Bachelor's Thesis (UAS)

Degree Programme in Electronics

2013

Constantino Miguélez Peña

EVALUATION OF A MICRO-POWER PLANT USING SOLAR CELLS

TURUN AMMATTIKORKEAKOULU
TURKU UNIVERSITY OF APPLIED SCIENCES

BACHELOR´S THESIS | ABSTRACT
TURKU UNIVERSITY OF APPLIED SCIENCES

Degree Programme in Electronics

May 2013| 60 pages

Yngvar Wikström, M.Eng.

Constantino Miguélez Peña

EVALUATION OF A MICRO-POWER PLANT USING SOLAR CELLS

The purpose of this thesis was to evaluate the operation of a photovoltaic system, installed by Dise-Tech company in the locality of Korppoo, in South-West Finland.

This thesis is divided in three parts: a brief introduction about photovoltaic systems, a description of the micro power plant, and finally, a study of its operation in energy and economic terms.

The work was implemented by studying and examining the individual components on the installation, their configuration and the global set up. Calculations were carried out using computer simulation and data collected on the field. The results show the range of potential that this system has in order to cover the energy demands from the loads connected, along with an economic study of costs and the amortization time.

Due to the local insolation conditions at this latitude, there are great differences in photovoltaic power generation throughout the year. However, results show that this micro-power plant will generate, in the long-term, both economic and environmental paybacks greater than its manufacturing and implementation costs.

As an outcome, the most important issues concerning a micro power plant design are the handling of surplus energy under higher insolation conditions as well as the configuration of energy storage subsystem.

KEYWORDS:

Photovoltaic, bioclimatic architecture, solar energy, sustainability.

CONTENT

LIST OF ABBREVIATIONS

AGM	Absorbent Glass Mat
DoD	Depth of discharge
Gel	Gel-cell
GTO	Gate Turn-off Thyristor
IGBT	Insulated Gate Bipolar Transistor
Ni-Cd	Nickel-Cadmium
OCV	Open circuit voltage
Pb-a	Lead-acid
Pm	Maximum power point
SoC	States of charge
PV	Photovoltaic
STC	Standard Test Conditions
SCR	Silicon Controlled Rectifier
VRLA	Valve-Regulated Lead-Acid
Wp	Peak watt

FIGURES

TABLES

1 INTRODUCTION

The aim of this thesis was to examine the operation and configuration of a photovoltaic system installed and configured by the owner on his private house. There is a variety of solar energy thesis about photovoltaic installations, however, regarding this particular system, no previous studies had been performed.

The present text approaches this task by a describing the different elements comprised in a photovoltaic system, analyzing its performance and configuration; and finally, studying the costs and payback time of the installation.

The performance of the system depends on several factors such as local insolation, orientation of the solar panels and configuration of the inverter, regulator and batteries. This thesis describes the different features of the elements on the system, with especial focus on the batteries; which are the most sensitive element in the installation, as their life time is greatly affected by their operating conditions.

The estimations of energy generation were obtained from computer simulations with nearby weather data, over a one year period. Energy consumption data was obtained through statistical analysis of samples taken periodically during seven months.

Results exhibit the capability of the system in order to cover the energy demands from different sets of loads in the system, over different months of the year; as well as estimations for battery sizing according to the measured energy consumption and some recommended changes in the configuration in order to improve the performance of the installation.

2 BACKGROUND

The Sun is a yellow dwarf star of the fifth magnitude, separated from Earth a distance about 150 million kilometers. It is a 10^{24} ton nuclear fusion reactor which radiates energy at a rate about$3.8 * 10^{24}\ MW$.It generates energy at a rate that will remain unchanged during several billion years

Solar energy is an inexhaustible and green energy that over last years, has experimented a reduction on manufacturing costs as photovoltaic installations have become more common and widespread. Bioclimatic architecture integrates solar technologies on new or existing buildings; making them more environmentally friendly and less dependent on the provider's grid as main source of energy.

The installation of photovoltaic systems on existing buildings is a long term investment, on both, energy and sustainability. Installation costs can be paid out before the end of life of the installation, as the price per kilowatt hour increases, the more profitable the installation becomes. By choosing this green energy, the user saves the environment from CO2 emissions by reducing his dependence on fossil fuels.

2.1 Solar radiation

Solar radiation is the set of electromagnetic radiations produced by the sun. The sun behaves practically as a black body that emits energy according to Plank's law, at a temperature around 6000 ºK. Not all solar radiation hits the Earth's surface; ultraviolet light is absorbed mainly by atmospheric ozone.

The radiation that reaches the surface of Earth has a direct component and diffuse one. Direct radiation comes directly from sun, without reflections. Diffuse radiation, which is approximately 50% of the solar available energy, is emitted by sky due to reflection phenomena on atmosphere, clouds and other atmospheric and terrestrial elements.

Direct radiation may be reflected and concentrated for its utilization but it is no possible to concentrate diffuse light coming from every direction. Both direct and diffuse radiation components can be used to produce energy.

Radiation intensity varies throughout the day and it is also determined by atmospheric conditions and latitude. On good conditions, the radiation power on the surface of earth is 1000 W/m2, this power density is known as irradiance.

The direct normal irradiation (perpendicular to solar rays), outside atmosphere, is called solar constant, it has an average power density of 1354 W/m. [2]

2.2 Photovoltaic effect

Solar cells convert the sunlight into electrical current in virtue of the photovoltaic effect.

Photovoltaic (PV) cells are made of semiconductor materials such as silicon, commonly doped with phosphorous to create an excess of electrons (n-type) and boron, to create an excess of holes (p-type). When two layers of these materials are placed together, they form a pn junction. Due to the charge disparity, both layers create an electrical field between them. When a photon is absorbed by a solar cell, its energy is transferred to an atom of its structure, exciting an electron, which travels to a further orbit from the nucleus or higher energy level. When the energy of the photon is high enough, the electron can escape from the atom, leaving a hole behind. This electron will tend to move into the n-type side of the junction, while the hole will tend to move to the p-type layer of silicon.

On the front side of the solar cells there are conductors or metallic grids which behave as current collector, since the pn-junction creates an electrical field, each released electron will move into the current collector, generating electrical current and then reappearing on the p-type silicon layer

On the back side, solar cells have an antireflective layer to increase the amount of absorbed photons, maximizing the generated current. [2]

2.3 Solar cells

Solar cells are between 200 and 400 µm in width and they normally have an area between 8 and 10 square centimeters. The output power they can produce relies mainly on the sunlight spectra and temperature conditions, for this reason they are classified in terms of power by their nominal power rating.

The most common solar cell types that are used to generate electricity are Polycrystalline silicon, Monocrystalline silicon and Amorphous (thin film) cells.

2.3.1 Monocrystalline cells

Monocrystalline cells are built from a single silicon crystal. These modules have efficiency 2 % to 15 % higher than polycristalline modules making them the most efficient photovoltaic technology.

Monocrystalline cells are characterized for having a continuous crystal structure. They are manufactured by using the Czochralski process, an expensive and time-consuming technique that requires large amounts of energy and is used to fabricate high quality, electronic-grade silicon crystals.

Manufacturing costs are currently decreasing for this technology; it is expected to be the most cost-efficient PV technology within few years.

Since monocrystalline cells normally have a rounded or square-rounded shape, when they are mounted on the modules, it is not possible to use all the area on the panel for collecting energy.

Nowadays, monocrystalline modules offer better efficiency, but at a higher cost than polycrystalline silicon ones. [2]

2.3.2 Polycrystalline

Polycrystalline cells are also called semi-crystalline or multi-crystalline. They have efficiencies around 10 %.

These modules are built from several silicon crystals fused together. This characteristic is an advantage in a way that they can be shaped to fit the full area of a module.

During the recent years this technology has been the most popular in the market, until the recent drop of monocrystalline silicon manufacturing costs.

They are cheaper to produce than monocrystalline modules and more efficient than thin film technology ones. [2]

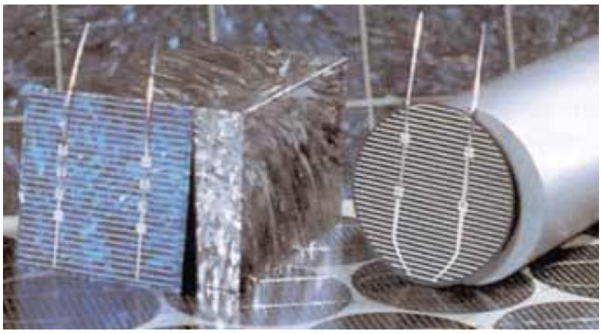


Figure 1 Polycristalline cell (left), Monocrystalline cell (right) [3]

2.3.3 Amorphous or Thin Film

Thin film solar technology is based on amorphous silicon, which has a more random orientation among the atoms of its structure.

These modules offer better performance at higher temperatures. On the manufacturing process, silicon is sprayed on the cell by a vapor deposition process, which can deposit a 1µm thick silicon layer, which is much thinner in comparison with polycrystalline or monocrystalline (200 µm).

The manufacturing process is highly automated and less energy-demanding than monocrystalline or polycristalline, there is a lower need for silicon and these modules do not need of an aluminum frame.

This technology the cheapest available nowadays but on the other hand, its efficiency is poor (5 %-6 %), taking greater areas for the same power output than other technologies.

The most significant feature of this thin film cells is their performance at higher temperatures and under lower sunlight irradiation levels.

Since it is a relatively new technology, it offers less proven reliability. [2]

2.4 Local insolation

Local solar insolation measures the solar potential for a region and typically is expressed as the ideal number of kilowatts per hour per square meter per day, so it shows the ideal maximum amount of power that could potentially be generated.

Knowing what is the efficiency of the solar panels that will be installed, which is normally below 20 %, local insolation values along the year will give an idea of how much power the system is going to generate.

2.5 Photovoltaic installations on existing buildings

Over the last years, it has been experienced a great development towards integration of photovoltaic systems on existing buildings or other types of structures exposed to sunlight.

The main objective is taking advantage of the architectonical possibilities on many roofs or walls of buildings in order to reduce the building’s use of energy from the external electrical grid and reducing its carbon dioxide footprint.

By installing solar energy technologies on new or existing buildings, it is possible to reduce the electrical consumption from the grid near to zero; these buildings are called near-zero or zero energy buildings.

Integration of photovoltaic systems on buildings is easier and more cost-effective. In many occasions PV panels can replace structural elements, lowering building costs, such as covers, roofs or tiles. [3]

2.6 On grid/off grid installations

On grid installations are photovoltaic installations connected to the energy provider network. Energy from the provider is only used then the demand is not satisfied by photovoltaic generation. Surplus energy is injected and the global electrical cost decreases.

Off grid or Stand-Alone photovoltaic installations are meant to deliver energy on isolated locations or rural areas far away from the energy provider network. They are relatively simple since they only require solar modules for power generation and batteries for energy storage. Stand-Alone PV configurations are also used for energy supply on many other devices located on remote places or where connection to the electrical grid is difficult or too expensive, such satellites, railway crossings or marine battery charge systems. [4]

2.7 Advantages and disadvantages of Photovoltaic energy

Advantages:

Solar energy is an inexhaustible source, offers high reliability and excellent operative availability.

Photovoltaic solar energy is one of the most promising energy sources, it is nonpolluting, and it does not need of a big set-up to start operating. Solar panels can be installed on buildings so they can produce their own energy in a clean and quiet way for up to thirty-five years under minimal maintenance.

Solar modules resist extreme climatic conditions and can be installed almost anywhere and are ideal for rural areas or isolated location where there is no electrical grid available. Solar installations offer easy scalability since it is possible to increase the total power produced by only adding more modules.

Non centralized energy generation helps to spread environmental consciousness on people since solar energy users become producers and users of energy they produce themselves, reducing their CO2 footprint and meeting their energy demand in a more sustainable way.

Manufacturing costs of photovoltaic panels are expected to decrease dramatically within next few years. [2] [5]

Disadvantages:

The main disadvantage of solar energy is that a solar installation requires an important initial investment and its amortization takes a long period of time. It is not economically competitive with other energy sources and requires a large area. Electrical energy is difficult to store and requires considerable space.

Manufacturing techniques of photovoltaic modules are complex, expensive and require high amounts of energy.

The energy generation is variable according to meteorology, location and time of the year, and optimal performance, which normally between 15 % and 25 %, requires readjusting the panels seasonally. [5]

3 MAIN COMPONENTS OF A PHOTOVOLTAIC INSTALLATION

3.1 Photovoltaic panels

For the practical use, individual solar cells are interconnected together forming a module, several modules are mounted on a larger frame called panel.

Solar panels can be installed in a wide variety of locations as long as they receive sunlight. Normally the optimal installation orientation is facing South direction and an inclination 5º or 10º less than the latitude angle of the location.

The conversion efficiency is the ratio of sunlight that every cells turns into electrical energy. Their average life ranges from thirty to thirty-five years.

When choosing solar panels there the most important characteristics to take into account are the following:

Maximum power point (Pm): It is the maximum amount of power that a module can deliver. It is specified on its characteristic curve for a range of different voltages and currents.

Peak watt (Wp): It is the maximum output power under standard test conditions or STC: Irradiance = 1 kW/m², Temperature = 25 ºC.

Solar cell conversion efficiency (η): It is the STC effective conversion from solar radiation power into electrical power.

$$\boldsymbol{\eta}(\%) = \frac{\boldsymbol{P}max}{A * \boldsymbol{E}} * 100$$

The value of 1000 corresponds to the irradiancy level under STC.

Pmax: Maximum power of the module (Wp)

E: Input light (W/m²)

A: Area of the module (m²) [6]

Cost-efficiency: It is the relation between the cost of a solar module and its efficiency in terms of euros per watt. It serves as comparison between different technologies that have different costs and efficiencies.

Warranty: The warranty of solar modules is expressed as assuring the maintenance of a percentage of the nominal power output during several years, which can be up to 35. Modules are in compliance with ISO 9001 normative and have a class-2 isolation. [1] [2]

3.2 Inverter

The inverter is the device responsible of converting the DC output of the PV panels and the batteries into alternate current. This conversion is done by a bridge of semiconductor switches (Thyristors, IGBT, GTO, SCR) depending on the frequency and power needed at the output. The conversion is done by PWM and its quality depends on the amount of pulses (on-off) performed by the inverter, so the higher it is the higher is the purity of the sinusoidal wave at its output. This is of special importance as the harmonic content increases as the output falls away from a pure sinusoid and gets closer to a square wave. This is inadmissible for inductive loads such as electrical engines which will dissipate higher amounts of energy as heat.

According to their output, inverters can be classified as square wave inverters (least efficient), modified wave inverters and sinusoidal wave inverters, which have efficiencies above 90%.

In the case of photovoltaic systems, there are specific inverters which can vary the output frequency according to the power input. Most technologies incorporate a system that varies the load seen by the PV array in order to operate on its maximum power point.

The performance of an inverter is not constant; it depends both of the type of the load (capacitive, inductive or resistive) and the power input, obtaining greater performances as it increases.

The most important characteristics of an inverter are:

- Voltage and Current inputs and outputs.
- Waveform type: Square, modified or sinusoidal.
- Voltage limit at the input.
- Total Harmonic Distortion (THD), which measured the purity of the output.
- Output power. [7]

3.3 Regulator

The regulator is the device responsible of controlling the charge and discharge of the batteries. On photovoltaic systems, on some devices it is included along with an inverter on the same box.

