energy harnessed from the Sun's radiation, which can produce heat to generate electricity [14]. Solar energy is a renewable energy source found abundantly on Earth's crust. It can be used for different purposes and it is a perfect replacement for fossil fuels. It is free energy that is converted into either thermal or electrical energy to be used accordingly in the everyday lives of people. With the emerging technological development, solar energy is the most feasible and trending energy source today, producing 303 gigawatts of energy globally, which accounts for 1.8 % of the total electricity consumption. [15.] Solar energy can be the answer to the electricity shortages in the developing countries, especially in the areas that are not connected to a national grid.

Energy generating companies in different countries are producing 570 TWh of electricity using solar power plants in 2018 [15]. Besides for generating electricity in a large quantity, solar energy can also be installed for personal use in both grid-connected and off-grid houses. Different sized SHSs and mini grid systems are emerging as popular choices in areas with electricity shortage. Since they are a sustainable way of generating energy, solar systems have been given much emphasis in rural areas of developing countries, instead of fossil fuels as primary source of energy. Solar energy has also been included in SDGs. [50] Solar power will not just bring brightness into the dark, but it will also help eliminating poverty and stabilizing the financial status of a country.

4 Off-grid Solar PV

Solar energy is divided into two categories: thermal energy and electrical energy. Thermal technologies are commonly used for generating heat or to heat fluids and to run turbines for generating electrical energy. Photovoltaic technology is used to generate electrical energy with the photovoltaic phenomenon. Generating electricity via thermal energy is expensive and requires more skilled manpower than generating electricity with the photovoltaic phenomenon. Despite both technologies being used to generate electricity, PV systems are more accessible, especially in developing countries. [16.]

Principle of Photovoltaic

Photovoltaic systems react to light by transforming light energy into electrical energy. This conversion phenomenon is called the photovoltaic effect. [16.] The principle is illustrated in figure 6.

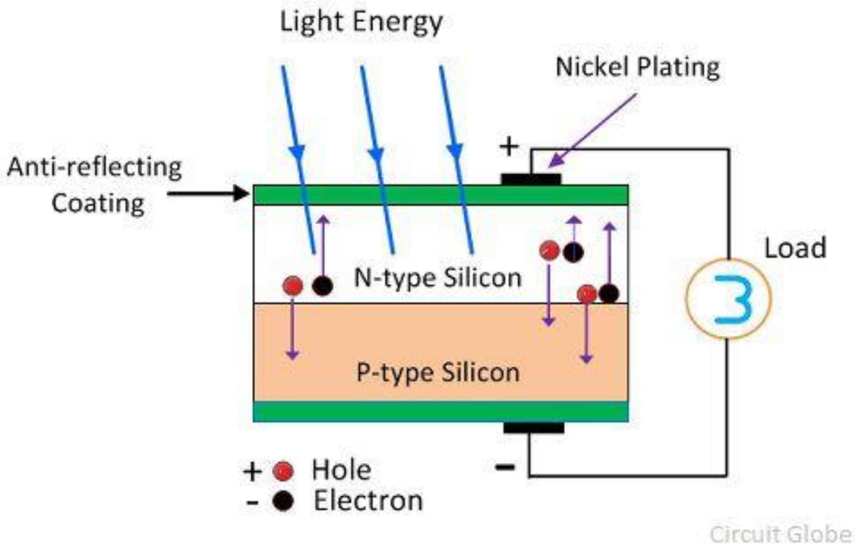

Figure 5. Construction of PV cell by Circuit Globe [17].

PV panels are equipped with semiconducting PV cells that consist of high-purity silicon. The cells are coated to form a P(positive)-N(negative) structure as an internal electric field. The P-type silicon has a tendency to give up electrons whereas the N-type accepts electrons. The light contains a photon, which, when it hits the PV cells, creates excitement in the electrons of the cells and induce a separation of negative and positive pairs into two different directions. Then the electrons move to the negative electrode (N) and the holes move to the positive electrode (P). Finally, when a conducting wire is connected to both P and N with load, it results in a low of electrical current. The current, or output, of a PV panel depends on its surface area, its efficiency, and it is directly proportional to the intensity of sunlight striking on the surface. [18; 19; 20.]

4.1 Types of PV Solar Systems

There are three types of PV solar power systems: on-grid systems, off-grid systems and hybrid systems. On grid systems depend on electrical grids, off-grid systems are independent systems and hybrid systems are off-grid systems with a grid connection [21].

As mentioned above, on-grid systems are dependent upon a municipal or national electrical grid. A grid-tied system runs parallel synchronously with the utility and it is arranged so that the load will always consume the generated solar power first. These systems do not need batteries as they are connected to both solar inverters and public electricity grid. There is a metering system attached to this system as the excess solar energy runs through the meter to the main gird, calculating the exported or imported power into or from the house. Any excess energy can be used by other consumers. [21; 22.]

Off-grid solar systems are not connected to the electrical grid but use solar power as the main source of energy. A battery storage keeps the electricity at one’s own disposal as the generated power recharges a battery and is used to meet the needed capacity even during the winter. This concept is for the users who want to be 100 % self-sustaining and want to use 100 % of renewable energy. These systems are also used in areas with no utility connections, especially rural areas. The potential users of off-grid systems range from single user to entire villages or communities. [21; 22.] Initially an off-grid system can be installed in two different ways, as a solar home system or a micro-grid system. Both have a different approach to the delivery of electricity to remote areas or areas with no grid connection. The choice of either one depends on several factors such as the budget for installation, cost of distribution and the power required. A SHS is used for one family whereas a micro off-grid system can be used by a number of buildings or a village. Combining both concepts can provide electricity to more than one family and less than a locality with the addition of small extra fund, which can be up to 10 families.

A hybrid solar system is similar to an off-grid solar system, but it is connected to grid electricity as a backup. The idea is to use renewable free energy when the cost of electricity is at its highest and use the grid during nights when the sun is down, and the rate of electricity is low. Similarly, to an on-grid system, this system can also be set up so that once the batteries are fully charged, excess solar power can be exported to the grid via a metre. [21;22]

Since this thesis aims at introducing the concept of providing electricity and connecting rural areas that are far away from the electricity grid, off-grid systems are looked at as the desired solution for most electricity problems.

4.2 Shared Off-grid Solar Power Plant

A shared off-grid power plant is meant to meet the energy demands of a specific area. Such off-grid systems are built for more than one family in areas that are far away from a utility grid and have no connection or any form of transmission and distribution infrastructure to the grid line. [21.] Furthermore, in an area without proper infrastructure, skilled manpower and applicable financial stability, an off-grid micro-grid plant is a boon to the people living in the dark during the night in such areas. The system is gaining popularity in less developed areas because of its low cost and the fair amount of energy produced [22]. This kind of a solar system can be funded by the government and locals or with foreign aid and by the locals.

A regular micro or mini grid is a compressed version of bigger grids with transmission lines and a built distribution system [23]. The system suggested in this thesis will not include the installation of an actual electricity generating grid but will operate as a SHS. The reason for not including a grid system is because installing a grid and its components is expensive and requires skilled manpower. Thus, it might not be feasible in the rural areas of a developing country. A SHS is basically used as a one-home system, but a micro off-grid system is designed for a maximum of five to eight families living in fairly close to each other.

4.3 Components of PV System

The thesis suggests the following components to be used in a shared off-grid PV solar system whose concept is created in this final year project.

Photovoltaic panel array

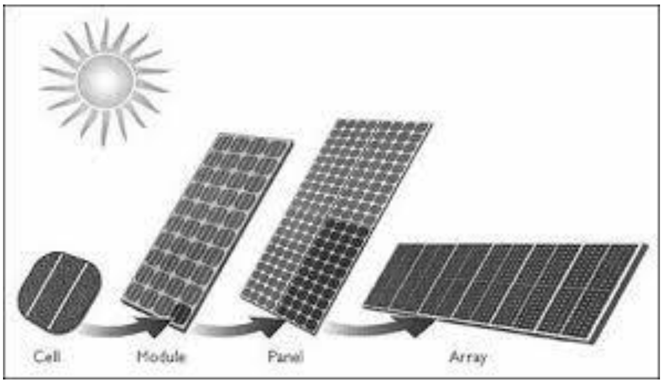

Figure 6. Types of PV array [24].