Its main duty is to disconnect the batteries from the load when their voltage drops below certain values in order to prevent damage to them and disconnects the batteries from charging when the voltage rises above certain level in order to prevent damage from overcharging as well. It helps to prolong the batteries’ life by monitoring the charge and discharge processes.

The main characteristics of a charge controller are nominal voltage and maximum operating current.

More sophisticated regulators allow selection of the cutoff voltages as a function of temperature in order to optimize charge and discharge processes; they take into account the type of the batteries and their operating temperatures. Some regulators can also monitor the maximum power point of the PV panels with the purpose of maximize the energy transfer from the panels to the batteries. In addition, some other regulators have monitoring systems that records the operational parameters of the system which can be transferred and configured from a computer. [7]

3.4 Battery array

Batteries store electrical energy, they absorb and release energy by chemical reactions. In PV systems, they allow the operation of the loads during the night or when there is not enough energy generated at the solar panels.

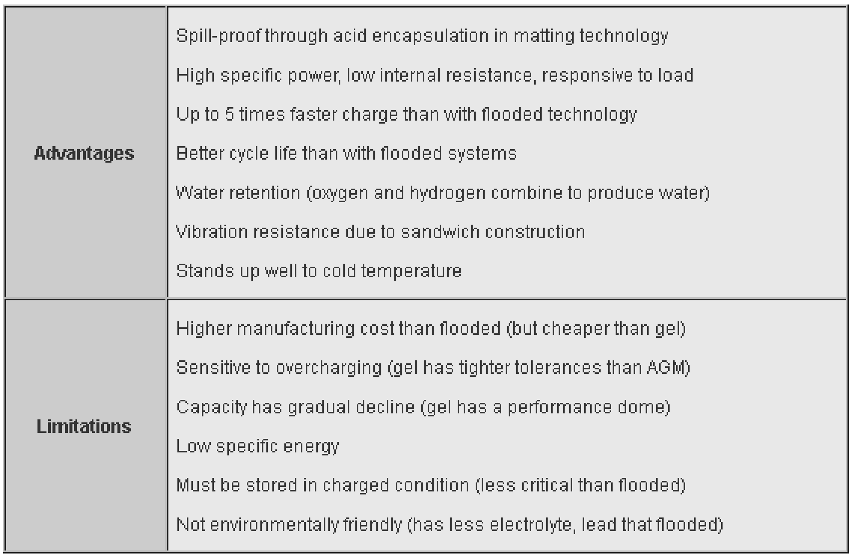
They serve to other objectives such as voltage stabilization or being a source of energy for power peaks that some appliances may require such as starting water-pumps or washing machines.

3.4.1 Common battery types in PV systems

Most common battery types are Lead-acid (Pb-a) and Nickel-Cadmium (Ni-Cd). Due to the higher price of the second ones, lead-acid are more widespread.

On photovoltaic systems most used batteries are Valve-Regulated Lead-Acid type (VRLA); which has two subtypes: AGM and Gel cell.

AGM batteries (Absorbent Glass Mat), in these batteries, the electrolyte is kept inside a glass mat, they support full discharges without being damaged, these batteries are ideal for solar systems, the energy stored on them can be used more efficiently than standard lead-acid batteries. These batteries are maintenance free, they are sealed in way there is no gas generation, they have low self-discharge and low internal resistance.



Advantages	Spill-proof through acid encapsulation in matting technology High specific power, low internal resistance, responsive to load Up to 5 times faster charge than with flooded technology Better cycle life than with flooded systems Water retention (oxygen and hydrogen combine to produce water) Vibration resistance due to sandwich construction Stands up well to cold temperature
Limitations	Higher manufacturing cost than flooded (but cheaper than gel) Sensitive to overcharging (gel has tighter tolerances than AGM) Capacity has gradual decline (gel has a performance dome) Low specific energy Must be stored in charged condition (less critical than flooded) Not environmentally friendly (has less electrolyte, lead that flooded)

Figure 2 Advantages and disadvantages of AGM batteries. (Gel-cell type batteries share many of these. [9]

In gel-cell (Gel) batteries the sulphuric acid is jellified by addition of silica fume. They are maintenance-free, withstand better deeper discharges, are less sensitive to temperature, are shock-resistant and have longer life. [8] [10]

3.4.2 Charging process

VRLA batteries and are Pb-a based, therefore, they are in the same way than standard Pb-a batteries. The procedure comprises three different charging stages according to battery charge level:

Bulk or Charge stage: The current is kept constant, the battery admits as much load as it can charge as long as its temperature does not exceed approximately 38ºC (AGM or Cell). During this stage, 80% of the total capacity of the battery is charged.

Acceptance or Topping stage: The voltage is maintained and the current slows down until fully charged, this prevents excessive acid stratification and gassing that shorten battery life.

Float stage: Voltage is reduced in order to compensate self-discharge, the battery is maintained charged indefinitely.

During charging process, the voltage levels on the battery's cells must be controlled in order to change from one state to other. The figure below shows a typical charging process of a lead-acid cell; during the first stage the cell is accepting constant current as voltage increases, during the second stage, current decreases until full load while voltage remains constant, batteries start gassing as they approach their full charge point if the charging rate is too high, the charging rate must be temperature-compensated in order to attain optimal operation, this is achieved by the use of a regulator with temperature compensation and voltage regulation. On third stage, voltage is reduced. While the battery is maintained fully loaded, floating charges are periodically performed in order to replenish the battery load from self-discharge losses. [10] [11]

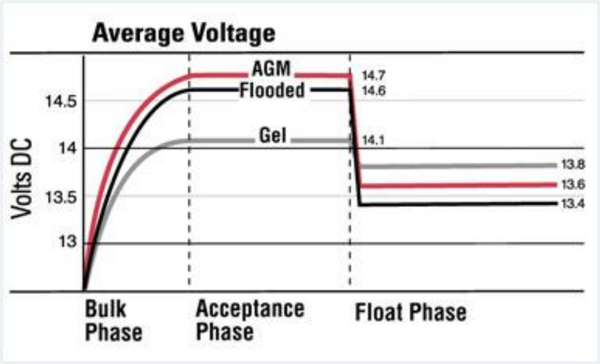


Figure 3 Typical charging states for a Pb-a battery [11]

2.4.3 Temperature

Chemical reactions have a strong dependency on temperature as a catalyzer. Under low temperatures chemical reactions occur more slowly, total capacity of the battery is decreased and gas production starts at higher voltages. The opposite happens at higher temperature, the speed increase on chemical reactions has also an effect of increased internal corrosion.

During charging, batteries produce hydrogen and oxygen, VRLA batteries are sealed and this gas production translates into an increase of the inner pressure.

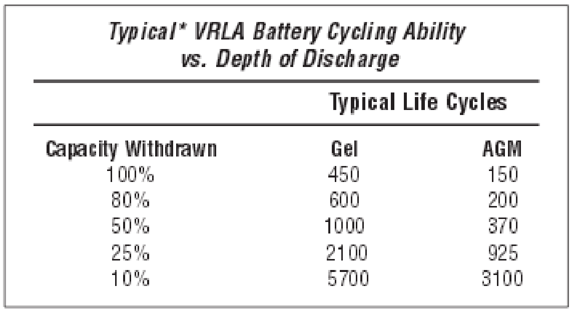
As temperature increases, the charging voltage should be reduced for temperature-compensation. A too high voltage would drive the battery to overcharging, which generates gassing, and therefore, leading to an increase of the inner pressure and temperature, gases will be expulsed by the security valves if pressure raises over 5 psi (0.34 bar). By losing these gases, the battery losses its capacity to store energy as these gases are needed to recombine into the electrolyte during the discharging process. When charging rates are too high, the heat generation creates an effect called Thermal Runaway, as the temperature of the battery raises, its capacity to absorb current increases as well, this can lead to and endless loop that can destroy the battery, this affects older batteries that have been exposed to overcharges and gassing, which are susceptible to generate heat due to their incapability to perform gas recombination.

Advanced regulators or smart chargers incorporate temperature correction features for setting the overcharge cutoff voltages, which vary with a rate of approximately -0.005 V/ºC. [12] [11]

3.4.3 Depth of discharge and battery life

The Depth of Discharge (DoD) is the percentage of the total capacity of a battery that is discharged during a discharge cycle.

As the DoD is increases, the battery life shortens, as the following figure illustrates:



Typical* VRLA Battery Cycling Ability vs. Depth of Discharge

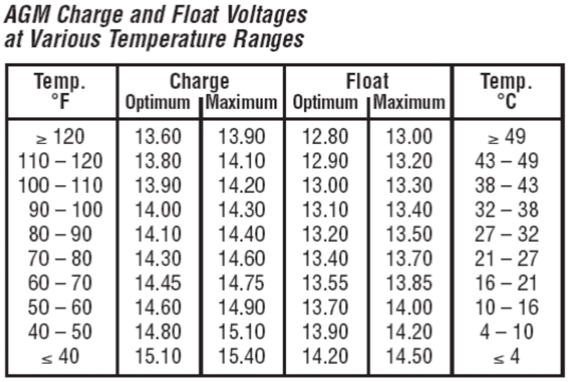
	Typical Life Cycles	
Capacity Withdrawn	**Gel**	**AGM**
100%	450	150
80%	600	200
50%	1000	370
25%	2100	925
10%	5700	3100

Figure 4 Number of cycles of life versus DoD [11]

Deeper discharges shorten battery life, a DoD of 50 % is recommended for optimum battery life, 80 % DoD is up to 200 cycles while 10 % may reach 3100 cycles. Hence, it is important to size the total capacity of the battery array in order not to go beyond 50 % DoD to maximize battery life while maintaining certain margin of usability on the system, optimal size of battery array is approximately as big as three or four times higher than the average daily energy demand.

VRLA batteries are not affected by the “memory effect” shown in Ni-Cd batteries in which the batteries, once the experiment certain DoD discharge cycle, on successive cycles, the battery losses its ability to operate beyond the previous depths of discharge.

The following table contains optimal and maximum voltage values for Charge and Float stages on 12V AGM batteries, adjusted for temperature compensation.

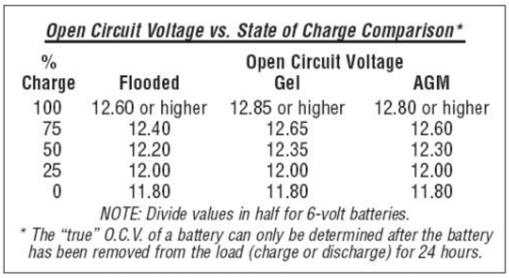


AGM Charge and Float Voltages at Various Temperature Ranges

Temp. °F	Charge Optimum	Charge Maximum	Float Optimum	Float Maximum	Temp. °C
≥ 120	13.60	13.90	12.80	13.00	≥ 49
110 – 120	13.80	14.10	12.90	13.20	43 – 49
100 – 110	13.90	14.20	13.00	13.30	38 – 43
90 – 100	14.00	14.30	13.10	13.40	32 – 38
80 – 90	14.10	14.40	13.20	13.50	27 – 32
70 – 80	14.30	14.60	13.40	13.70	21 – 27
60 – 70	14.45	14.75	13.55	13.85	16 – 21
50 – 60	14.60	14.90	13.70	14.00	10 – 16
40 – 50	14.80	15.10	13.90	14.20	4 – 10
≤ 40	15.10	15.40	14.20	14.50	≤ 4

Figure 5 Charge (Absorption) and Float voltages for AGM charging [11]

The following figure shows approximate open circuit voltage (OCV) values for different states of charge (SoC) in the battery from 0 % to 100 %, this measure should be done after disconnecting the battery and letting it rest for a minimum of four hours. [12]



Open Circuit Voltage vs. State of Charge Comparison*

% Charge	Open Circuit Voltage Flooded	Gel	AGM
100	12.60 or higher	12.85 or higher	12.80 or higher
75	12.40	12.65	12.60
50	12.20	12.35	12.30
25	12.00	12.00	12.00
0	11.80	11.80	11.80

NOTE: Divide values in half for 6-volt batteries.

** The “true” O.C.V. of a battery can only be determined after the battery has been removed from the load (charge or discharge) for 24 hours.*

Figure 6 OVC vs. SoC comparison. [11]

AGM batteries show an approximate voltage of 12.30V when loaded with a 50 % of the total capacity. [11]

3.4.4 Charging time

During Bulk charge, the battery can admit as much current as four times the Amp-hour capacity of the battery but the charging rate of the battery should be controlled to avoid excessive heating, typical charging currents are 15 % to 20 % of battery capacity. [13]

During floating charge stage, current is progressively reduced until full charge. This means that during a typical charge cycle, it will take 60 % of the time to charge a battery up to the 90 % of its capacity while the other 40 % of the time would be used to charge the remaining 10 %. [11]

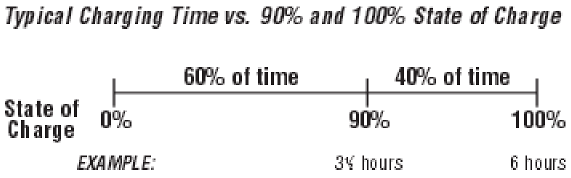
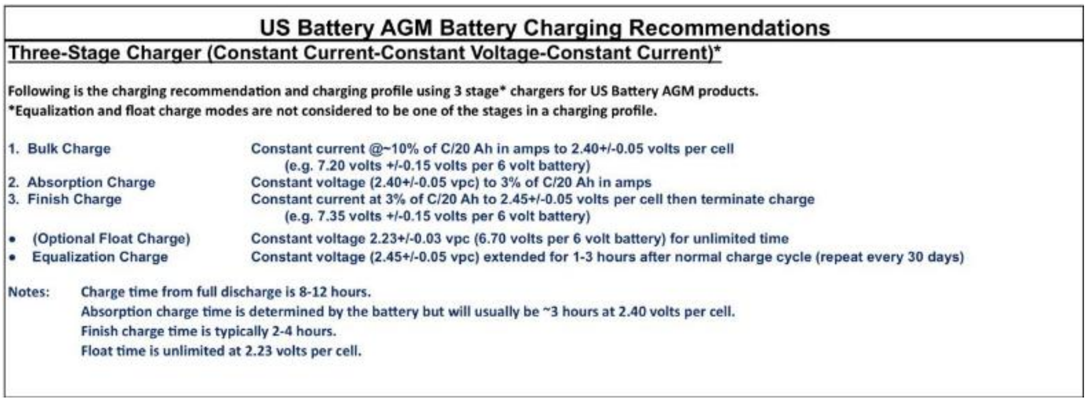


Figure 7 Charging time vs. 90 % and 100 % of SoC [11]

The following figures show an example of recommended values for the charging stages of AGM type batteries and a typical charging profile:



US Battery AGM Battery Charging Recommendations

Three-Stage Charger (Constant Current-Constant Voltage-Constant Current)*

Following is the charging recommendation and charging profile using 3 stage* chargers for US Battery AGM products.
*Equalization and float charge modes are not considered to be one of the stages in a charging profile.

1. Bulk Charge	Constant current @~10% of C/20 Ah in amps to 2.40+/-0.05 volts per cell (e.g. 7.20 volts +/-0.15 volts per 6 volt battery)
2. Absorption Charge	Constant voltage (2.40+/-0.05 vpc) to 3% of C/20 Ah in amps
3. Finish Charge	Constant current at 3% of C/20 Ah to 2.45+/-0.05 volts per cell then terminate charge (e.g. 7.35 volts +/-0.15 volts per 6 volt battery)
• (Optional Float Charge)	Constant voltage 2.23+/-0.03 vpc (6.70 volts per 6 volt battery) for unlimited time
• Equalization Charge	Constant voltage (2.45+/-0.05 vpc) extended for 1-3 hours after normal charge cycle (repeat every 30 days)

Notes: Charge time from full discharge is 8-12 hours.
Absorption charge time is determined by the battery but will usually be ~3 hours at 2.40 volts per cell.
Finish charge time is typically 2-4 hours.
Float time is unlimited at 2.23 volts per cell.

Figure 8 US Battery AGM Charging Recommendations [13]

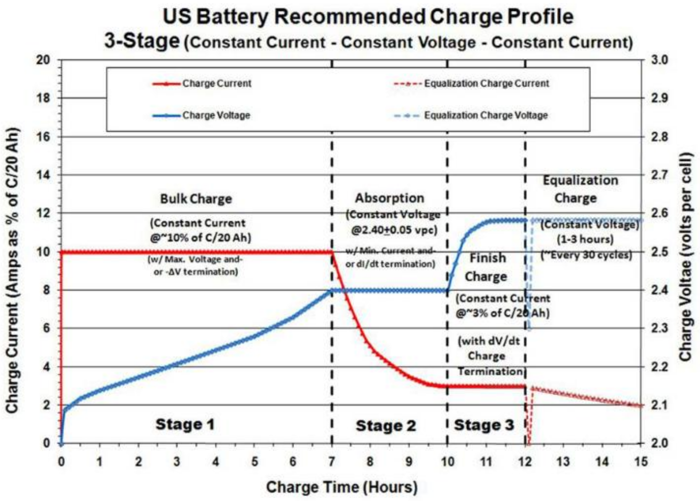


Figure 9 US Battery recommended Charge Profile [13]

3.4.5 Maintenance

All cells are connected in strings within the battery, on flooded standard Pb-a batteries after several charge and discharge cycles, differences in electrolyte stratification levels among the cells appear and their voltages start to differ. Conducting equalization charges corrects this by setting the charge voltage to the maximum voltage that the battery accepts during the bulk stage, when the battery reaches full charge, will force any reminders of stratification on the inner plates to react. On AGM batteries, stratification levels are much lower than flooded type batteries, while some manufacturers recommend performing equalization charges periodically, other advice not to do them at all.

It must be ensured that batteries do not withstand freezing temperatures in order to avoid being damaged, discharged batteries freeze faster than charged ones. Batteries should be stored fully charge and must undergo periodic full recharges in order to replace self-discharge losses. Batteries can be sealed in a container and buried underground to prevent them from freezing.

It is very important to set correct charging rates and avoid overcharging, this generates gassing, internal corrosion and a reduction in battery life. Batteries should be placed in a well-ventilated area. [12] [11]

4 CONFIGURATION OF THE INSTALLATION

4.1 Location

The Photovoltaic installation is located on a private house in the village of Korppoo (Korpo), in the Finnish Archipelago, at 60° 8' 60'' N latitude, 21° 34' 48'' E longitude and 13 meters above the sea level. [9]

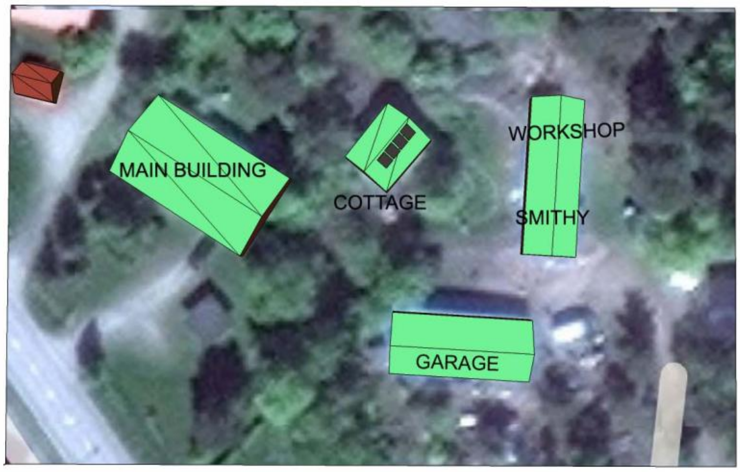


Figure 10 View of the installation's location

The PV panels are installed on the cottage's roof; they are connected to an inverter located on its basement. The inverter's output is connected to a breakers box on the cottage's outer wall; from there, the energy generated from the PV panels is sent to the smithy's breakers box, which is connected to a programmable regulator/inverter connected to the battery array. This device has two internal programmable switches that can be used to derivate energy into other appliances such as a water boiler, when there is an energy surplus or the voltage of the batteries is above the upper cutoff limit.

4.2 Climate

Korppoo's climate is milder than inland Finland: Summers in Korppoo are the longest in Finland and winters may not start until December, which is two months later than the starting date in Northern Finland (Artic region).

The average starting date of permanent snow cover in Korppoo's region is the latest among most inland Finnish regions, 26th December - 5th January. Average ending date of snow cover happens between 21st and 31st of March, which is earlier than most inland

Finnish regions as well. The average number of days with snow cover has been observed to fall between 85 and 100 days. All these statistics have been obtained from data within 1981 - 2010 time periods. [10]

4.2.1 Local Insolation

The average yearly values for solar irradiation determine the power output of the system. As the following figure shows in the red bars, the average yearly irradiation per square meter is 2.6 kWh/m² for this location on a horizontal plane. The green bars represent the simulated results of the average yearly power density that the solar panels will see according to their mounting configuration (tilt angle and orientation), which is higher than the horizontal plane since the angle of incidence of sunbeams is higher, energy is distributed is a smaller area. This average value is 3.2 kWh/m² but its deviation for the summer months is pretty high, reaching values above 5 kWh/m² between May and August while during winter it drops to less than half a watt per square meter.

The Photovoltaic installation is located on a private house in the village of Korppoo (Korpo), in the Finnish Archipelago, at 60° 8' 60" N latitude, 21° 34' 48" E longitude and 13 meters above the sea level. [9]

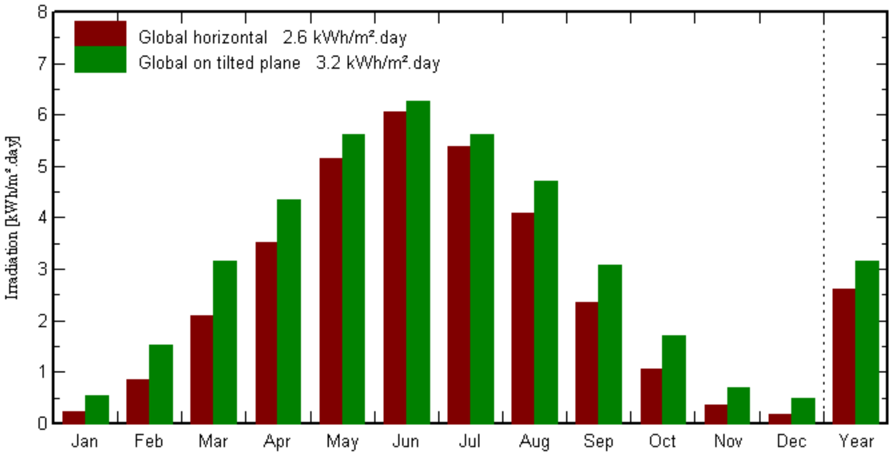


Figure 11 Average daily irradiation per square meter in Korppoo

These accused deviations on the monthly averages from the yearly average are due to both, the difference in length of the day and differences in instant power density through the year regarding the variation on the elevation of the Sun. The total insolation that the panels see, and thus their power output depend on both the exposure length and irradiation levels.

4.2.2 Orientation and Tilt angle

The orientation of the panels is 140º South-East, following the orientation of the Southern wall of an existing building, deviation from the optimal angle (180º South) is 40º.

Azimuth measures the orientation of the solar panels, in Northern hemisphere it is defined as the angle between South and the panels, so South direction is 0º while North 180º, regarding the configuration of this installation, the azimuth for the solar panels is -40º as it is taken in the opposite direction towards East.

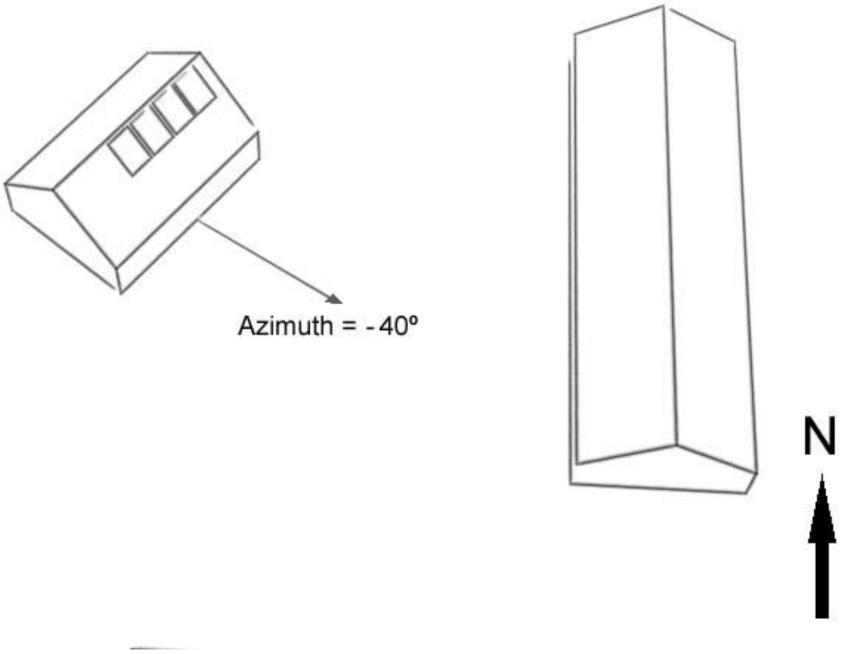


Figure 12 Orientation of the array

The panels are roof-mounted, having the same inclination angle as the building's roof, which is approximately 45º. This angle is few degrees under lower limit of the optimal range for this latitude (52º - 72º) but it has the advantage that there is no need of installing an expensive structure to support the panels, which payback time considering the difference in power generation from the optimal angle would exceed the panels' life, in other words, it is more cost-effective to install the panels at the roof's angle rather than mounting them on a special tilted frame for such a small difference in degrees from the optimal tilt range. 45º degrees of inclination is the minimum recommended tilt angle for panels installed on locations where snow is expected in order to avoid structural overloads.

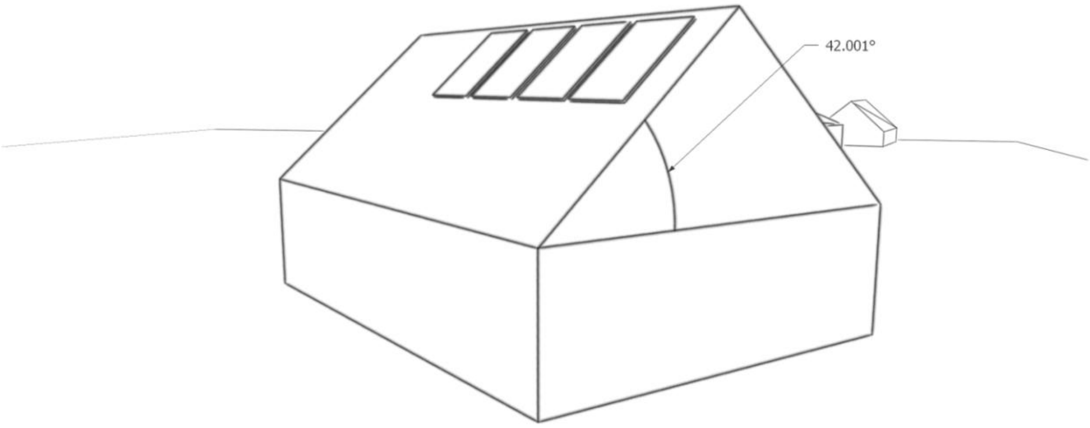


Figure 13 Tilt angle of the array

4.2.3 Trajectory of the Sun

As it was commented in the preceding section, the length of the day and the altitude or angle of the Sun varies significantly through the year. As the following picture shows, the shortest days occur between November and January, when the length of the day reaches its shortest on December 21st during the winter solstice. At this moment, Earth’s axis it heading to opposite direction from the Sun on Northern latitudes, exactly the opposite happens during the summer months, when days are long up to 19 hours during summer solstice in June 21st .

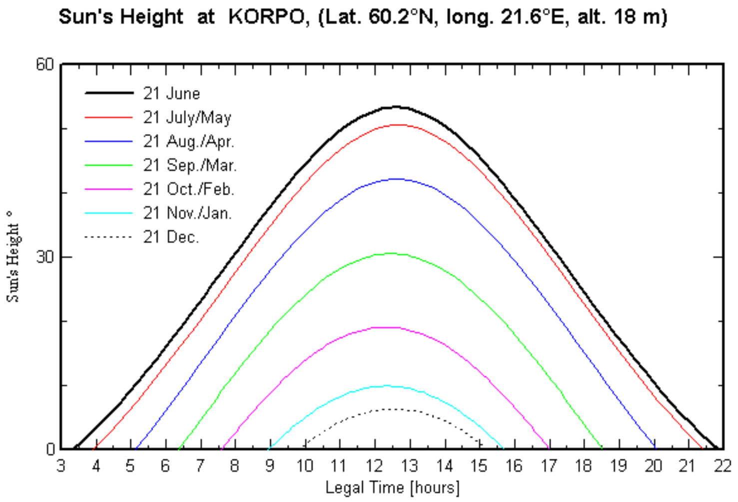


Figure 14 Height angle of the Sun during the day.

Length of the day will have the greatest impact on the global output of this system, ranging from very high performances during summer months to very low productions during winter time.

Another factor to consider is the angle that the sunbeams reach the Earth with, optimal incidence angle is perpendicular to the PV module’s plane in order to maximize the PV power output; due to the fact that Sun is constantly changing its relative angle to the solar panels during the year at the same time.

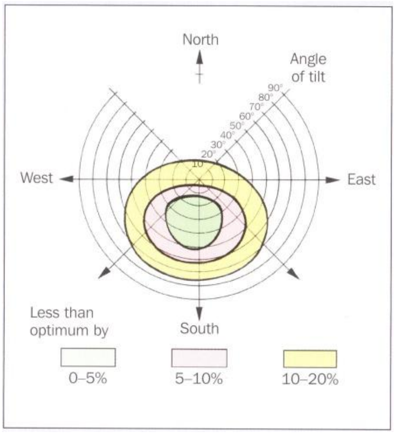


Figure 15 Influence of orientation and tilt on solar panel output. [2]

For optimal performance it would be needed to readjust the tilt angle of the panels periodically, nevertheless, deviations of ±10º from the optimal angle, cause no significant decrement on power output and therefore, having in mind that the actual tilt of the panels is approximately -8º outside this range, this effect is only of second order in comparison with the length of the day for this latitude.