A solar or photovoltaic panel array converts solar energy into electrical energy. A PV panel consists of solar cells made up of two types of semiconductors, called P-type and N-type silicon. As mentioned above in chapter 4.1, the solar cells generate electricity when light energy falls on them. A PV array is the entire electric power creating unit, comprising several PV modules. The PV modules are made up of several interconnected PV cells. In short, a PV array is composed of several PV modules. The amount of solar energy generated depends on various factors such as the orientation and tilt angle of the solar panels, peak hours, solar panel efficiency, and loses due to shading, dirt or even ambient temperature. [25.]

Battery Bank

Since off-grid systems are not connected to any other power source than solar power, the power production is zero in the evenings, nights and cloudy days with no sunlight. Therefore, excess energy generated during the day is stored in battery banks that provide electricity during these times. A battery bank consists of a number of batteries which are further wired in either series or parallel combination according to the requirements of the PV system. Selecting a storage option is complicated as factors like battery capacity and power ratings, depth of discharge (DoD) and efficiency should be evaluated beforehand. Establishing the battery capacity is important as it gives an overall picture of the total amount of electricity stored. In addition to capacity, power rating is essential as well because power rating is the amount of electricity that a battery can deliver at a single time. Capacity and power are measured as kWh and kW, respectively. These should always be calculated as a battery with high capacity and low power rating would deliver a low amount of electricity for a long time and a high-powered rating could run an entire house for a limited number of hours. The DoD of a battery indicates the amount, or percentage, of a battery's capacity that has been used. The battery lifespan also depends on the number of frequent charges and discharges. For the optimal performance of a battery, it should not be discharged entirely. [26.] There are three types of batteries for solar power systems: saltwater, lead acid and lithium ion batteries. Lithium ion batteries are more common because of their physical properties as well as affordable price range. These batteries have a higher DoD and longer lifespan than the other alternatives, and they are more convenient to use [26]. The lithium ion batteries have a low maintenance rate and can also be used when the battery discharge percentage falls below 50 % [26].

Inverters (AC-DC) Optional

An inverter is an electronic device that converts direct current (DC) into alternating current (AC). The electricity generated by a solar PV system is DC. [26.] Most small devices run with DC, there are only a few appliances that require AC. Small portable devices like flashlights, mobile chargers, LED bulbs, laptops and battery embedded electronic devices use DC power stored in batteries. An inverter is not required in such cases. However, large electrical equipment, generally with three phase wires, need AC to operate. [26.] This thesis discusses small solar PV systems that generate enough energy for light bulbs, charging battery appliances, radio and fans, and these devices can conveniently be used with DC. Therefore, alternating the current is barely needed. However, a family with a need of AC can add a DC-AC inverter to their home wiring system.

Electrical wires and cables

Cables and wires are another important part of an electrical installation. Although the system discussed in the thesis does not require thousands of kilometres of cables, the system does need cables that can handle the connection from the solar panels to a battery and to houses nearby. A solar cable is a group of conductors whereas a wire is a single conductor. It is important to size and measure the length of cables as it helps preventing overheating problems and loss of electrical energy while transmitting electricity from one point to another. The size of a cable is measured in American Wire Gauges (AWG). The AWG number is inversely proportional to the size of the wire. For example. A 16 AWG wire is smaller than a 12 AWG wire. [27.]

Charge controller

A PV charge controller is a device that controls the flow of the current to and from the battery and protects the battery from overcharging after reaching its required voltage capacity [28]. The charge controller also determines the operating life and efficiency of the entire solar system, including the batteries [28]. The device is an important component within a PV off-grid system as it bolsters the life of the overall system saving expenses in its technical maintenance. But the system does not always need a charge controller. The rule of thumb is that if there is either more than 5 watts of solar energy for every 100 amp hr of battery capacity or if the solar system is limited to 1-5 W panels. [29; 30.] Even though the use of a charge controller is optional, it would be advisable to use one on an off-grid system as the system lacks a grid that would endure load variations and adjust the input and output powers.

Loads

Loads are the electrical devices operated by electrical energy. The loads are connected to the solar system and they can be both AC and DC devices. Since the system suggested in the thesis is a low output or low generating system, DC loads are recommended for daily household activities. Some such loads are CFL or LED light bulbs and a radio. For AC loads, an inverter is used to convert DC into AC.

5 Calculation Process and Design

As established in chapters 3 and 4 above, sustainable energy is important in the present world. Of the sustainable energy sources, solar energy is one of the most sustainable ones. The thesis presents a concept that supplies solar energy to two to nine families at a time. The proposed system does not include a grid, the generated energy would only be used by a few families rather than an entire village or town. Figure 8 is a picture of a spreadsheet showing a calculation of average energy required for a single family living in a rural area for their basic needs like lighting, playing the radio, using a small fan during the summer and, perhaps, a portable router for the internet. The data in the spreadsheet is based on information from various websites. [31; 32; 33.]

				TIME OF USE					
				During Sunhour		After sunhour			
priority	applicances	quantity	typical power in watt	hrs	Wh	hrs	Wh	total usage (in hours)	total energy consumed per day (Wh)
HIGH	bulb LED small low energy	2	2	0	0	5	20	5	20
MEDIUM	bulb LED small medium energy (360lumens)	1	4	0	0	3	12	3	12
MEDIUM	radio	1	10	5	50	3	30	8	80
HIGH	mobile phone charger	2	5	2	20	1	10	3	30
LOW	small fan	1	15	4	60	2	30	6	90
	Total data		36	11	130	14	102	25	232

energy demand during sunhours in KWh	0.13
energy demand after sunhours in KWh	0.102
Total energy demand over 24hour period in KWh	0.232
Minimum energy demand on battery bank in KWh	0.102

Figure 7. Figure of Spreadsheet calculating the average energy demand over 24 hours

In the spreadsheet above, the energy needs for and use of a single-family house (SHS) has been calculated. The spreadsheet includes small appliances that are used in a family with poor financial conditions or in a rural area where people have no electricity of any kind. The appliances are selected by comparing the basic needs of an average family globally in the developing countries, their average budgets and possible appliances that can run with solar electricity. The usage times of each appliance are noted down in different columns, first during sun hours and then when the sun is down, or after sun hours. Total usage is calculated by adding the sun hours and after sun hours. [31; 32.]

$$Total\ usage\ (hrs) = during\ sun\ hours\ (hr) + after\ sun\ hours\ (hr)$$

Finally, total energy consumed per day is calculated by adding the gross data of the energy consumed by each appliance per day, which is further calculated by multiplying the number of appliances, power of appliances in watt, and total usage in hours.

$$Total\ energy\ consumed\ per\ day = quantity\ of\ appliances * power\ of\ appliances\ (W) * total\ usage\ (hrs)$$

Two types of systems were calculated in the final year project: a single-family house and a shared family system in order to determine which system is better. The simulation was conducted to obtain more information on the suggested solar system in this thesis, as well as to compare two systems. The simulation was run on Calculation solar webpage [37]. The calculation is done for an exact location whose coordinates are given by the user. This makes it easier to establish the angle of inclination and disorientation from the North for the calculations for a photovoltaic system. The simulation also generates the monthly data of available sun hours for electricity generation. Finally, the program generates a report on the estimated consumption of a solar photovoltaic off-grid system from the input data instituted. The output data are produced according to the needs and consumption, and the solar radiation of a specific location, its orientation and inclination of the installation.

5.1 Types of Solar House System

The thesis discusses two types of solar systems or solar users: a single-family solar home system and a shared solar system.

Single Family Solar Home System

The spreadsheet in figure 8 shows that in the rural part of a developing country, a single family requires 232 Wh of electricity every day. As mentioned above, this is the maximum amount of electricity used by a small family in the rural parts of developing countries. In urban areas, the usage may be more.

Shared Solar System

The focus of this thesis is on a shared solar system. This system is smaller in size and capacity than a micro or mini-grid system, and it is designed to benefit a small number of houses. The spreadsheet in figure 8 above displays the calculated use of electricity for a single-family house. The same procedure can be used to calculate the need of 8-10 houses. The thesis assumes ten single family houses in the system. As a single-family home requires 232 Wh of electricity, ten single family houses require 2,320 Wh of electricity.