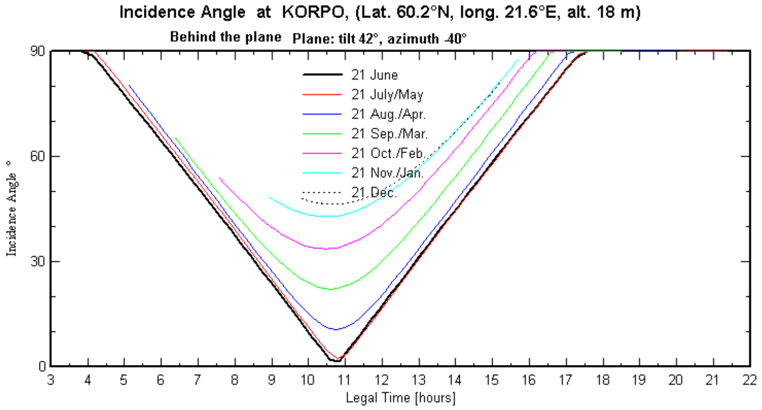


Figure 16 Sun's angle of incidence referenced to the plane’s normal for a 42º tilt angle and -40º azimuth

4.2.4 Shadowing

There is no direct shadowing over the modules since there are no objects such as buildings or trees close enough to cause it.

4.3 Photovoltaic panels

The solar panels model is Solarxon ES-230P, polycrystalline silicon type; each panel has 60 individual cells of 156x156 mm. These panels can deliver a maximum power of 230Wp each one, and have an efficiency of 14.5 %.

Figure 17 PV array mounted on cottage's roof

The PV array is comprised by two rows; each one is formed by two panels in series providing a maximum output voltage of 60V and a current of 15.3A. The output of each row is connected to an inverter.

The total nominal maximum power of the PV array is 920Wp with a total area of 6.53 m².

These panels are guaranteed to 80 % performance after 25 years of use.

Panels	
Max Power (W)	230
Max Voltage (V)	29.8
Max. Current (A)	7.72
Open c. volt. (V)	37.0
Short c. curr. (A)	8.26
Series fuse rating	15 A

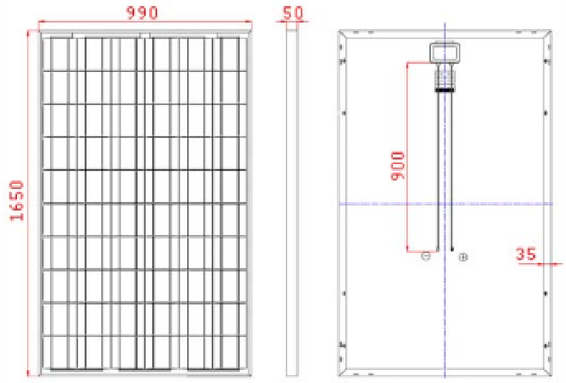


Figure 18 Solarxon 230 solar panel [19]

Array:

PV array	
Max Power (Wp)	920
Vmpp (60ºC) (V)	50 /Row
Vmpp (20ºC) (V)	61 /Row
Open c. volt. (-10ºC)(V)	83
Impp (A)	15.3
Short c. curr. (A)	16.6
Series fuse rating	15 A

(Specifications under Standard Test Conditions (STC) of irradiance of 1000W/m and cell temperature of 25ºC) [11]

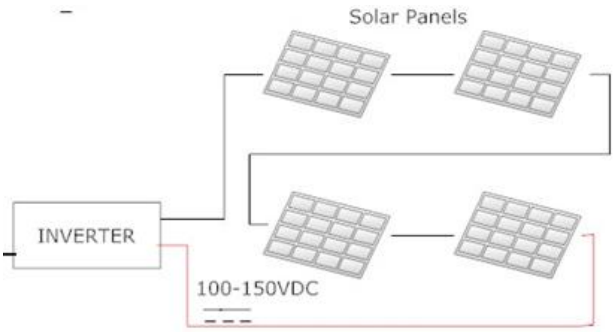


Figure 19 Configuration of the PV array

4.3.1 Orientation and inclination of the PV Array

The orientation of the array is highly important in order to maximize the total power output of the system. The altitude of the sun varies throughout the year depending on the latitude of the installation site. In order to maximize power generation capabilities, PV panels can be mounted on structures than can change its angle in order to optimize irradiation.

Best orientation for the panels is facing south, however the energy difference from not being oriented around 25º on southwest or east direction, is only about 0.2 % by each deviation degree from South.

As a general rule, the best tilt angle angles for a solar panel are the degrees of latitude of the installation's site latitude, considering an error of approximately ±10 degrees. This angle should be adjusted during winter and summer seasons in order to achieve maximum performance.

In any case, it is always recommended an angle above 15º on rainy locations or over 45º on locations where snow is expected. [4]

4.3.2 Orientation and Tilt angle

The orientation of the panels is 140º South-East, following the orientation of the Southern wall of an existing building, deviation from the optimal angle (180º South) is 40º.

Azimuth measures the orientation of the solar panels, in Northern hemisphere it is defined as the angle between South and the panels, so South direction is 0º while North 180º, regarding the configuration of this installation, the azimuth for the solar panels is -40º as it is taken in the antitrigonometric direction towards East.

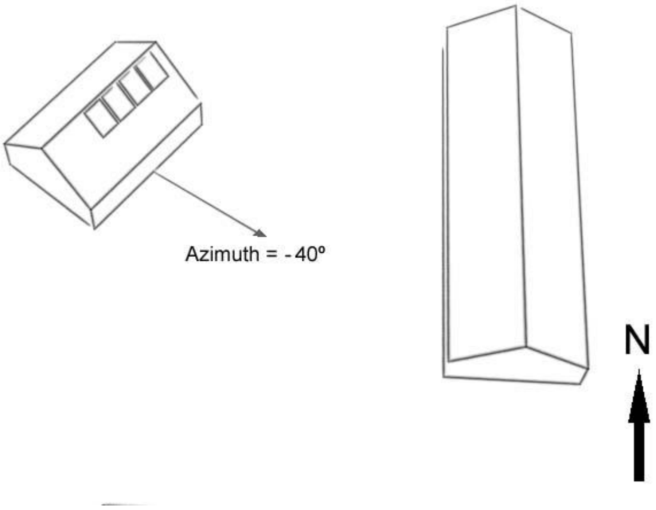


Figure 20 Orientation of the array

The panels are roof-mounted, having the same inclination angle as the building's roof, which is approximately 45º. This angle is few degrees under lower limit of the optimal range for this latitude (52º - 72º) but it has the advantage that there is no need of installing an expensive structure to support the panels, which payback time considering the difference in power generation from the optimal angle would exceed the panels' life, in other words, it is more cost-effective to install the panels at the roof's angle rather than mounting them on a special tilted frame for such a small difference in degrees from the optimal tilt range. 45º degrees of inclination is the minimum recommended tilt angle for panels installed on locations where snow is expected in order to avoid structural overloads.

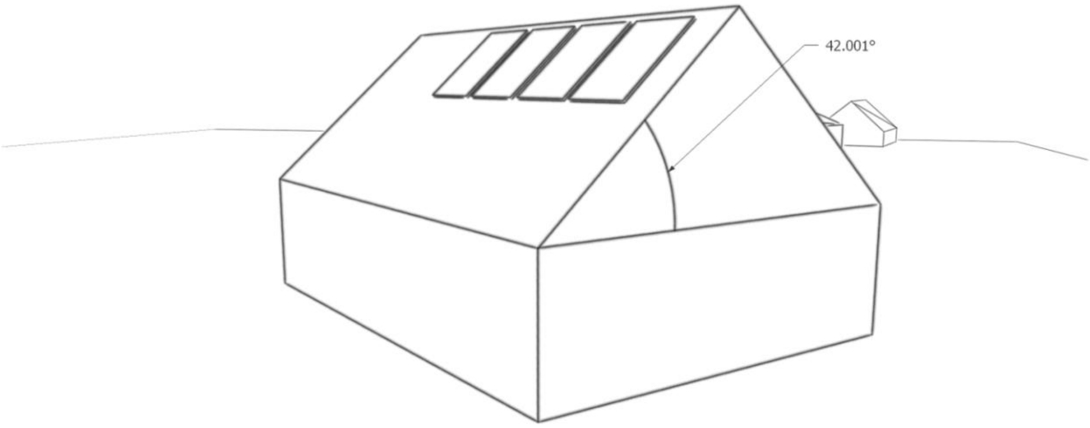


Figure 21 Tilt angle of the array

4.4 Inverter

There are two inverters installed at the cottage building, one at the output of each row of the PV array. The inverters' model is AECA Steca Grid 500-m with maximum power point tracking technology and an efficiency of 99 %. It is a wall-mounting model meant for indoor use. [12]

DC SIDE (PV ARRAY)	
Max input volt. (V)	230
Min, input volt. (V)	45
Max. input current (A)	5A
AC SIDE (Grid)	
Grid voltage (V)	230V
Max output curr. (A)	2.17A
Max active Power	500W
Frequency (Hz)	50

Figure 22 AECA STEGA Grid 500-m [20]

4.5 Battery array

The battery bank is comprised by two Absorbent Glass Mat batteries, connected in parallel with a total capacity of 250Ah or 3 kWh.

Type	Capacity
AGM Pb-a 12V	70 Ah
AGM Pb-a 12V	180 Ah
TOTAL	250 Ah / 3kWh

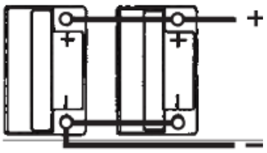


Figure 23 Configuration of the battery array [11]

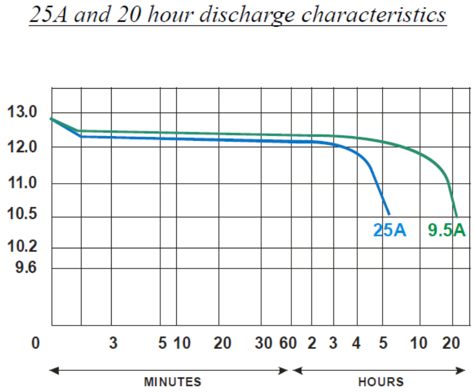

25A and 20 hour discharge characteristics

Figure 24 Discharge time vs. Loading voltage [21]

4.6 Regulator/Inverter

The device installed at the smithy (see connections) is an advanced multifunction regulator/inverter device Victron Multiplus 12/2000/80. It comprises a sinusoidal and modified wave inverter along with a programmable regulator.

It has two CA outputs; one can manage the UPS, in case of failure of the external grid it provides ultrafast switching so there is no interruption of operation on the loads. The other output is only active when there is CA feeding at one of the multiples' inputs; loads can be connected to this output, such a water boiler.

It has triphasic operation capability and it can be connected in parallel with other Multiplus devices in order to increase the total maximum power.

Its regulator can be configured to different charging rates by setting limits on the battery charging currents. When there is a higher current that the one set in the charging limit coming from the generator(s) connected (the PV panels in the scope of this thesis, but a windmill as well in the real hybrid configuration of this installation), the remaining current is used to feed a load connected to the second output (virtual switch).

Different charging rates are Bulk, absorption, float and storage; it offers temperature compensation, equalization, forced absorption and voltage detection in order to prolog battery life (see 2.4) and prevention of excessive gassing as well. It can simultaneously charge another battery or set of batteries.

In this installation, the virtual switch is connected to the main house's water boiler, so the excess of energy during the sunniest or windiest hours of the day will be used to heat the water.

Another of its features is peak power compensation, when any of the loads need an instant peak current such as a starting washing machine, the multiplus will compensate the current that cannot be instantaneously supplied by the generator, from the batteries.

The multiplus has a temperature sensor that has to be placed on the negative pole of the battery; its readings are used to temperature compensation of the charging voltages. The following image illustrates the temperature compensation performed by multiplus.

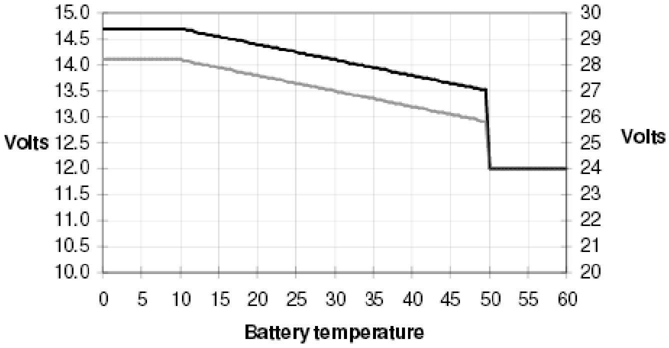
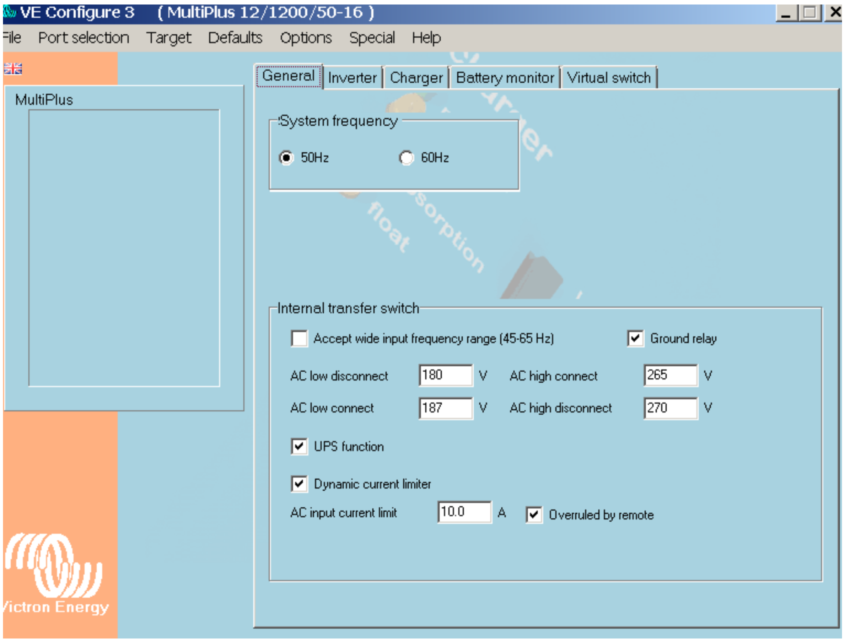


Figure 25 Temperature correction for charging voltages [22]

It can be configured with DIP switches and remotely controlled with an external 3-way switch or a multi control panel and configured from a computer using MK2-USB, MK2-RS232 or VE interface connectors. It can send notifications to cell phones via modem using SMS and GPRS. [13]

Using the MK2 USB interface, the Multiplus can be configured from a computer using the VE configure software. This application allows configuring general settings as well as specific ones for the inverter, charger and virtual switch. Some of the most relevant settings for this installation are explained below.

4.6.1 General Settings



System frequency

● 50Hz ○ 60Hz

Internal transfer switch

☐ Accept wide input frequency range (45-65 Hz) ☑ Ground relay

AC low disconnect 180 V AC high connect 265 V

AC low connect 187 V AC high disconnect 270 V

☑ UPS function

☑ Dynamic current limiter

AC input current limit 10.0 A ☑ Overruled by remote

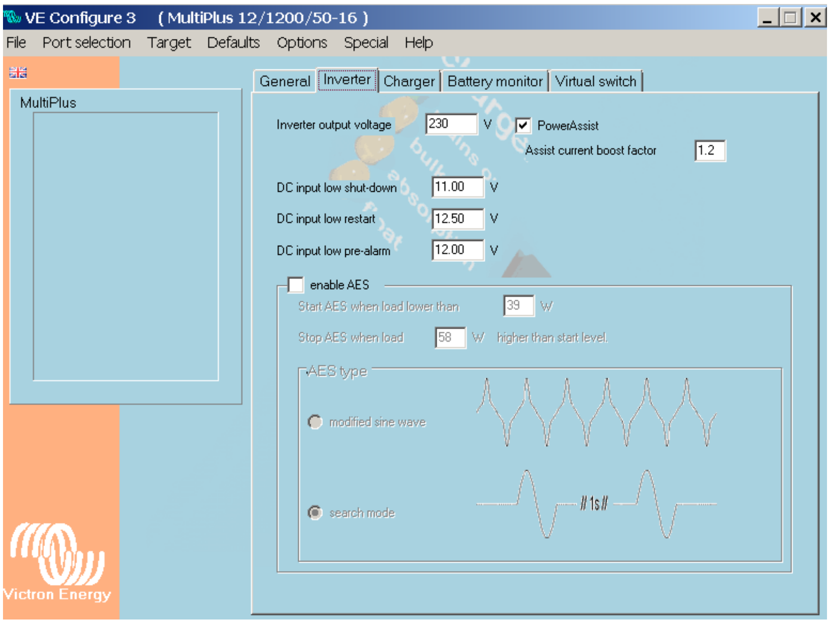
Figure 26 General settings on the VE configure software

Dynamic current limiter: If the voltage on the batteries varies too much when they are required to provide high currents, it limits automatically the current limit. Turned ON in this configuration.

UPS function: Uninterrupted power supply mode, when activated power source switching is much faster. Turned ON.

AC input current limit: Limits the current at the input of the inverter to the value set. If this current is too high, batteries may overheat resulting on a reduced life. The maximum recommended value is around 10 % of battery capacity, which is 25 A. In this configuration it is set to 10 A providing a margin of 15 A up to the maximum permissible current of the battery array.

4.6.2 Inverter settings



Inverter output voltage 230 V

☑ PowerAssist

Assist current boost factor 1.2

DC input low shut-down 11.00 V

DC input low restart 12.50 V

DC input low pre-alarm 12.00 V

☐ enable AES

Start AES when load lower than 39 W

Stop AES when load 58 W higher than start level.

AES type

○ modified sine wave

● search mode

Figure 27 Inverter settings on the VE configure software

Inverter output voltage: Output voltage of the inverter. 230V

Power assist: If the demand for current is higher than the value set in "AC input current limit" the extra current needed is supplied from the solar panels. Turned ON.

AES: Automatic Economy Switch, if activated, the energy consumption under low or no load is reduced by a 20 %. The output has higher harmonic content since its waveform has been “narrowed”.

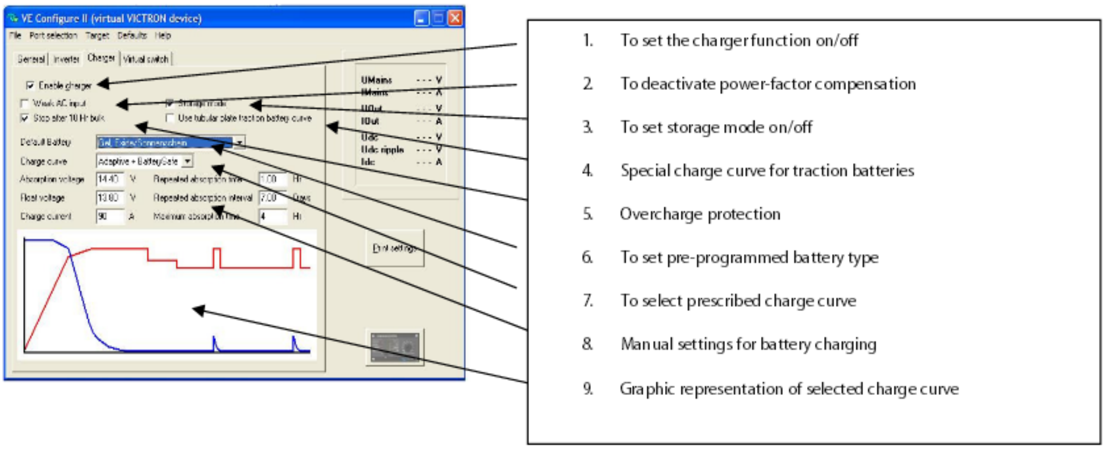
Search mode: Power consumption is reduced by a 70 %, the inverter is shut down when no load is connected and checks again for loads every two seconds. The watt range of the connected loads in order to turn on the inverter can be set in the configuration.

DC input low shut-down: Voltage limit for the battery in order to shut down the inverter. The lower this value is, the higher the depth of discharge will be at expense of reduction in battery life. 11.0 V, this voltage can be set higher, up to around 12 V for maximizing battery life. (See figures 24, 4 and 7). In order achieve the recommended DoD of 65 %, it is necessary to know to which loading voltage it corresponds to. For example, measuring the OCV when the loading voltage reaches 11 V and looking at figure 6, will give an idea to which state of charge 11 V corresponds to.

DC input low restart: Voltage limit for the battery at which the inverter will be turned on. Set to 12.5 V (See figure 24)

DC input low pre-alarm: Voltage at which the multiplus will display a low battery warning. Set to 12.0 V

4.6.3 Charger settings



☑ Enable charger
☐ Weak AC input
☑ Storage mode
☑ Stop after 10 Hr bulk
☐ Use tubular plate traction battery curve

Default Battery: Gel Exide/Sonnenschein
Charge curve: Adaptive + BatterySafe
Absorption voltage: 14.40 V
Float voltage: 13.80 V
Charge current: 90 A
Repeated absorption time: 1.00 Hr
Repeated absorption interval: 7.00 Days
Maximum absorption time: 4 Hr

1. To set the charger function on/off
2. To deactivate power-factor compensation
3. To set storage mode on/off
4. Special charge curve for traction batteries
5. Overcharge protection
6. To set pre-programmed battery type
7. To select prescribed charge curve
8. Manual settings for battery charging
9. Graphic representation of selected charge curve

Figure 28 Charger configuration panel of the VE software [22]

Storage mode: Periodically recharges the batteries to compensate self-discharge losses.

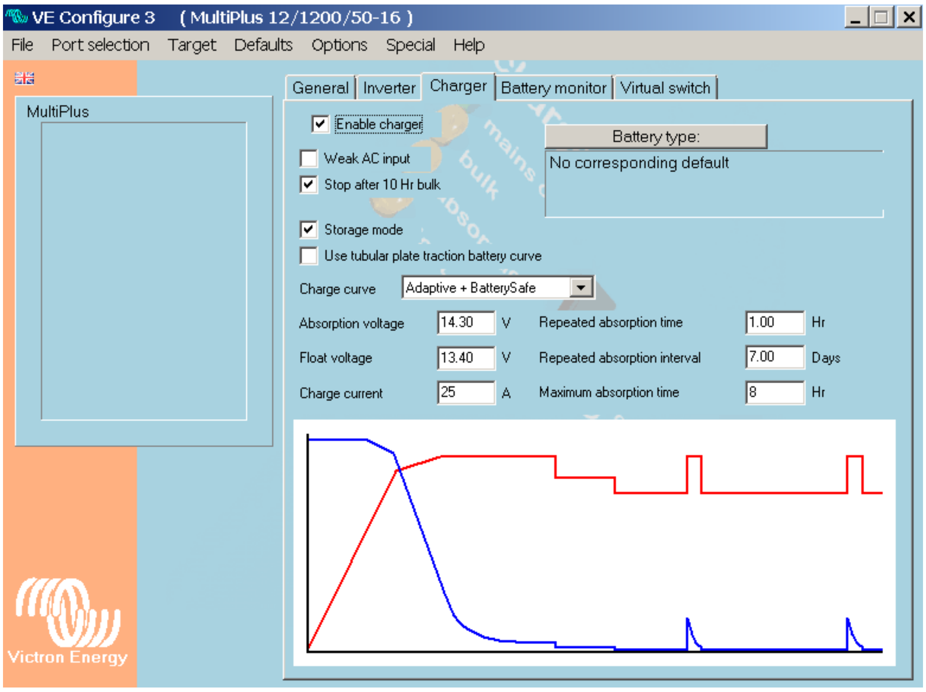
Stop after 10 Hr. bulk: Overcharge protection, detects if the absorption voltage has not been reached after 10 hours of charging and shuts off charging. This may indicate a battery failure.

Absorption voltage: Charging voltage during absorption phase (25º), 14.3 V (See figure 5).

Float voltage: Charging voltage during float phase. This is the voltage at which the battery will be held once fully charged. It is very important not to exceed the recommended limits as it will result in overheating and battery degeneration. 13.4 V (See figure 5).

Charge current: The total capacity of the battery bank is 250 Ah, the typical charging currents for AGM batteries are 10 % of total capacity during Bulk charge (25 A) and 3 % during Absorption (7.5 A), (see figure 8).

Maximum absorption time is irrelevant in adaptive mode as it is used for fixed current charging.



☑ Enable charger
☐ Weak AC input
☑ Stop after 10 Hr bulk
☑ Storage mode
☐ Use tubular plate traction battery curve

No corresponding default

Charge curve: Adaptive + BatterySafe

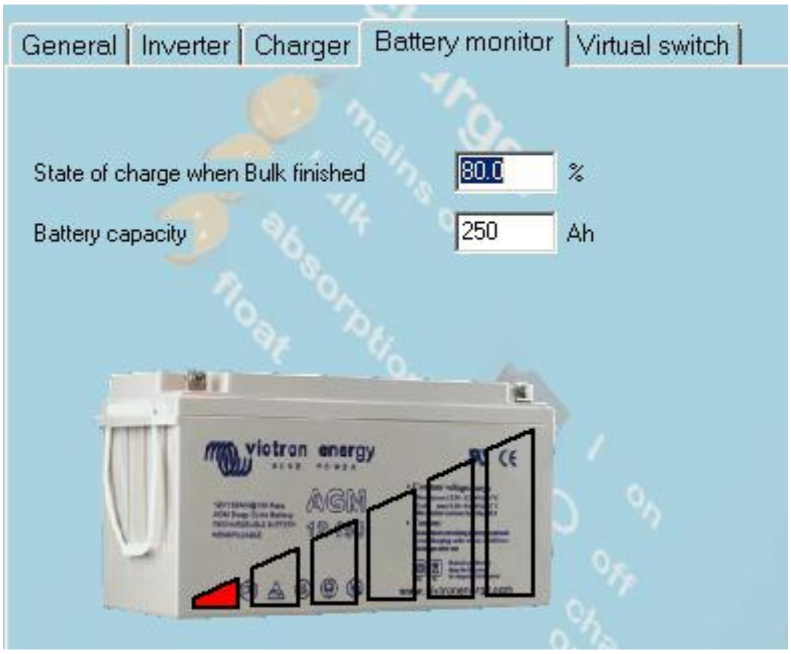
Absorption voltage 14.30 V
Float voltage 13.40 V
Charge current 25 A
Repeated absorption time 1.00 Hr
Repeated absorption interval 7.00 Days
Maximum absorption time 8 Hr

Figure 29 Charger settings on the VE configure software

VE configuration software includes different charging profiles for several different battery types, in this case the selection is Gel/AGM which charging voltage settings are Absorption=14.4 V, Float=13.8 V and Storage=13.2 V. [13]

Charge curve: Adaptive+Batterysafe, provides an smoother absorption curve.

4.6.4 Battery monitor



State of charge when Bulk finished 80.0 %
Battery capacity 250 Ah

Figure 30 Battery monitor settings on the VE configure software

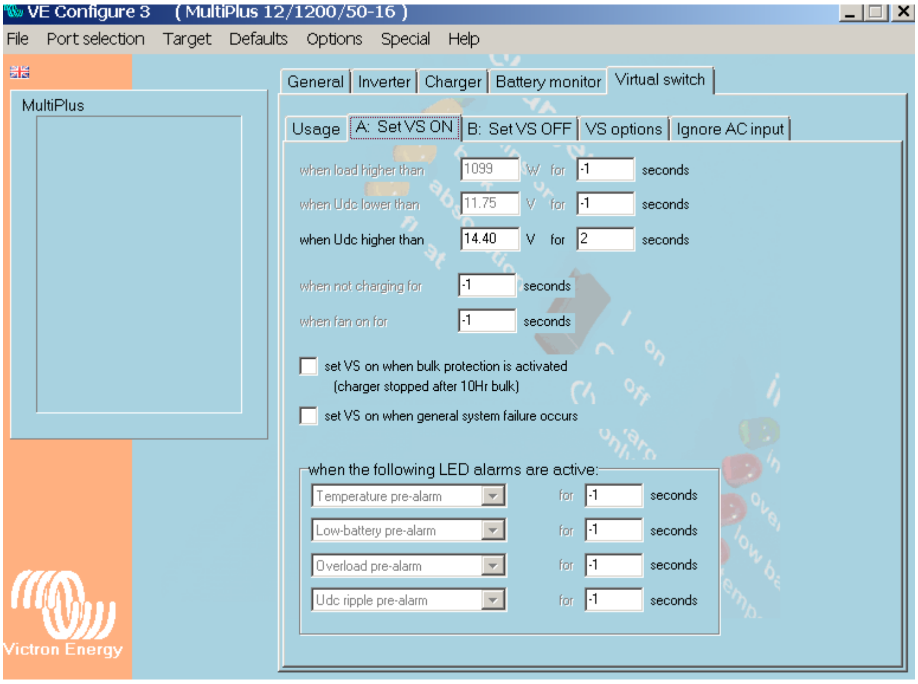
Bulk charge should stop when the battery reaches 80 % of Sock Here the total capacity of the battery is set.

4.6.5 Virtual switch

The operating mode of the virtual switch is set by the option “drive auxiliary relay (VS on=close) + dedicated ignore AC input”, in this mode of operation, two voltage levels can be set:

Set VS ON, when Udc higher than 14.40 V for 2 seconds. This will redirect the power from the solar panels to the loads connected to the virtual switch when the batteries have reached this level.

Set VS OFF, when Udc lower than 12.20 V for 2 seconds. When batteries reach this level will shut off virtual switch operation.



when load higher than 1099 W for -1 seconds

when Udc lower than 11.75 V for -1 seconds

when Udc higher than 14.40 V for 2 seconds

when not charging for -1 seconds

when fan on for -1 seconds

☐ set VS on when bulk protection is activated (charger stopped after 10Hr bulk)

☐ set VS on when general system failure occurs

when the following LED alarms are active:

Temperature pre-alarm for -1 seconds

Low-battery pre-alarm for -1 seconds

Overload pre-alarm for -1 seconds

Udc ripple pre-alarm for -1 seconds

Figure 31 Virtual switch settings on the VE configure software

4.6.6 Specifications

INVERTER

DC SIDE (PV ARRAY)	
Input volt. Range (V)	9.5-17/19-33
Max. input current (A)	5
AC SIDE (Grid)	
Grid voltage (V)	230
Max output curr. (A)	2.17
Output Power (W)	1200
Max peak power (W)	2400
Frequency (Hz)	50
Maximum efficiency (%)	92/94

Figure 32 Multiplus Inverter/Regulator

REGULATOR

AC input (V)	187-265
Charge voltage (absorption mode) (VDC)	14.4/28.8
Charge voltage (float mode) (VDC)	13.8/27.6
Storage mode (VDC)	132/26.6
Charge current	50/25

4.7 Wire sizing

By sizing the electrical wires on the system, the maximum current that can safely flow through the system is determined. Decreasing the wire diameter and increasing the length increases the resistance. As resistance increases, the wire heats according to Joule’s law, it may reach a point of overheating risk and electrical fire.