The thesis discusses a PV off-grid system installed in a small village or close community of 8-10 families. The PV panels are ground mounted at a certain angle or orientation to the sunlight, and batteries are connected to them. The batteries are further connected by wires and connected to the houses that needs electricity. The system is built to generate the basic energy need of an average family in a rural area. The basic needs covered in this final year are listed in figure 8. The concept discussed in the thesis is not for rich people or even middle-income people living in rural areas, but for those who cannot afford the cost of the installation of electricity and who live without lighting.

5.2 Cases and Simulations

In order to better understand both systems discussed in the thesis, a simulation is run for both a single and a shared system using the website simulation program Calculation-Solar.com. The simulations are run for two places in two countries, Malawi and Niger. Malawi and Niger are in different hemispheres so two different calculation outputs are generated.

5.2.1 Malawi

The first case location is an African country, Malawi. Malawi is among the countries that provide the least electricity in the world with only 9,8 % of the population enjoying access to it [12]. Several organizations work in Malawi in order to bring light to the citizens. The calculations carried out in this thesis can be used all over the country because of the similar physical landscape of the country. The calculations in this thesis were done for a place near the town Salima, Malawi.

Table 1. Details of locations and orientation.

coordinates	13.792939, 34.439972
PV array inclination	5 º
PV array disorientation regarding the North	0 º
system voltage	110V

Table 1 above lists the location and features of the PV systems suggested for the case location in Malawi.

Single Family House System

As calculated in the spreadsheet in figure 8, the energy consumed daily is 232 Wh/day, which is also the required electricity generation from a single family house system. However, there are losses affecting the electricity generation when looking at the performance ratio.

Performance ratio is one of the most significant factors associated with any solar PV system because it indicates the relationship between the real and theoretical output of a solar off-grid PV system very well [36]. Table 2 below shows the parameters for the calculation of performance ratio and energy losses for the single family house PV system.

Table 2. The parameters for the calculation of performance ratio and energy losses.

Parameters	**Value**
Coefficient battery losses	5 %
Battery self-discharge coefficient	0.5 %
Battery discharge depth	60 %
Loss coefficient DC/AC conversion	11 %
Loss coefficient wiring	5 %
Autonomy System	1 day
Performance Ratio	**78.34 %**

According to the simulation, the performance ratio of the single family house system is 78.34 %, which also indicates the efficiency of the system. It means that the system utilizes 78.34 % of the total available solar energy and uses it to generate electricity. The total daily energy requirement of a single family house is 296.15 Wh/day.

The power of PV modules for the single family house system are calculated automatically in the simulation program. Table 3 below shows the parameters or values for the calculations of modules.

Table 3. Details for the calculations of PV power system

Parameters	Value
Annual optimal inclination	13.22º
Monthly average maximum daily temperature (for 3 months)	26.12º
Maximum Sun Hours worst in months	4.58 HSP
Calculated power necessary	85 W
Power System	12V

The output power of the single family house PV system achieved under full solar radiation is 95 W. Hence the photovoltaic power of the entire system is 95 Wp.

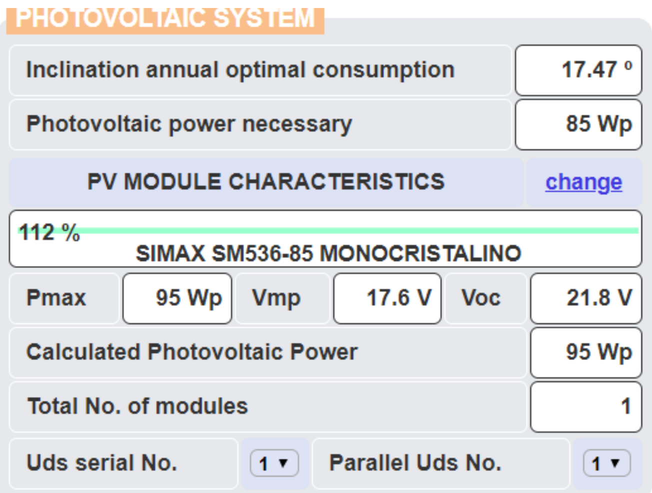

Figure 8. Brief details of the PV module used.

To calculate the capacity of the battery needed for the single-family house system, the system voltage and the depth of discharge and autonomy of the system are considered. For this calculation, the number of autonomy days is assumed as 1.

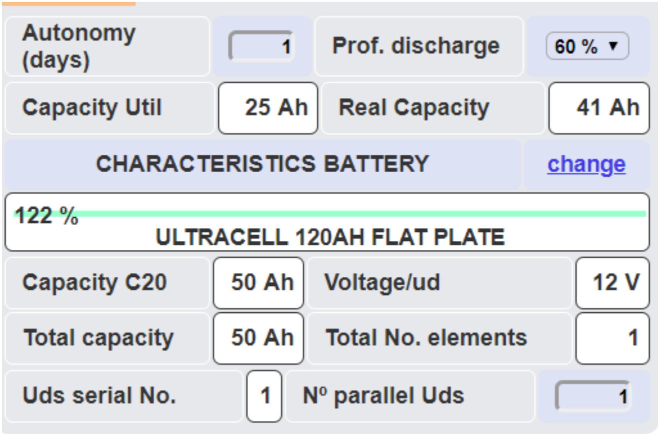

Figure 9. Information of Battery for the system

The nominal voltage of a battery used in the simulation for a single-family house system is 12 V and the depth of discharge of the battery is 60 %. As a result, a battery with a 41 Wh capacity should be used in order to contain daily energy of 296 Wh. Since extra losses, such as short circuits, can occur during the transmission of current, a battery with more capacity is valued. Therefore, the total capacity of the battery for a single-family house system, after considering the losses, is a 50 Ah battery.

Shared Solar System

The energy consumption of a shared solar system is 2,320 Wh per day. This amount is divided among a maximum of ten families. The simulation for a shared solar system is run on CalculationSolar.com, similar to the previous simulations.

Performance ratio is one of the most significant factors associated with any solar PV system because it indicates the relationship between the real and theoretical output of a solar off-grid PV system very well. The parameters for the calculation of performance ratio and energy losses for a shared solar system are shown in table 4 below.

Table 4. The parameters for the calculation of performance ratio and energy losses.

Parameters	**Value**

Coefficient battery losses	5 %
Battery self-discharge coefficient	0.5 %
Battery discharge depth	60 %
Loss coefficient DC/AC conversion	12 %
Loss coefficient wiring	5 %
Autonomy System	1 day
Performance Ratio	**77.35 %**

According to the simulation, the performance ratio of the shared solar system is 77.35 %, which also indicates the efficiency of the system. It means that the system utilizes 77.35 % of the total available solar energy and uses it to generate electricity. The total daily energy requirement for the shared solar system is 2,999.35 Wh/day.

The power of PV modules for the shared solar system are calculated automatically in the simulation program. Table 5 below shows the parameters or values for the calculations of modules.

Table 5. Details for the calculations of PV power system

Parameters	**Value**
Annual optimal inclination	13.22º
Monthly average maximum daily temperature (for 3 months)	26.12º
Maximum Sun Hours worst in months	4.58 HSP
Calculated power necessary	778 W
Power System	24 V

The output power of the shared solar PV system achieved under full solar radiation is 855 W. Hence the photovoltaic power of the entire system is 855 Wp.

Inclination annual optimal consumption					17.47 º
Photovoltaic power necessary					778 Wp
PV MODULE CHARACTERISTICS					change
110 % LG 285SC1C-L4 MONOCRISTALINO					
Pmax	285 Wp	Vmp	31.7 V	Voc	38.8 V
Calculated Photovoltaic Power					855 Wp
Total No. of modules					3
Uds serial No.	1	Parallel Uds No.			3 ▾

Figure 10. Brief details of the PV module used

For the calculation of the battery for the shared solar system, the system voltage and the depth of discharge and autonomy of the system are considered. For this calculation, the number of autonomy days is assumed as 1.