Since the electrical currents in this system are relatively high, it is important to choose adequate wire dimensions by using proper cable sections and shorter lengths in order to minimize voltage drops on the conductors, which have maximum admissible values lower than 3 % of the nominal voltage and are defined by CENELEC TR 50480 normative, it also must be guaranteed that the temperature of the conductors will be kept under certain limits during normal operation: 70 ºC for PVC coating and 90 ºC for XLPE or EPR coatings. Short circuit limit temperatures (under 5 seconds) are standardized as well: 160 ºC for PVC coating and 250 ºC for XLPE or EPR coatings. [7] [8]

Wire section is calculated according to the following expression for alternating current:

$$S = \frac{2 * L * I * cos\Phi}{\sigma * (\mathrm{Va} - \mathrm{Vb})}$$

S: Wire section area

L: Wire length

Va-Vb: Maximum voltage drop (V)

I: Nominal current (A)

σ: Conductivity (m/ Ωxmm^2) (44 m/ Ωxmm^2 for Cu)

cosΦ: Active power, for calculation on DC current is taken as = 1 [6]

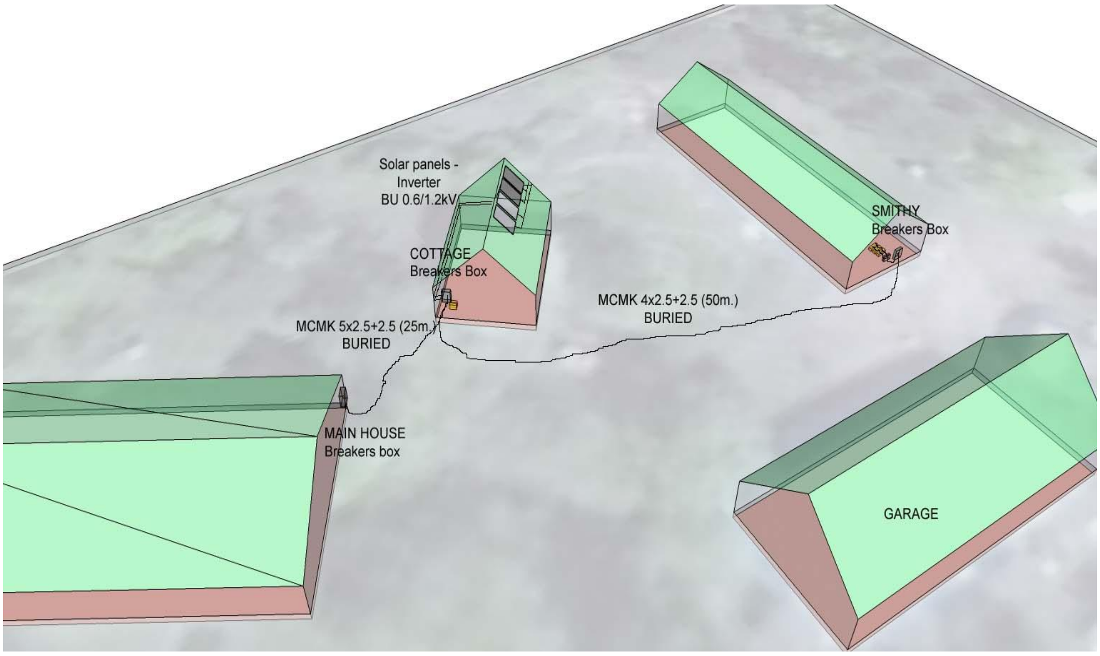


Figure 33 Diagram of the wiring between the buildings.

Table 1 Cable types on the installation

Wired Stretch	Wire type	Cross Section mm^2	Diameter mm	Length m	Load capacity (A)
Cottage-Workshop (AC)	MCMK 0.6/1kV	4 x 2.5+2.5	26.9	~50	35 (Buried) [13]
Smithy-Main house (AC)	MCMK 0.6/1kV	5 x 2.5+2.5	13	~25	57 (Buried) [13]
PV panels-Inverters (DC)	CYKY SUN 1kV DC	2 x 10	16.5	~25	52 (In air) [14]
Battery bank (DC)	BU 0.6/1.2kV	25*	11.5	<5*	127 [15]

*As specified in [16] p.10

4.8 Grounding and protections

Grounding provides a low-resistance path to earth ground. Since it is meant to carry any intensity due to system’s malfunction, ground cables’ cross section must be as big as the biggest section among every conductor present in the system.

System ground: The negative conductor is wired to ground, stabilizing the maximum voltage with respect to ground and it discharges any currents produced by lighting.

Any metal exposed to contact should be grounded, including equipment boxes and array frames. A PV array can attract lightning; damages may occur by the direct lightning hit or by induced currents into systems’ conductors. Installation of buried wiring on grounded metallic conduit will decrease the susceptibility to lightning. [8]

The grounding of this installation is connected to the grounds on the existing electrical distribution on the different parts of the system (see figure 13). All of them are interconnected so there are no floating grounds, this avoids the generation of differences of potential among different parts of the system. [6]

4.9 Protections

The following table shows a summary of the breakers on the PV installation:

Table 2 List of breakers installed

Location	Circuit breaker
Main house 1 (Main box)	35 A
Main house 2 (To loads using power from the PV system)	16 A
Main house 3 (Breaker box connected to the other buildings)	25 A
Smithy	16 A

:

4.10 Connections

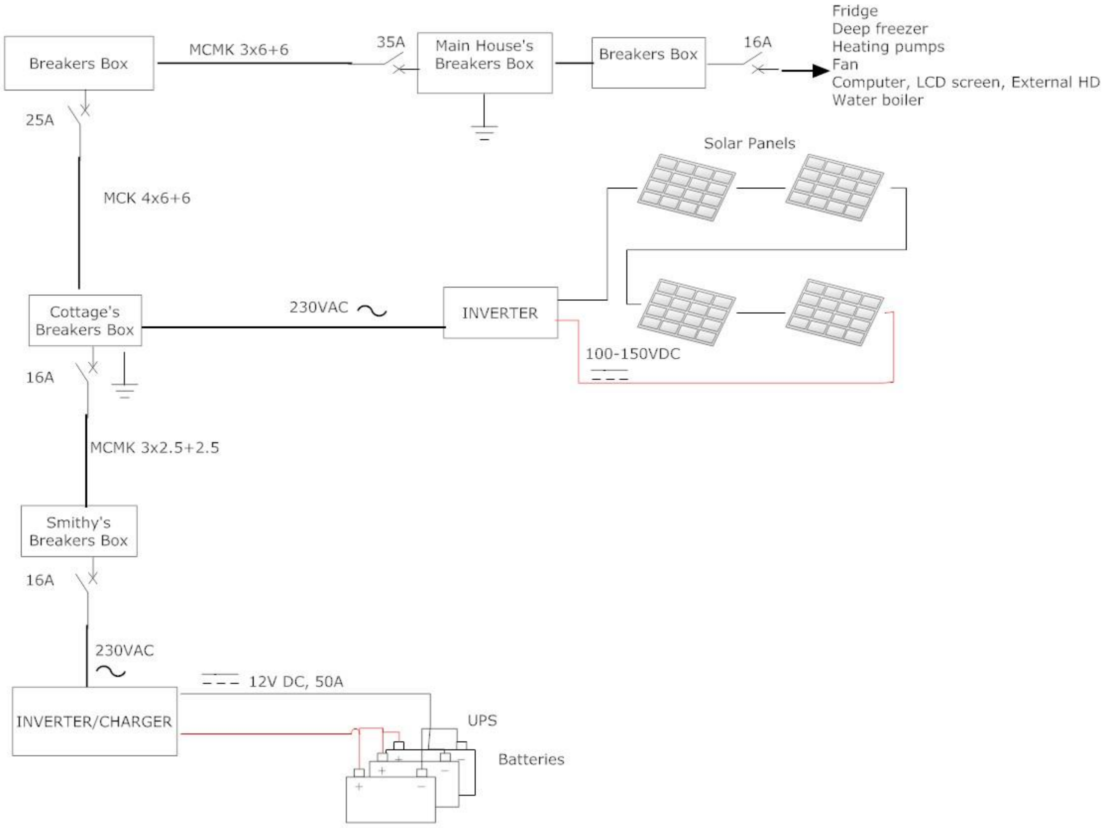


Figure 34 System diagram

4.11 Maintenance

Photovoltaic installations require minimal maintenance. Solar modules are very well insulated within synthetic resin; they have a self-cleaning surface which means that no large amounts of dust or any other particles will accumulate over them. Even though that these particles would not have a significant effect on the performance of the module, it is recommended to sweep the surfaces once a year.

Elements such as fell leafs should be removed from the surface of the modules, shadowed cells in the module would absorb energy from other cells to a point that these cells will result damaged decreasing the performance of the whole PV array.

Good ventilation on the location of the inverter must be maintained in order to avoid overheating. Good air flow is also important at the location or the battery array to avoid the accumulation of the gases generated during the charge and discharge. [2]

Besides all of the above, some other recommended periodic checks are:

- All connections in the system should be tight and unexposed.
- Batteries connections should be clean and free of corrosion.
- Electrolyte level on batteries should be correct
- With the batteries under load, check the voltage of each battery cell and ensure it does not differ more than 0.05 V from the other cells voltage.
- All junction boxes must be closed and sealed, without signs of corrosion and well ventilated.
- Inspect the array mounting structure.
- Switches operation must be solid. Switches must be free of any corrosion.
- Fuses must not show discoloration. They should be checked with a voltmeter. [8]

5 ENERGY ANALYSIS

On the following sections, a series of energy analysis will be performed:

- Estimation of the total energy production of the PV system during one year.
- Estimation of energy consumption from the grid.
- Estimation of the energy demand for only those appliances connected to the PV system.
- Energy consumption of the water heating system.
- Battery capacity and autonomy.

Energy production calculations have been done using the photovoltaic simulation software PVsys which includes weather data from Jokoinen weather station, which is the closest to Korppoo on its database.

The whole energy consumption data has been measured from Oct 14th 2012 to May 7th 2013 in 15-minute intervals and has been analyzed with Microsoft SPSS and EXCEL, estimating the consumptions for May to October with the purpose of obtaining the total yearly power consumption.

5.1.1 Estimation of Energy production during one year

The photovoltaic system has a nominal power of 920 Wp and is capable of delivering approximately 850 kWh under the local insolation conditions the figure below shows the average simulated energy production per month of the installation.

Table 3 Average energy production of the installation per month.

	kWh/day	**kWh**
January	0,41	13
February	1,12	31
March	2,35	73
April	3,21	96
May	4,16	129
June	4,63	139
July	4,17	129
August	3,49	108
September	2,29	69
October	1,25	39
November	0,52	16
December	0,35	11
YEAR	2.34	852

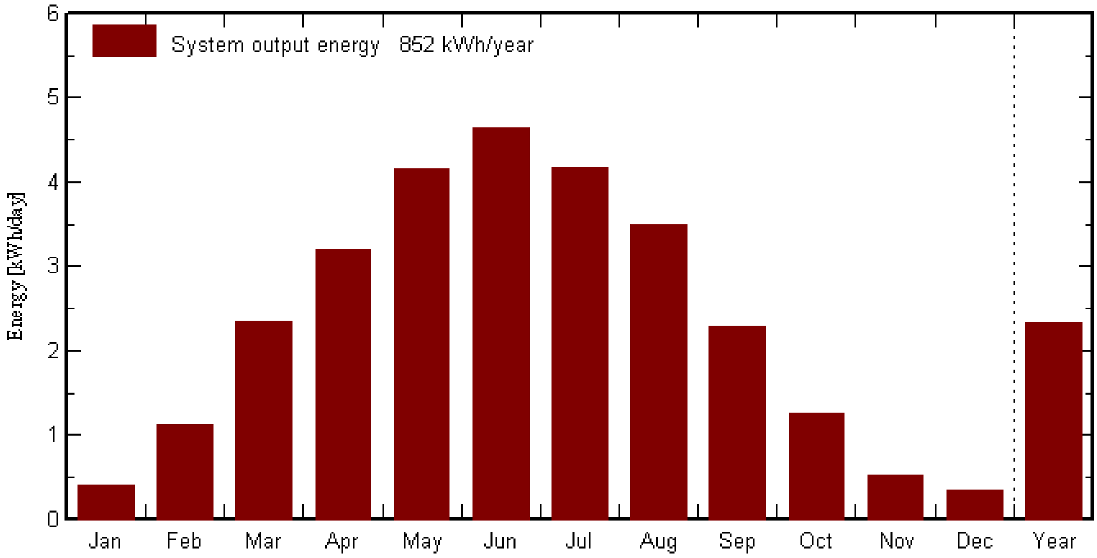


Figure 35 Simulated power output of the PV array throughout the year.

5.1.2 Energy consumption from the grid

Energy consumption data is acquired by a monitoring device attached to the electricity meter, which counts the flashes of a LED at the energy counter, (1000 pulses/Kw), sending the data wirelessly to a main terminal that stores it on a SD card.

The average energy consumption taken from the energy provider yearly is estimated approximately by 10.834 kWh, this means that the energy supplied by the PV systems is around 0.4 % of this total energy demand.

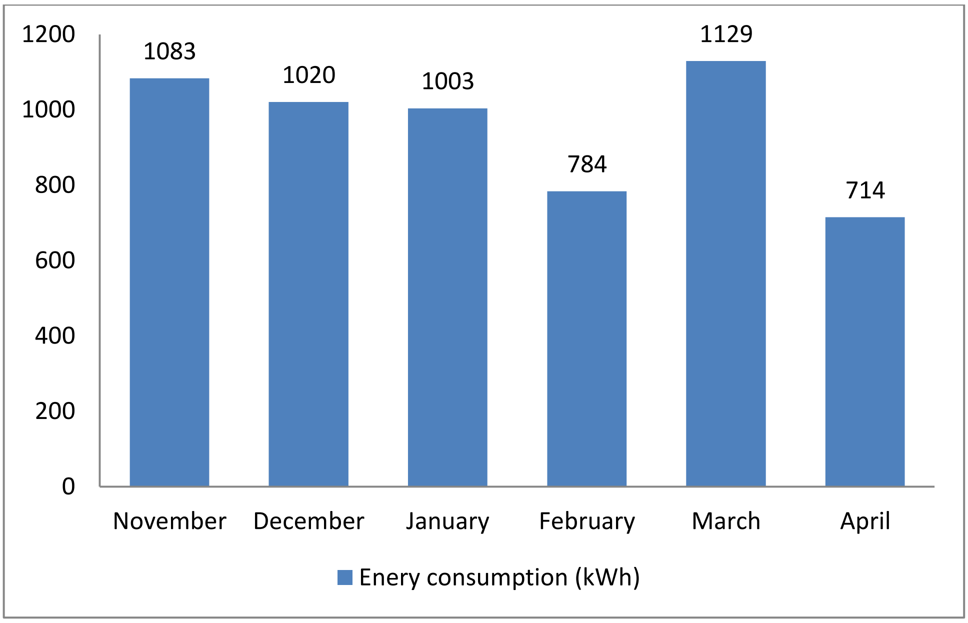


Figure 36 Measured monthly energy consumptions from November 2012 to April 2013

This values show the energy that has been used to fully feed the loads in the four buildings and partially feed the loads connected to the PV system, as it was explained in the regulator section, the Multiplus regulator/inverter shuts off the power supply from the battery array when their voltages drops below the lower cutoff value, supplying at that moment the energy demanded from the grid, therefore, part of the energy consumptions shown within the values above has been used to feed the loads connected to the PV system during the time intervals that the batteries were below the lower cutoff voltage (11 V) due to insufficient power output from the PV array. Therefore, this situation is most likely to happen during the night and the darkest hours of the day, while during the sunniest hours of the day, the energy produced from the PV array will be used to charge the batteries and feed the loads connected to the PV system. This will have a partial impact on the energy taken from the provider as the PV-connected loads will be mainly fed from photovoltaic energy during these hours, decreasing, on the average, the amount of energy that the Multiplus regulator is taking from the grid during these sunniest hours. (Note the PV production will be higher during this time interval even on cloudy days since 50 % of the PV-generated energy comes from diffuse radiation).

The following graph shows the average energy consumption during the day measured at the electricity counter between October and April. It can be seen that the lowest energy consumption takes place between 09:00 and 14:00, which, on the average, correlates to the sunniest time interval during these months.

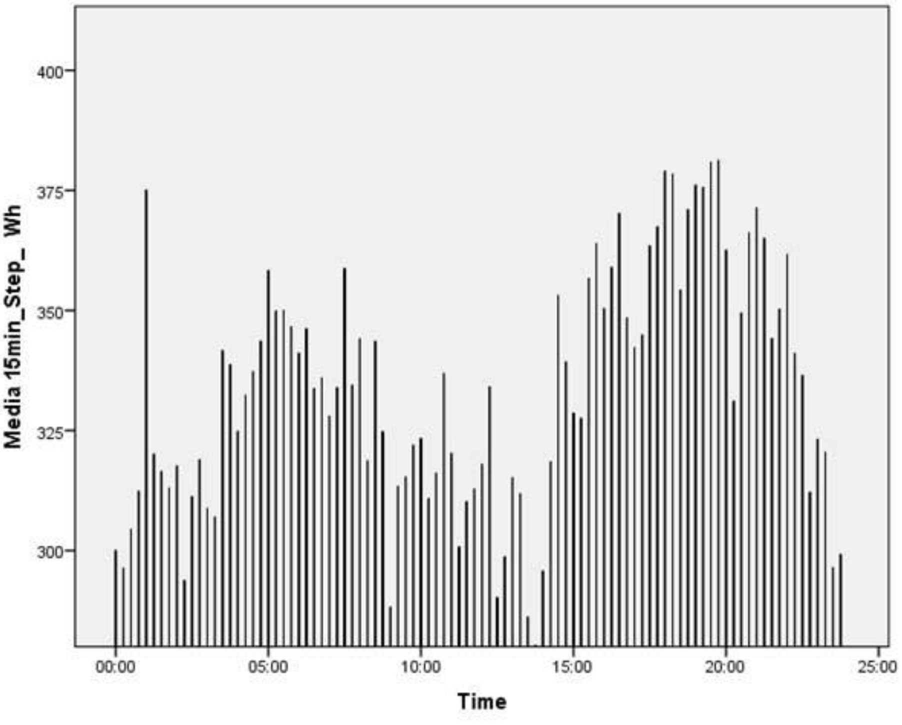


Figure 37 Average energy consumption over the day in 15 minute intervals for October 14th 2012 to May 6th 2013 (Wh)

From analysis of measured samples within October 14th and May 6th, the average energy demand every 15-minute falls within the 0.319 and 0.334 kWh with a 95 % probability, which would sum a 1.3 kWh consumption during these months. Nevertheless, the real hourly consumption may not fall within this confidence interval due to extreme deviations in usage among this time since some appliances may requires very high amounts of energy during short time intervals, polluting the average results. For example on 15.12.2012 between 13:45 and 14:00, 63 kWh consumption was registered, which is 210 times higher than the average.

On the other hand, an important part of the energy is used for heating during the coldest months, but during February the total energy consumption was significantly lower that the January of March being not possible to establish reliable predictions on energy consumption for a 25-year gap, as it is intended on the next section.

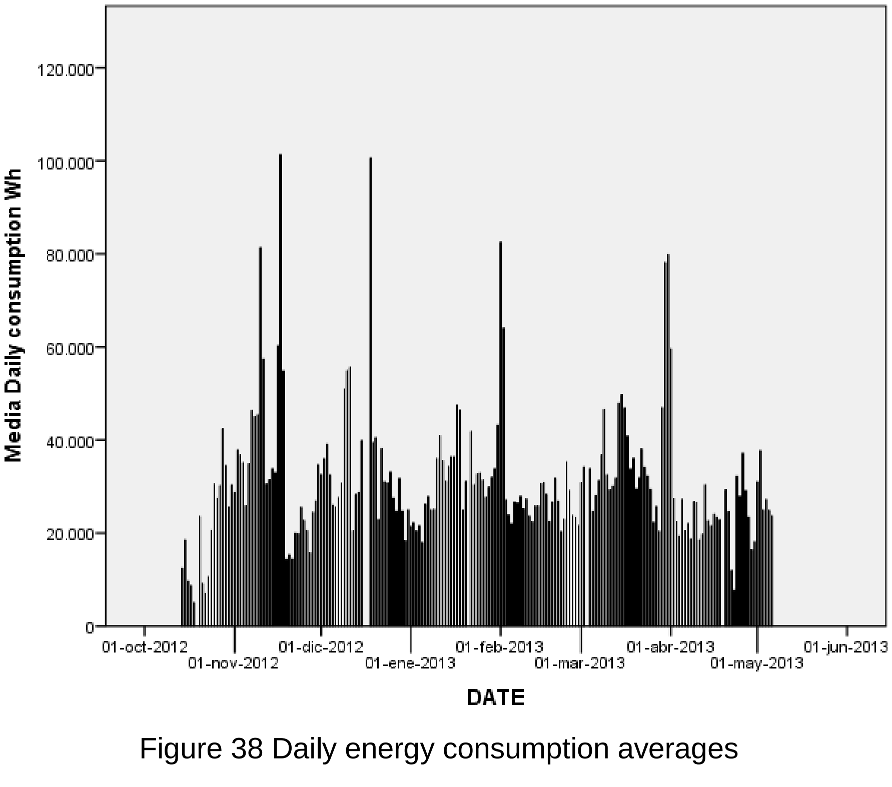


Figure 38 Daily energy consumption averages

Nevertheless, the figure below shows a rude estimation of the yearly consumption. Taking into account the existing symmetries on the weather data and Sun’s trajectory around winter and summer solstices and that heating usage may not differ much among summer months, I have estimated that the PV production one month before 21st June would be similar to that one month after, and so on for two months from April to August. Having the energy consumption values from first week of May, I have predicted the same consumption until August. This assumption is prone to errors but it is only intended to be illustrative.

All appliances which are constantly running or constantly switching from “on” mode to standby mode generate a background energy requirement.

Background energy requirement is shown in the following graph by finding the minimums in sampled energy demand at the same time, over a six-month period and displaying the results arranged by the time of the day.

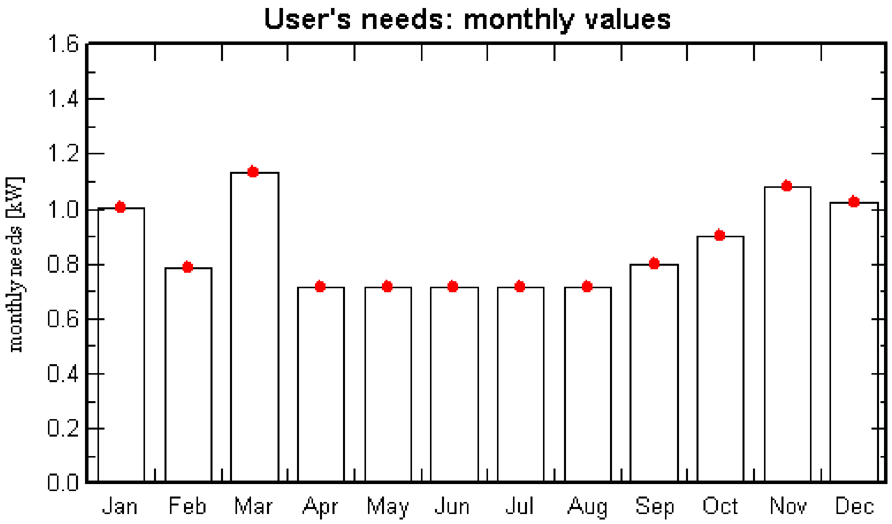


Figure 39 Gross estimation of yearly energy usage by monthly needs (kWh)

Energy generated by the system ranges from 4,63kWh in June to 0,35kWh in December, which covers from 220 % to 16 % of total minimum demand.

The following table shows a summary of the measured and estimated energy consumptions from the provider.

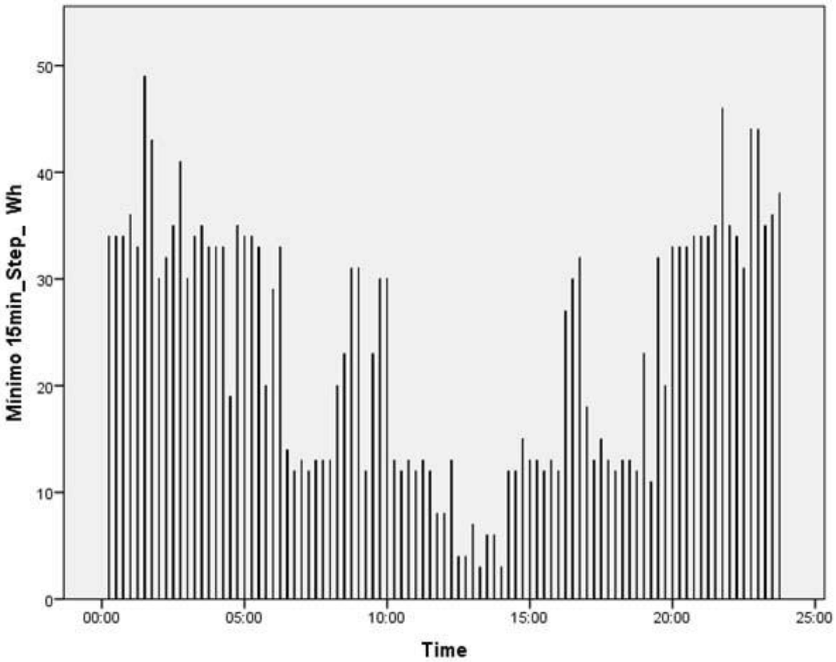


Figure 40 Average minimum energy consumption over the day in 15 minute intervals (Wh)

There are four differenced time intervals among which the background energy consumption varies significantly within the day: Approximately 35 Wh/15min within 20:00-06:00, 15 Wh/15 within 06:00-10:30 and 14:00-20:00 and finally 5 Wh/15min between 10:30-14:00. This gives an approximate daily minimum average of $\frac{(35Wh*4*10)+(15Wh*4*4.5+6)+(5Wh*4*3.5)}{24} = 87.5\ Wh/hour$ and 2.1 kWh/day.

Table 4 Energy consumptions

Energy Consumptions	**Kilowatts-hour**
Average hourly consumption (kWh)	0,986
Average daily consumption (kWh)	23,66
Minimum average daily consumption (kWh)	2.1
Average monthly consumption (Nov-April) (kWh)	955,7
Estimated monthly energy consumption (May-Oct) (kWh)	850
Estimated yearly energy consumption (kWh)	10834
Estimated 25-year period energy consumption (kWh)	379191

5.1.3 Energy consumption of the appliances connected to the PV system

The devices connected to the PV system are shown in the following table, they operate with the energy provided either from the solar panels or the battery bank, when there is no photovoltaic energy available, the multiplus inverter/regulator feeds these loads with energy from the grid. Fast switching between energy sources is one of its features so there is no interruption on the loads operation. The average yearly consumption of these loads if approximately 4490 kWh, which means that, with a yearly average generation of 850 kWh from the PV system, it covers around 19 % of their energy demand per year.

Table 5 Estimated energy consumption of loads connected to the PV system.

Device	Power (W)	Number of devices	Average daily use (hours)	Total daily consumption (kWh)	Monthly consumption (kWh)	Total yearly consumption (kWh)
Refrigerator	70	1	24	1,68	51,24	613,2
Deep freezer	70	1	24	1,68	51,24	613,2
Heating system Circulation pumps	30	2	8	0,48	14,64	175,2
Laptop IBM Thinkpad T43	32	1	4	0,128	3,904	46,72
Display BenQ BL2400PT	72	1	4	0,288	8,784	105,12
External Hard Disc 2Tb	6	1	4	0,024	0,732	8,76
External Hard Discs 3TB	6	1	4	0,024	0,732	8,76
Boiler AC resistor	500	2	8	8	244	2920
Air extractor fan	2	1	24	0,048	1,464	17,52
TOTAL				12,304	375,272	4490,96

The table below shows the percentage of the energy demand from the loads connected to the PV system that is supplied by photovoltaic energy.

Table 6 Percentage of the demand from the loads connected to the PV system covered by solar energy

	kWh	**% of demand**
January	13	3,0
February	31	7,1
March	73	16,8
April	96	22,1
May	129	29,7
June	139	32,0
July	129	29,7
August	108	24,9
September	69	15,9
October	39	9,0
November	16	3,7

December	11	2,5
YEAR	852	16,4

During summer months it is approximately, solar energy covers one third of the energy demand, while during winter it drops below 10 %.

5.1.4 Energy consumption of the water heating system

The water heating resistors have a power of 1000 W, by being turned on 8 hours daily their average energy demand is 2920 Kw yearly, if the energy generated by the PV modules was used exclusively for heating the water, it would cover 30 % of the total required.

Heating water pumps have a total power of 2 x 30 = 60 W, by working an average of 8 hours daily, the yearly energy demands is 175 W, in this case, the energy generated by the solar panels would cover almost 500 % of their demand per year.

Table 7 Percentage of energy demand of the water heating system that can be covered by solar energy

	kWh	**% for water pumps**	**% for boiler resistors only**	**% of total for water heating**
January	13	88,8	5,3	5,0
February	31	211,7	12,7	12,0
March	73	498,6	29,9	28,2
April	96	655,7	39,3	37,1
May	129	881,1	52,9	49,9
June	139	949,5	57,0	53,7
July	129	881,1	52,9	49,9
August	108	737,7	44,3	41,8
September	69	471,3	28,3	26,7
October	39	266,4	16,0	15,1
November	16	109,3	6,6	6,2
December	11	75,1	4,5	4,3
YEAR	852	486,9	29,2	27,5

On the whole water system, the yearly demand is approximately 3100 kWh; the PV system would supply a 30 % of the total energy demand if the photovoltaic energy was used exclusively on the water heating system.

The following table shows a monthly summary of the monthly demand of energy that can be covered by solar energy:

5.1.5 Battery capacity and autonomy

The battery bank has a total capacity of 250 Ah or 3 kWh, the average hourly consumption of the loads connected to the system is 0.6 kWh, this means that, without solar power generation, the battery bank can keep them operating approximately for 5 and a half hours until full discharge, 4 hours to 80 % depth discharge or two and a half hours until a 50 % discharge.

Table 8 Charge of batteries at the end of the day starting from 20 % charge and assuming no load.