Autonomy (days)	1	Prof. discharge	60 % ▾
Capacity Util	125 Ah	Real Capacity	208 Ah
CHARACTERISTICS BATTERY			change
106 % BLACKBULL BOX-C FLAT PLATE			
Capacity C20	220 Ah	Voltage/ud	12 V
Total capacity	220 Ah	Total No. elements	2
Uds serial No.	2	Nº parallel Uds	1

Figure 11. Information of Battery for the system

The nominal voltage of the battery used in the simulation for a shared solar system is 24 V and the depth of discharge of the battery is 60 %. As a result, a battery worth 208 Wh capacity should be used in a shared solar system in order to ensure the daily energy of

2,999 Wh. Since extra losses, such as short circuits, can occur during the transmission of current, a battery with more capacity is valued. Therefore, the total capacity of the battery for a shared solar system, after considering the losses, is a 220 Ah battery.

5.2.2 Niger

Niger is an African country where only 14.4 % of the population has access to energy commodity [12]. According to recent data, the country has 284 MW worth of electricity use, all from fossil fuels. More than 85% of the people in the country are still without power [37]. Organizing and generating awareness about sustainable energy sources can be a very important step in the development of this country as well as in reducing the massive use of fossil fuels. The calculations carried out in this thesis can be used in the whole country because of the similar physical landscape of the country. The calculations in this thesis were done for the rural community of Akoubounou, Abalak in Niger.

Table 6. Details of locations and orientation.

coordinates	15.055355, 6.210815
PV array inclination	14 º
PV array disorientation regarding the North	0 º
system voltage	110V

Table 6 above lists the location and features of the PV systems suggested for the case location in Niger.

Single Family House System

As calculated in the spreadsheet in figure 8, the energy consumed daily by a single family house is 232 Wh/day, which is also the required amount of electricity generation by a single family house PV system. However, there are losses affecting the electricity generation when looking at the performance ratio

Performance ratio is one of the most significant factors associated with any solar PV system because it indicates the relationship between the real and theoretical output of a solar off-grid PV system very well. The parameters for the calculation of performance ratio and energy losses for a single family house system are shown in table 7 below.

Table 7. The parameters for the calculation of performance ratio and energy losses.

Parameters	**Value**
Coefficient battery losses	5 %
Battery self-discharge coefficient	0.5 %
Battery discharge depth	60 %
Loss coefficient DC/AC conversion	11 %
Loss coefficient wiring	5 %
Autonomy System	1 day
Performance Ratio	**78.34 %**

According to the simulation, the performance ratio of the single family house system is 78.34 %, which also indicates the efficiency of the system. It means that the system utilizes 78.34 % of the total available solar energy and uses it to generate electricity.

The power of PV modules for the single family house system are calculated automatically in the simulation program. The calculated parameters in table 7 show that the total daily energy requirement of the single family house system is 296.15 Wh/day. Table 8 below shows the parameters and values for the calculations of modules.

Table 8. Details for the calculations of PV power system

Parameters	**Value**
Annual optimal inclination	14.09 º
Monthly average maximum daily temperature (for 3 months)	30.18 º
Maximum Sun Hours worst in months	5.94 HSP
Calculated power necessary	65 W
Power System	12V

The output power of the single family house PV system achieved under full solar radiation is 66 W. Hence the photovoltaic power of the entire system is 66 Wp.

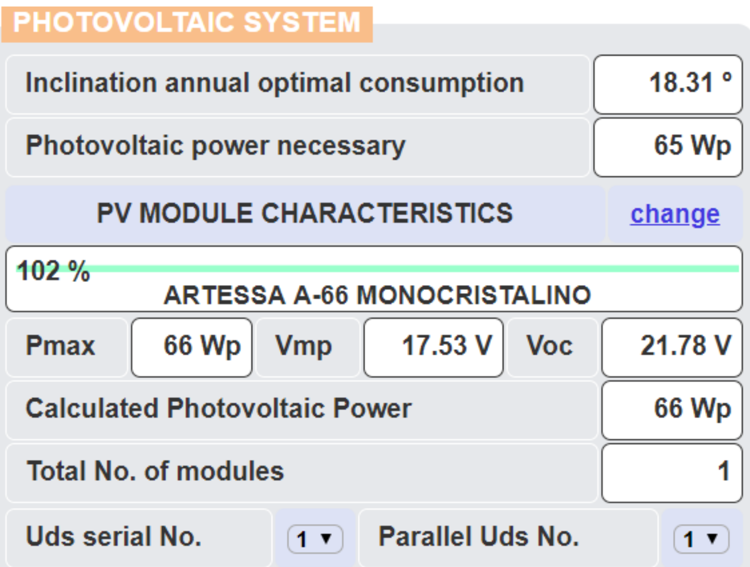

Figure 12. Brief details of the PV module used

To calculate the capacity of the battery, the system voltage and the depth of discharge and autonomy of the system is considered. For this calculation, we assume the autonomy day as 1.

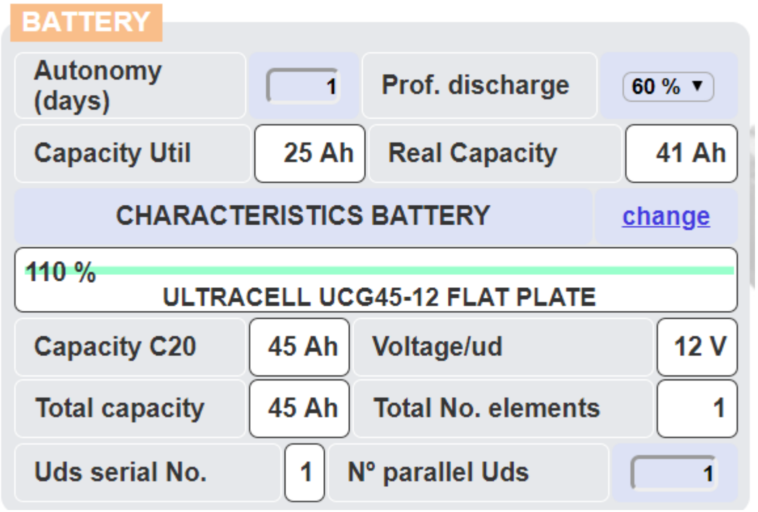

Figure 13. Information of Battery for the system

The nominal voltage of a battery used in the simulation is 12 V and the depth of discharge of battery is 60 %. As a result, in order to contain daily energy of 296 Wh, battery worth 41 Wh capacity should be used. Since extra losses, such as short circuit, can occur during the transmission of current, more capacity battery is valued. Therefore, total capacity of battery after considering the losses is 50 Ah battery.

5.2.2.1 Shared Solar System

The energy consumption of a shared solar system is 2320 Wh per day. This amount is divided among a maximum of 10 families. The simulation is run on CalculationSolar.com, similar to the previous simulations.

Performance ratio is one of the most significant factors associated with any solar PV system because it indicates the relationship between the real and theoretical output of a solar off-grid PV system very well.

Table 9. The parameters for the calculation of performance ratio and energy losses.

Parameters	**Value**
Coefficient battery losses	5 %
Battery self-discharge coefficient	0.5 %
Battery discharge depth	60 %
Loss coefficient DC/AC conversion	12 %
Loss coefficient wiring	5 %
Autonomy System	1 day
Performance Ratio	**77.35 %**

The parameters for the calculation of performance ratio and energy losses for a shared solar system are shown in table 9 above.

According to the simulation, the performance ratio of the shared solar system is 77.35 % which also indicates the efficiency of the system. It means that the system utilizes 77.35 % of the total available solar energy and uses it to generate electricity. The total daily energy requirement of the ten houses is 2,999.35 Wh/day.

The power of PV modules for the shared solar system are calculated automatically in the simulation program. Table 10 below shows the parameters or values for the calculations of modules.

Table 10. Details for the calculations of PV power system

Parameters	**Value**
Annual optimal inclination	14.09 º

Monthly average maximum daily temperature (for 3 months)	30.18 º
Maximum Sun Hours worst in months	5.94 HSP
Calculated power necessary	560 W
Power System	24 V

The output power of the shared solar PV system achieved under full solar radiation is 690 W. Hence, the photovoltaic power of the entire system is 690 Wp.

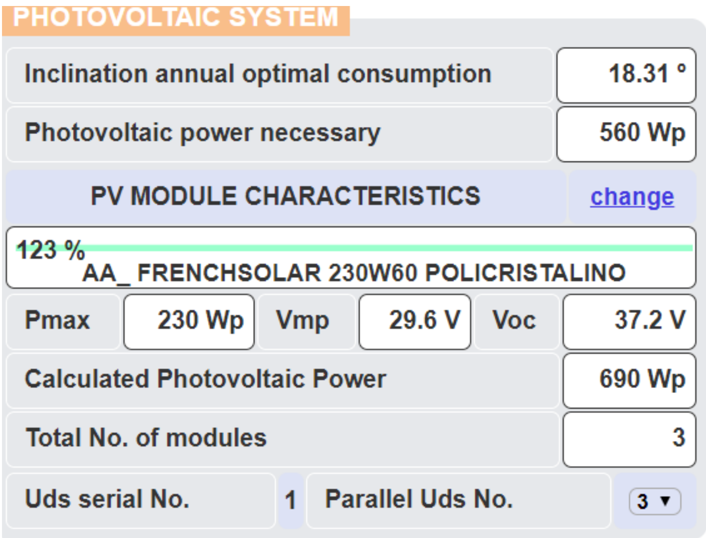

Figure 14. Brief Details of PV module.

For the calculation of the battery for the shared solar system, the system voltage and the depth of discharge and autonomy of the system are considered. For this calculation, the number of autonomy days is assumed to be 1.

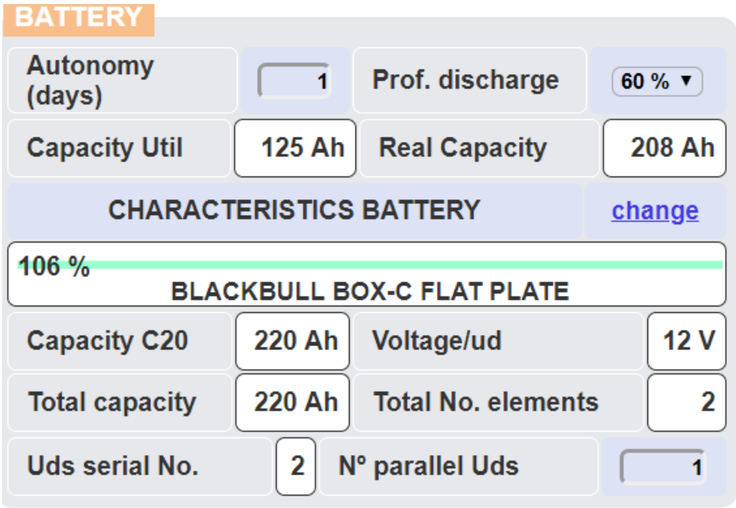

Figure 15. Information of Battery for the system.

The nominal voltage of the battery used in the simulation is 24 V and the depth of discharge of the battery is 60 %. As a result, a battery of 208 Wh capacity should be used in the shared solar system in order to provide the required daily energy of 2,999 Wh. Since extra losses, such as short circuits, can occur during the transmission of current, a battery with more capacity is valued. Therefore, total capacity of the battery after considering the losses is 220 Ah.

6 Calculation Results

The calculation in the previous chapter covered the information on both single-family house systems and shared systems. The calculation was made on the basis of several reports, collected in the appendix, and by evaluating the need of sustainable electricity in developing countries.

Chapter 5 shows the calculations for a PV system for both a single-family house system and a system for a small village. The spreadsheet in figure 8 above calculates the needs of an average single family in developing countries. This calculation acts as baseline for all the calculations made for the cases in Malawi and Niger.

6.1 System Design and Configuration

Tilt Angle

The tilt angle of a PV array is the key to determining the optimum energy yield. Given that the value of the tilt angle is different for different countries, the value is directly proportional to energy production. A small change in the angle can change the amount of production. The tilt angles or inclination angles are 5° for Malawi and 14° for Niger. The angles are determined automatically by the software by locating the latitudes and longitudes on a given location.

Ground-Mount System

A ground mount system was chosen because rooftops are not always constructed strong enough as in developed countries. For the calculations, it is assumed that both the single home system and the shared PV system panels are attached to the ground and slightly elevated according to the inclination required for optimum radiation. Some rooftops are too small or have too many obstructions, e.g. chimneys and vents. Rooftop mounting can also be problematic for shared systems, as all rooftops might not face the same direction, or towards the sunlight. Furthermore, a ground-mounted system is more accessible to all the houses, leaving complex wirings and roof problems aside (see figure 17). [38.]

Figure 16. ground-mounted solar PV system [39].

Selection of System Voltage

In the calculations, the single house system is a 12V system whereas the shared system is 24V system. The system voltage is selected based on the requirements of the system. For picking the right one, the system compatibility with battery, load, solar panels and charge controller are checked. The general rule of thumb is that the system voltage increases with an increased daily load. Since a single house system has a smaller load than a shared system, a 12 V system is enough for a single house.

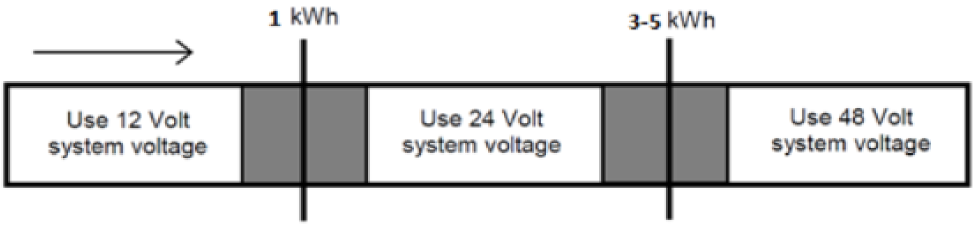

Figure 17. System voltage with different loads.

PV arrays

The PV module used in the calculations was selected by looking at the performance, warranty, high efficiency and availability of various modules. Monocrystalline solar panels are chosen in the simulations as they are the technologically most developed solar panels available.

Table 11. Energy demands and design

Solar system type	**Power system**	**Required power system**	**Degree of optimization**	**Total PV modules**
Malawi 1 family	95 W	85 W	112 %	1
Niger 1 family	65 W	66 W	102 %	1
Malawi 10 family	855 W	778 W	110 %	3

Niger 10 family	690 W	560 W	123 %	3

The calculation result in table 11 shows that the degree of optimization is tactically made to be more than 100 % in all system types so that if more power is consumed in a day, the system can still produce more than the required amount to cover the extra needs. Especially in the shared system, if any family uses more than the allocated amount of electricity, the extra power will help to cover the needs of other families. It will also be advantageous during the winter as the extra power of one day can provide power for following days when there is not much sunlight.

Battery Bank Sizing and Selection

In the calculations, the days of autonomy were kept at one day for both the single house system and the shared systems because the systems are for home purposes only and for the rural people of developing countries, and having more days of autonomy would have required more battery banks and that would have been expensive. Furthermore, the budget for the systems would mostly be covered by loans or subsidiaries from various organizations or the government, which means that the budget is more likely to be small. Another parameter for sizing the battery bank is determining the amount of storage required to provide the off-grid system families. The required loads are considered an important part besides the autonomy days in sizing a battery bank. A further important factor in the sizing of a battery bank is the depth of discharge. In all the simulations, the depth of discharge is 60 %.

Table 12. Load specifications of batteries

Solar system type	Total/Nominal Capacity	Real/Usable Capacity	No. of battery	Degree of Optimization	Battery Voltage
Malawi 1 family	50 Ah	41 Ah	1	122 %	12V
Niger 1 family	45 Ah	41 Ah	1	110 %	12V
Malawi 10 family	220 Ah	208 Ah	2	106 %	24V

Niger 10 family	220 Ah	208 Ah	2	106 %	24V

In table 12, the degree of optimization is calculated to be above 100 % for better performance of the battery and the system, as well as to prolong the battery age. Nominal capacity of a battery is the amount of energy than can be withdrawn from it at a constant current, whereas usable capacity of a battery is the amount of energy available for specific purposes. [40.]