	Energy generation (kWh/day)	**Charge of the batteries at the end of the day (%)**
January	0,41	17,1
February	1,12	46,7
March	2,35	97,9
April	3,21	133,8
May	4,16	173,3
June	4,63	192,9
July	4,17	173,8
August	3,49	145,4
September	2,29	95,4
October	1,25	52,1
November	0,52	21,7
December	0,35	14,6
YEAR	2.34	

The following table shows the battery capacity needed for feeding the loads connected to the PV system under full autonomy (Multiplus not switching to grid) in two cases, assuming that the solar panels would fully-recharge the batteries on a daily basis: Ideal case of 80 % depth discharge (admissible by AGM-type batteries in exchange of reduced battery life) and 100 % battery efficiency; and the worst-lowest-autonomy case: 20 % depth discharge taking into account a 60 % contingence factor for the efficiency of the batteries. [8]

When there is an energy demand from the connected loads and the batteries' voltage reaches the lower cut-off value set in the Multiplus regulator configuration, it will start providing the loads with energy from the grid. If this lower cutoff voltage is reached, which is approximately 12.4 VOC for a 50 % DoD, it means that the battery bank has given a total of 3 kWh x 0.5 = 1.5 kWh from full charge state. The regulator protects the batteries from draining further beyond that limit; therefore, this will be the maximum discharge they will bear. In the following table it is shown how much the batteries will be potentially charged during the day by the solar panels assuming that they have reached the 12.4 V point during the night and there is not energy demand from the loads during charging state.

The values over 100 % show that during the summer months the generated solar energy would be more than enough to fully recharge the batteries in one day. Note that the regulator senses the battery voltage and when the batteries' voltage is above the higher cutoff limit, it automatically redirects the surplus energy to a second load such as the water boiler.

Table 9 Battery-sizing calculations for full autonomy

Daily needed power (kWh)	14,2
80 % DISCHARGE - 100 % BATTERY EFFICIENCY	
Battery size to ensure 80 % discharge cycles (kWh)	17,8
Battery size to ensure 80 % discharge cycles (Ah)	1481,7
20 % DISCHARGE - 60 % BATTERY EFFICIENCY	
Daily needed P + 60 % Contingency Factor for battery efficiency (kWh)	22,8
Battery size to ensure 20 % discharge cycles (kWh)	113,8
Battery size to ensure 20 % discharge cycles (Ah)	9482,7

6 ECONOMICAL ANALYSIS

The table below shows the costs for the devices and material in the photovoltaic installation:

Table 10 Cost of material on the installation

Item	Amount	Cost per unit	Cost
Solar panel SolarXon ES-230P	4	350,0 €	1.400,0 €
Inverter AECA Steca Grid 500-m	2	400,0 €	800,0 €
Inverter/Regulator Victron Energy Multiplus 12/1200/80	1	770,0 €	770,0 €
Standard Pb-a 12V 62Ah Car battery	2	85,0 €	170,0 €
Pb-a 12V 70 Ah AGM	1	180,0 €	180,0 €
Pb-a 12V 180 Ah AGM	1	330,0 €	330,0 €
MCMK 4X6+6 0,6/1kV	25	6,0 €	150,0 €
MCMK 3X6+2,5+2,5 0,6/1kV	50	5,5 €	275,0 €
CYKY SUN 1kV DC	25	4,5 €	112,5 €
BU 0,6/1,2 kV	5	4,2 €	21,0 €
35A breaker	1	25,0 €	25,0 €
16A breaker	2	30,0 €	60,0 €
25A breaker	1	8,0 €	8,0 €
TOTAL			4.301,5 €

The cost of the materials in the installation is 4.300 € for a peak power of 920 W which results in a cost of 4.7 €/W

Electrical energy price per kilowatt in Finland for households, including taxes: 0.15614 €/kW (Nov 2012) [17] The annual change in the cost of electricity for households (K2 Detached house 5 MWh/year) in Finland over the last six years has experimented an average variation of 7.7 %, for this calculation this annual rate will be used over the next 25 years of use. [18]

SolarXon 230P panels are guaranteed to an 80 % performance after 25 years of life, for this calculation, performance degradation over time is considered linear. [11]

The following table shows the yearly savings that the PV installation will generate over the next 25 years. Within approximately 14 years of usage, the energy savings generated will be the same than the cost of the installation:

Year	Total Energy generated (kWh)	Savings (€)	Cost per kWh (€)
2013	856	134	0,15614
	1705	287	0,16816
	2561	464	0,18111
	3417	667	0,19506
	4273	898	0,21008
2020	5129	1160	0,22625
	5985	1458	0,24367
	6841	1795	0,26244
	7697	2176	0,28264
	8553	2604	0,30441
2025	9409	3085	0,32785
	10265	3625	0,35309
2027	11121	4229	0,38028
	11977	4905	0,40956
	12833	5661	0,44110
2030	13689	6503	0,47506
	14545	7442	0,51164
	15401	8487	0,55104
	16257	9648	0,59347
	17113	10938	0,63916
2035	17969	12370	0,68838
	18825	13957	0,74139
	19681	15715	0,79847
	20537	17661	0,85995
2039	21393	19814	0,92617

Table 11 Amortization time of the installation

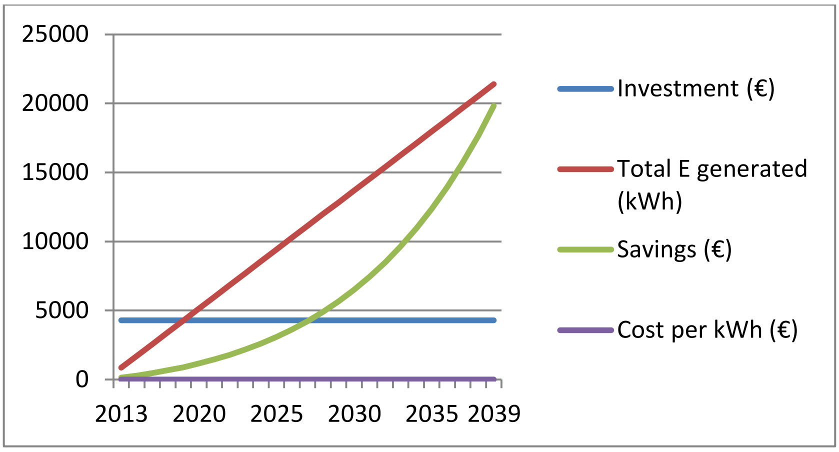


Figure 41 Savings generated by the installation [2]

As it can be seen on the results above, the economic payback period is around 14 years, this study focuses on the first 25 years of use, however it is estimated that with a proper maintenance, the operational life of this system may fall within 30 and 40 years so this system might generate energy for a longer period of time, increasing its profitability and the economic benefits shown in this study.

7 DISCUSSION AND CONCLUSIONS

7.1 Alternatives to current configuration

Since the actual capacity of the battery array would require deep discharges and intensive charge and discharge cycling in order to obtain the desired performance and battery life would be considerably reduced, some other configuration alternatives can be taken into consideration such as using the energy from the solar panels to exclusively feed the heating system and/or connecting the solar panels directly to the electric network without the usage of the battery array.

In the case of feeding all the loads in the system directly from the energy generated by the solar panels without storage, usage of solar energy would be achieved only during the day and therefore, the highest solar energy generation hours should have to be taken in consideration to maximize efficiency. If the solar energy is only used for the heating system, energy would be stored in form of heat within the water boiler, losing it during the dark hours of the day and heating the water proportionally to light intensity.

The connection of the panels and the loads can be done directly by injecting the energy into the grid from the inverters or by using the Multiplus, Taking in consideration the real hybrid configuration of this system in which not only the solar panels are generating energy but also a windwill, using the Multiplus would allow more flexibility in configuration of the energy usage, since both the windmill and the solar panels could be generating and injecting energy into the system in parallel..

The Victron Multiplus virtual switch configuration options allow the energy to be redirected into the loads connected to this virtual switch (Note that in the actual configuration of the system, the water boiler resistor is connected to the virtual switch), the turning ON and OFF of this virtual switch can be performed according to amount of watts of the connected loads or the charge level of the batteries. It also provides the option to stop inverting DC current from the batteries when turned ON. In other words, for a fixed power load of 1000 W of the water boiler, the virtual switch can be set to be turned ON indefinitely while not using the energy from the batteries, but giving the user the flexibility to reconfigure the device to use the energy from the batteries as well without having to modify the connections on the system.

7.2 Environmental payback

Simple cost payback is a rough estimation since it does not take into account the amount of saved CO2 emissions. On the average a 1 kWp photovoltaic systems prevents 400 kg/kWp carbon dioxide per year as well as other pollutants associated to fossil fuels.

Energy payback is the time needed by a PV module to generate as much energy that it was used for its manufacturing. On the case of crystalline silicon is about 2.1 years while for thin film technologies, it is around 1.2 years of operation. AGM batteries are made of recycled lead and they are 97 % recyclable. [2]

8 SUMMARY

The goal of this thesis was to examine how this photovoltaic system had been configured and how it was operating. During the evaluation of the installation, it has been found out several aspects about battery capacity and energy management configuration that are relevant in order to improve the efficiency of the system.

The battery turned out to be the most critical element in the system, in both, economical and functional terms.

The calculations for battery sizing showed that the required total capacity of the battery array must be considerably high in order to achieve smaller depths of discharge while providing the loads in the system the required energy.

By using smaller capacities and deeper discharges, similar performance can be obtained at expense of reduced battery life. Since batteries are costly and the most sensitive element of the installation, the user should consider if the need for storing energy for backup during the dark hours is balanced by assuming the cost of these elements and replacing them periodically.

Through the energy study, it has been shown that this system is capable of providing enough energy to run the water heating system throughout several months of the year. Since the heat isolation on the water boiler is another way of storing energy and the boiler resistors are the most powerful load on the system, using the energy directly from the solar panels to heat the water during sunniest hours may be a more cost-efficient alternative. However, if the energy from the batteries is used to run the heating system it becomes less efficient due to the reduced battery life and the cost for their replacement.

The most important setting that was needed to be changed was the “DC input low shut down” voltage value in the VE configure software. A level of 9 V would cause the battery bank to completely drain out, a 100 % DoD would reduce notably the battery life, below 300 cycles. This value has been set to 11 V and it even may be set higher up to 12 V in order to maximize battery life.

BIBLIOGRAPHY

[1] A. McCrea, Renewable Energy, A usere's guide, Ramsbury: Crowood Press, 2008.

[2] www.eurosolar.fi, «eurosolar.fi,» [Online]. Available: http://www.eurosolar.fi/aurinkosahko/. [Last access: 30 05 2013].

[3] Wikipedia, «Zero-energy building,» [Online]. Available: http://en.wikipedia.org/wiki/Zero-energy_building.

[4] P. A.R. Jha, Solar Cell Technology and Applications, NW: Auerbach Publications CRC Press, 2010.

[5] http://www.renewablegreenenergypower.com. [Online]. Available: http://www.renewablegreenenergypower.com/advantages-and-disadvantages-of-solar-photovoltaic-quick-pros-and-cons-of-solar-pv/.

[6] R. B. Jiménez, Instalatión solar fotovoltaica de 1.15MW conectada a la red electrica - 1.15MW photovoltaic installation connected to the electrical grid, Leganés, Spain: University Carlos III of Madrid, 2010.

[7] R. C. Neville, Solar Energy Conversion: The Solar Cell, University of Santa Barbara, California: Elsevier, 1978.

[8] M. A. Abella, Master en Energías Renovables y Mercado Energético - Master in renewable energy and energy market, Madrid, Spain: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas.

[9] batteryuniversity.com, «www.batteryuniversity.com,» [Online]. Available: http://batteryuniversity.com/learn/article/absorbent_glass_mat_agm. [Last access: 30 05 2013].

[10] batteryuniversity.com, «http://batteryuniversity.com/learn/article/charging_the_lead_acid_battery,» [Online]. Available: http://batteryuniversity.com/learn/article/charging_the_lead_acid_battery. [Last access: 30 05 2013].

[11] E. P. E. a. A. Workmanship, «Technical Manual - Valve-Regulated Lead-Acid (VRLA):Gelled Electrolyte (gel) and Absorbed Glass Mat (AGM) Batteries,» [Online]. Available: http://www.dekabatteries.com/assets/base/0139.pdf. [Last access: 02 06

2013].

[12] batteryuniversity.com, «www.batteryuniversity.com,» [Online]. Available: http://batteryuniversity.com/_img/content/clead1.jpg. [Last access: 2013 05 30].

[13] bdbatteries.com. [Online]. Available: http://www.bdbatteries.com/mcharging_procedures.php. [Last access: 02 16 2013].

[14] V. Energy, «Connecting your Victron product to a computer with VE Configure,» [Online]. Available: http://www.victronenergy.com/upload/documents/Manual%20-%20A%20Guide%20to%20VEConfigure%20-%20rev%2001%20-%20EN.pdf. [Last access: 04 06 2013].

[15] U. B. m. company, «http://www.wholesalesolar.com,» [Online]. Available: http://www.wholesalesolar.com/pdf.folder/battery-folder/charging_instruction_2011_2.pdf. [Last access: 2013 06 04].

[16] www.chargingchargers.com, «Battery charging tutorial,» [Online]. Available: http://www.chargingchargers.com/tutorials/charging.html. [Last access: 2013 05 04].

[17] «Korppoo, www.getamap.net,» [Online]. Available: http://www.getamap.net/maps/finland/lansi-suomen_laani/_korpo/.

[18] F. M. Institute, «Seasons in Finland / Snow Statistics,» [Online]. Available: http://en.ilmatieteenlaitos.fi/.

[19] SOLARXON, *Solarxon ES-230P datasheet,* Aurinkosähkötalo EUROSOLAR.

[20] AECA, *AECA StecaGrid 500 datasheet,* AECA.

[21] S. A.-E. Oy, Euroglobe 1806-77185 Datasheet, Startax Auto-Electronics Oy.

[22] V. Energy, *Multiplus compact manual,* Victron Energy.

[23] N. T. I. S. U. D. o. Commerce, «Stand-Alone Photovoltaic Systems - A Handbook of Recommended Design Practices,» Sandia National Laboratories, Springfield, U.S., 1995.

[24] Draka, *Kosketussuojattu 1kV voimakaapeli MCMK 0.6/1kV,* Helsinki: Draka NK Cables Oy, 2006.

[25] D. U. Limited, *Draka photovoltaic cables,* Derby, UK: Draka UK Limited.

[26] D. N. K. AS, *BU 0,6/1(1,2)kV P17 Power cable, Unarmoured,* Norway: Draka Norsk Kabel AS .

[27] «Europe's Energy Portal,» [Online]. Available: http://www.energy.eu/. [Last access: May 2013].

[28] «Statistics Finland - Price of Electricity by Type of Consumer, c/kWh (Prices include electrical energy, distribution of electricity, and taxes.) by Type of Consumer, Year, Month and Data,» 2013. [Online]. Available: http://193.166.171.75/Dialog/Saveshow.asp. [Last access: 24 May 2013].

[29] L. C. Tom Markvart, Solar Cells. Materials, Manufacture and Operation, University of South Hampton, University of Barcelona, Spain: Elsevier, 2005.

[30] C. f. O. Electronics, «Something new under the Sun,» 09 05 2013. [Online]. Available: http://www.newcastle.edu.au/research/achievers/something-new-under-the-sun.html.

[31] *http://edelweiss.smugmug.com/Cars/Porsche-Technical-Stuff/CTEK-US-Multi-3300-Charger/i-hSFV6hN/2/M/GEL-M.jpg.*