6.2 Simulation Result

The four simulations for the two countries indicate that a small solar PV system as a source of energy in rural areas of developing countries is successful. Both single and shared PV system types can be installed and used for personal purposes. The following discussion compares the technical and social effects of single and shared PV systems based on the data from the simulations described in chapter 5.

The energy production of a single-family house system is calculated on the production being 85 W for Malawi and 65 W for Niger, depending on the location and amount of sun hours, in order to produce 296 Wh in a day. For shared family PV system the calculation was based on a ten family shared PV system to produce 778 W for Malawi and or 560 W for Niger in order to produce 2,999 Wh in a day, which is at least 12 % less than the production of ten combined single PV systems.

For a single-family house PV system to produce 296 Wh of electricity, one 95 W rated solar panel in Malawi and one 66 W rated solar panel in Niger are enough. Whereas for shared family PV system to produce 2,999 Wh of electricity, three 285 W rated solar panels in Malawi and three 230 W rated solar panels in Niger are more than enough, whereas ten individual families would require more panels to reach same power production amount.

Similarly, each single-family house PV system requires 50 Ah of battery capacity in Malawi and 45 Ah of battery capacity in Niger to store the energy produced and run the system. A shared family PV system has as storage a battery with a capacity of 220 Ah.

Calculating the single-family data, ten families would require a total battery capacity of 500 Ah in Malawi and 450 Ah in Niger, or twice as much as the 220 Ah in a shared system.

The cost of a single-family house PV system varies around the world, averaging between 200-350€ for one system [54; 55]. Whatever the cost, the cost for ten separate single-family systems would be ten times the cost. A shared family PV system requires less power and fewer devices to operate and fulfil the needs of ten families than one single family house system for ten families. Therefore, each family would pay less for a shared system than they would pay for a single-family house system.

The maintenance of a single-family house system is straightforward and convenient, but the maintenance cost bearer is only one family, which might turn out to be expensive if a part needs to be replaced. The maintenance is highly unlikely to be free of cost if the system is funded by NGO or any private organisation. In a shared family PV system, the problems in the system are solved by the group. Moreover, when a part needs to be replaced everyone in the group will participate which will ease the burden of expensive costs for one family. If the system is funded or owned by a private NGO, the maintenance is likely to be free of cost.

Another important part is handling of the system. At least one family member must have the skills to operate the devices in case of errors and replacements if a single-family house PV system is chosen. When a shared family PV system is built, it is simpler to have one person of the group with a skill set to care for the whole system. If the area is extremely rural with low literacy rate, the one person with such skills in an entire village is a boon.

The use of solar power to replace fossil fuels reduces the carbon footprint of a family when a single-family house PV system is used. However, the reduction of the carbon footprint reached with a shared system is larger than that of ten families with a single family house PV system each, as not only is fossil fuel usage reduced but also less energy has to be generated in order to solve the energy crisis. So fewer equipment has to be produced in shared system.

As can be seen, the differences between energy generated by a single-family house system and by a shared PV system are clear. The thesis aimed at showing the importance of PV systems for sustainable development. The calculations supported the hypothesis. Moreover, in trying to establish which system would be better, a comparison suggested that a shared PV system is more efficient than a single-family house PV system as a single-family house PV system is less affordable than a shared off-grid PV system.

7 Investment and maintenance of shared off-grid PV system

When discussing the sustainability of rural electrification, it is also important to discuss the financing and operations of the systems. Various small factors line up as a project turns into an actual process. Such factors can be operations and maintenance, the role of the private sector, tariffs and the total management of process. A project design does not only include technical specifications but its financial and sustainable conditions. However, as the innovations on PV systems go strong, the prices of the total cost of financing the PV projects including all the components have fallen in the past decade, which has made investments in PV systems much easier in developing countries. Solar panels are evolving at a rapid pace, with their efficiency and availability around the globe, in different sizes and power, increasing. [41; 42.]

7.1 Investment in PV systems

It is very important to consider the socio-economic situation of rural villages when planning an off-grid power system. Since an entire PV project may be expensive to pay by the villagers themselves, the project can be funded by various bodies. The World Bank (WB) and the International Finance Corporation are major financiers of PV systems in developing countries [43]. Other contributing organizations are International Energy Agency, Eurosolar, Alliance for Rural Electrification and several UN bodies [44]. Several of these organizations, including International Non-government Organizations, have also been working together with local private companies to expand the solar development projects.

Alternative ways to fund PV projects (figure 19) in rural are as in developing countries are

- A project fully funded by an INGO or the national government
- A project funded partly by an INGO and partly by the national government
- A project funded by an INGO, the local government, a private company and the community/village together
- A project funded by the local government and a private company together.

Figure 18. Financing of Shared PV System [45].

The funds can be donations or subsidies. The project can achieve its sustainability when the community or the consumers get involved in the process. The involvement includes their support and manpower during installation of the panels and entire system, using locally available resources to help the installation of equipment. Furthermore, the space or land for the PV system should be provided by the local people. These are also parts of the investments.

7.2 Pay-as-you-use

The pay-as-you-use method for paying for the shared PV system is a system where a family (consumers) pay to the organization or company every month on the basis of the amount of electricity they consume. This system can be applied by using a small metre box to every family. The electrical metre box records the amount of electricity used in a month. Every country has different rates, plus in some regions rates differ throughout the country, therefore the rate of use can be decided by discussion between the community and the organization. The payments collected can be used either to pay back the project costs, or on various other purposes in the future.

7.3 Maintenance

The initial investment in PV systems can be expensive, but the systems may have low maintenance and operating costs. Taking good care of the equipment does not only prevent unanticipated disasters, but also prolongs the lifetime of the equipment used. The electricity generation and distribution equipment must be timely maintained to operate efficiently and to make the project as sustainable as possible. The panels must be cleaned in order to prevent dust deposit on their surfaces. The deposits of dust or foreign particles on the surface of panels block solar radiation entering the panels and this, naturally, reduces the energy yield. The connections between panels, batteries and other equipment should be kept firm, and any leakage or electrical fault should be dealt with immediately.

Normally when it comes to maintenance, there is always the question of costs, manpower and the person responsible for monitoring the ongoing maintenance. But in a shared off-grid PV system, there is no need for an additional budget for such purposes. When the users pay for the usage of electricity, the money can be saved, and that money can be used for these operations. The money will not only pay for the maintenance of parts and buying them, but it can also be used to hire manpower who will oversee all the projects in certain regions. Furthermore, this creates job opportunities in rural regions.

8 Positive Impacts of Off-grid Shared PV System

PV energy is always an easy alternative source of energy because the sun’s energy is abundantly found on the Earth’s surface. The generation of PV electricity has various benefits for nature, the society, and economy, as discussed below.

Benefits for Nature

PV systems keep the environment clean. Burning fossil fuels produces a lot of useful as well as harmful energy and substances. Such substances produce large quantities of carbon particles that trap heat in the atmosphere, which ultimately leads to climate change [46]. The main reason to use a renewable source is to replace non-renewable energy sources. A lot of non-renewable energy sources are used in far rural areas of developing countries because of a lack of grid electricity. The non-renewable sources are expensive and create a lot of negative impacts on both health and environment. Energy is produced in such regions by burning fossil fuels and woods. Replacing them with PV helps keeping the environment clean and preventing the negative impacts of carbon particles. Off-grid solar powered systems minimize the carbon footprint while keeping the air and environment clean.

Social Benefits

A shared PV system for at least eight to ten families living in the same village or in a close community requires active participation for the project to be sustainable and long-lasting. Such projects help generating awareness in the society about the importance of sustainability and renewable sources and creates special bonds and harmonies between the families in the community.

Figure 19. Active participation as importance to society [47].

Such community-based projects can provide local economic benefits through building skills, creating new jobs and providing work for local installers. The projects require man-power for installation and maintenance. Thus, a PV project produces skilled manpower which assists in solving unemployment problems in rural regions of a developing country.

Better lighting

Fuel based lamps, such as kerosene lamps are expensive, inefficient and provide poor lighting. On a long run, the use of a PV system can be a better money saving option for poor families. The great thing about a PV system is that the family only has to pay very little for the energy they use, a lot less than for using any kerosene-based products to light the house. A single family can use at least three LED lamps, which is further beneficial to all family members if they have several rooms.

Health benefits

According to reports, renewable solar systems have health merits. When kerosene lamps are burned, they not only produce a dim light which is bad of the eyesight but also a heavy amount of smoke, including fine particulates, carbon monoxide, nitric oxides and sulphur dioxide. These products can reduce the lung function increasing the risks for asthma and cancer. In the developing countries with a warm climate, there are various infectious insects, including mosquitos. Such insects spread malaria, cholera, dengue and typhoid fever to thousands of people. So, the use of kerosene and diesel lamps forces people to open the windows in order to let the smoke out, letting in various insects. The use of a solar system replaces oil lamps, which ultimately increases the health benefits of the rural people. [48; 49.]

9 Conclusion

The main aim of this thesis was to collect enough data to introduce the possibility of shared off-grid PV system. The need originated from millions of people living without light all around the globe. There have been several earlier projects, such as mini grid, SHS and national grid projects to help the needy ones. But because of a lack of funding for big projects and limited availability of SHS, there are still people living in the dark during the night. The power generated by a shared solar PV system is intended to cover a 100 % of the energy demand in a small village or community.

The shared off-grid PV system can be a success in bringing light to rural areas of developing countries around the globe. This would, ultimately, help improving the socio-economic situation in those countries. With electricity, rural areas can improve the quality of life and produce profound development effects. The world needs self-sufficient, sustainable projects where families produce the energy they need with renewable resources, participating in the project that create harmonies in the society. Although the case studies discussed in the thesis are limited in scope, the main findings can be used all around the globe. A shared off-grid PV project is, however, not aimed at rich or middle class people, but rather to people who live their everyday life in the light of a kerosene lamp or with less powerful SHS systems or with constant blackouts from the grid power.

The reason developing countries are interested in PV energy generation is mostly its cost competitive applications, continual technological development, and the control of environmental issues. Off-grid electrification offers the best solution to bringing electricity to remote areas, it is a clean, sustainable and economically viable method already available.

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Appendix 1. Formula and Parameters for Sun Hours

For the calculation of the time are pico, we used the NREL-NASA database, contemplating chosen inclination and orientation and location data instead.

The solar declination is calculated with the following formula:

$$[1]\ \delta = 23{,}45 \cdot \text{sen}\left(360 \cdot \frac{284 + \delta_n}{365}\right)$$

δ: declination (degrees)
δ_n: day of year (1 ... 365, taken 1 for the day January)

They have chosen a day of each month, which coincides with a day in mid-month.

For the calculation of the solar elevation values ??are taken:

- $(90^\circ - \varphi - \delta)$ on winter solstice
- $(90^\circ - \varphi + \delta)$ on the summer solstice

φ being the latitude and declination δ.

To determine the optimal inclination have used the following assumptions:

- $\beta = \varphi - \delta$ on the summer solstice
- $\beta = \varphi + \delta$ on winter solstice

through the value $\beta = \varphi$ at the equinoxes
φ being the latitude and declination δ.

To rad_glo_op parameter estimation, we have used the following formula:

$$G_a(\beta_{opt}) = \frac{G_a(0)}{1 - 4{,}46 \cdot 10^{-4} \cdot \beta_{opt} - 1{,}19 \cdot 10^{-4} \cdot \beta_{opt}^2}$$

$G_a(\beta_{opt})$: annual mean global irradiation optimally inclined surface (kW · h / m²)
$G_a(0^\circ)$: annual average global horizontal irradiation (kW · h / m²)
β_{opt}: Optimum surface inclination (°)

For obtaining irradiance factor (FI) have been used the following expressions:

$$FI = 1 - [1{,}2 \times 10^{-4} (\beta - \beta_{opt})^2 + 3{,}5 \times 10^{-5} \alpha^2] \quad \text{for } 15^\circ < \beta < 90^\circ$$

$$FI = 1 - [1{,}2 \times 10^{-4} (\beta - \beta_{opt})^2] \quad \text{for } \beta \leq 15^\circ$$

FI: Radiation factor (unitless)
β: Actual surface inclination (°)
β_{opt}: Optimum surface inclination (°)
α: surface azimuth (°)

Finally the peak sun hours (HSP) is the result of multiplying the optimal global radiation (Ga (ßopt)) by a factor of irradiation (FI).

Figure 1. Formula and parameters used for calculating maximum sun hours.

Appendix 2: Technical data from Simulation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of month	31	28	31	30	31	30	31	31	30	31	30	31
Declination	-21.27º	-13.62º	-2.02º	9.78º	19.26º	23.39º	21.18º	13.12º	1.81º	-10.33º	-19.6º	-23.4º
Nº day/year	15	45	76	106	137	168	198	229	259	290	321	351
Solar elevation	97.48º	89.83º	78.22º	66.42º	56.94º	52.82º	55.02º	63.08º	74.39º	86.54º	95.81º	99.61º
optimal inclination	7.48º	0.17º	11.78º	23.58º	33.06º	37.18º	34.98º	26.92º	15.61º	3.46º	5.81º	9.61º
rad_glo_hor	4.53	4.75	5.19	5.24	4.86	4.47	4.64	5.34	6.3	6.54	5.95	4.84
rad_glo_op	4.58	4.75	5.31	5.68	5.68	5.46	5.53	5.92	6.53	6.56	5.99	4.92
FI	1	1	0.99	0.96	0.91	0.88	0.89	0.94	0.99	1	1	1
HSP/day	4.58	4.75	5.25	5.45	5.17	4.8	4.92	5.57	6.47	6.56	5.99	4.92
HSP/month	141.98	133	162.75	163.5	160.27	144	152.52	172.67	194.1	203.36	179.7	152.52
Temp day max	25.74º	26.04º	25.83º	25.41º	24.34º	22.55º	22.55º	24.59º	27.78º	29º	28.49º	26.57º
Consu/HSP day	64.66	62.35	56.41	54.34	57.28	61.7	60.19	53.17	45.77	45.14	49.44	60.19

Figure 1. 12 months data for case study Malawi one family.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of month	31	28	31	30	31	30	31	31	30	31	30	31
Declination	-21.27º	-13.62º	-2.02º	9.78º	19.26º	23.39º	21.18º	13.12º	1.81º	-10.33º	-19.6º	-23.4º
Nº day/year	15	45	76	106	137	168	198	229	259	290	321	351
Solar elevation	97.48º	89.83º	78.22º	66.42º	56.94º	52.82º	55.02º	63.08º	74.39º	86.54º	95.81º	99.61º
optimal inclination	7.48º	0.17º	11.78º	23.58º	33.06º	37.18º	34.98º	26.92º	15.61º	3.46º	5.81º	9.61º
rad_glo_hor	4.53	4.75	5.19	5.24	4.86	4.47	4.64	5.34	6.3	6.54	5.95	4.84
rad_glo_op	4.58	4.75	5.31	5.68	5.68	5.46	5.53	5.92	6.53	6.56	5.99	4.92
FI	1	1	0.99	0.96	0.91	0.88	0.89	0.94	0.99	1	1	1
HSP/day	4.58	4.75	5.25	5.45	5.17	4.8	4.92	5.57	6.47	6.56	5.99	4.92
HSP/month	141.98	133	162.75	163.5	160.27	144	152.52	172.67	194.1	203.36	179.7	152.52
Temp day max	25.74º	26.04º	25.83º	25.41º	24.34º	22.55º	22.55º	24.59º	27.78º	29º	28.49º	26.57º
Consu/HSP day	654.88	631.44	571.3	550.34	580.15	624.86	609.62	538.48	463.58	457.22	500.73	609.62

Figure 2. 12 months data for case study Malawi Shared family

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of month	31	28	31	30	31	30	31	31	30	31	30	31
Declination	-21.27º	-13.62º	-2.02º	9.78º	19.26º	23.39º	21.18º	13.12º	1.81º	-10.33º	-19.6º	-23.4º
Nº day/year	15	45	76	106	137	168	198	229	259	290	321	351
Solar elevation	53.68º	61.32º	72.93º	84.73º	94.21º	98.33º	96.13º	88.07º	76.76º	64.61º	55.34º	51.54º
optimal inclination	36.32º	28.68º	17.07º	5.27º	4.21º	8.33º	6.13º	1.93º	13.24º	25.39º	34.66º	38.46º
rad_glo_hor	5.43	6.43	6.98	7.48	7.4	7.22	7.02	6.65	6.47	6.41	5.87	5.15
rad_glo_op	6.57	7.23	7.29	7.52	7.43	7.31	7.07	6.66	6.65	7.03	6.97	6.38
FI	0.94	0.97	1	0.99	0.99	1	0.99	0.98	1	0.98	0.95	0.93
HSP/day	6.17	7.01	7.29	7.45	7.36	7.31	7	6.53	6.65	6.89	6.63	5.94
HSP/month	191.27	196.28	225.99	223.5	228.16	219.3	217	202.43	199.5	213.59	198.9	184.14
Temp day max	28.2º	30.73º	35.54º	38.94º	37.9º	35.46º	31.3º	30.88º	33.65º	35.98º	33.14º	29.19º
Consu/HSP day	48	42.25	40.62	39.75	40.24	40.51	42.31	45.35	44.53	42.98	44.67	49.86

Figure 3. 12 months data for case study Niger SHS System

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days of month	31	28	31	30	31	30	31	31	30	31	30	31
Declination	-21.27º	-13.62º	-2.02º	9.78º	19.26º	23.39º	21.18º	13.12º	1.81º	-10.33º	-19.6º	-23.4º
Nº day/year	15	45	76	106	137	168	198	229	259	290	321	351
Solar elevation	53.68º	61.32º	72.93º	84.73º	94.21º	98.33º	96.13º	88.07º	76.76º	64.61º	55.34º	51.54º
optimal inclination	36.32º	28.68º	17.07º	5.27º	4.21º	8.33º	6.13º	1.93º	13.24º	25.39º	34.66º	38.46º
rad_glo_hor	5.43	6.43	6.98	7.48	7.4	7.22	7.02	6.65	6.47	6.41	5.87	5.15
rad_glo_op	6.57	7.23	7.29	7.52	7.43	7.31	7.07	6.66	6.65	7.03	6.97	6.38
FI	0.94	0.97	1	0.99	0.99	1	0.99	0.98	1	0.98	0.95	0.93
HSP/day	6.17	7.01	7.29	7.45	7.36	7.31	7	6.53	6.65	6.89	6.63	5.94
HSP/month	191.27	196.28	225.99	223.5	228.16	219.3	217	202.43	199.5	213.59	198.9	184.14
Temp day max	28.2º	30.73º	35.54º	38.94º	37.9º	35.46º	31.3º	30.88º	33.65º	35.98º	33.14º	29.19º
Consu/HSP day	486.12	427.87	411.43	402.6	407.52	410.31	428.48	459.32	451.03	435.32	452.39	504.94

Figure 4. 12 months data for case study Niger Shared System

SIMAX SM536-85 MONOCRISTALINO			
Open circuit voltage (Voc):	21.8 V	Voltage at maximum power (vmp):	17.6 V
Short circuit current (isc):	5.51 A	Current at Maximum Power (Imp):	5.11 A
Maximum power:	95 W	Temperature Coefficient of Pmax:	0.065 %/ºC
Real power max Average temperature:	95.0728 Wp	Serial Number of modules:	1
Total Pico Power modules:	95 Wp	No. parallel series:	1
Optimization installation / needs most unfavorable month:	1.12	Total modules:	1
The degree of optimization election equipment / real needs is			112 %

Figure 5. Details of the module and load selected for Malawi SHS

CALCULATIONS REGULATORS

For the choice of the controller takes into account the voltage of the system, the parameters of photovoltaic modules, which gives us a certain degree of optimization. View following:

* Power system: 12 V
* Open circuit voltage modules: 21.8 V
* Maximum voltage power modules: 17.6 V
* Short circuit current module:5.51 A
* Current at maximum power module: 5.11 A
* No. of series modules installed: 1
* Number of parallel modules installed: 1
* Total modules installed:1
* Intensity module to system voltage (open): 5.51 A
* Current to voltage module system (closed): 5.11 A
* Total current system (open):6 A

The choice of the regulator is as follows:

STECA SOLSUM 8/8 PWM			
Tension:	12-24 V	Voltage:	47 V
Rated power:	96 Wp	Consumption:	4 mA
Capacity:	8 A	Utilization ratio:	0.76
The degree of optimization election equipment / real needs is	133 %	Number of Regulators:	1

Figure 6. details of Regulators selected Malawi SHS

ULTRACELL 120AH FLAT PLATE									
Capacities according to their hours of download:									
C 10:	77 Ah	C 20:	50 Ah	C 40:	70 Ah	C 100:	2 Ah	C 120:	12 Ah

Tension	12 V	Serial No. elements:	1
Nominal capacity accumulator:	50 Ah	No. parallel series:	1
Battery Nominal voltage:	12 V	Total elements:	1
The degree of optimization election equipment / real needs is			122 %

Figure 7. Details of Battery selected Malawi SHS

MCSOLAR MC-IE 20004000			
Tension:	12 V	Rated power:	4000 W
Continuous power:	2000 W	Pico Power:	2000 W
Consumption empty:	4.8 W	Efficiency:	89 %
Utilization ratio:	96 %	Number of inverters:	1
The degree of optimization election equipment / real needs is			104 %

Figure 8. Details of Inverter selected Malawi SHS

LG 285SC1C-L4 MONOCRISTALINO			
Open circuit voltage (Voc):	38.8 V	Voltage at maximum power (vmp):	31.7 V
Short circuit current (isc):	9.5 A	Current at Maximum Power (Imp):	9 A
Maximum power:	285 W	Temperature Coefficient of Pmax:	-0.39 %/ºC
Real power max Average temperature:	284.5632 Wp	Serial Number of modules:	1
Total Pico Power modules:	855 Wp	No. parallel series:	3
Optimization installation / needs most unfavorable month:	1.1	Total modules:	3
The degree of optimization election equipment / real needs is			110 %

Figure 9. Details of Module and load selected Malawi Shared System

CALCULATIONS REGULATORS

For the choice of the controller takes into account the voltage of the system, the parameters of photovoltaic modules, which gives us a certain degree of optimization. View following:

* Power system: 24 V
* Open circuit voltage modules: 38.8 V
* Maximum voltage power modules: 31.7 V
* Short circuit current module:9.5 A
* Current at maximum power module: 9 A
* No. of series modules installed: 1
* Number of parallel modules installed: 3
* Total modules installed:3
* Intensity module to system voltage (open): 9.5 A
* Current to voltage module system (closed): 9 A
* Total current system (open):29 A

The choice of the regulator is as follows:

STECA TAROM 235 PWM			
Tension:	12-24 V	Voltage:	48 V
Rated power:	0 Wp	Consumption:	14 mA
Capacity:	35 A	Utilization ratio:	0.84
The degree of optimization election equipment / real needs is	12[illegible] %	Number of Regulators:	1

Figure 10. Details of Regulators selected Malawi Shared System

BLACKBULL BOX-C FLAT PLATE									
Capacities according to their hours of download:									
C 10:	199 Ah	C 20:	220 Ah	C 40:	235 Ah	C 100:	250 Ah	C 120:	265 Ah
Tension	12 V	Serial No. elements:	2						
Nominal capacity accumulator:	220 Ah	No. parallel series:	1						
Battery Nominal voltage:	24 V	Total elements:	2						
The degree of optimization election equipment / real needs is	106 %								

Figure 11. Details of Battery selected Malawi Shared System

INVERTER

For the sizing of the inverter is used the following data:

* Voltage DC system: 24 V
* AC output voltage: 110 V
* Maximum power: 2197 W
* Coefficient Concurrency: 0.7
* Power requirement: 1538 W
* Safety factor: 0.8
* Power calculation: 1922 W

The choice of inverter is as follows:

MUST EP30-2KW PRO			
Tension:	24 V	Rated power:	6000 W
Continuous power:	2000 W	Pico Power:	750 W
Consumption empty:	2 W	Efficiency:	88 %
Utilization ratio:	96 %	Number of inverters:	1
The degree of optimization election equipment / real needs is			104 %

Figure 12. Details of Inverter selected Malawi Shared System