BUILDING AND STUDY OF A SMALL SCALE MICRO-GRID

The use of PV panels as an alternate energy source

Joni Knuuti

Bachelor's thesis
January 2013
Electrical Engineering
Power Electronics
Supervised by T. Verbeerst

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ABSTRACT

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Bachelor's thesis 43 pages, appendices 8 pages
January 2013

Today's emphasis in teaching energy technology to engineering students lies heavily on the renewable section. The renewable energy-engineering students in KHBO are studying a multitude of topics of theory that cover a wide variety of renewable energy sources. To implement the theory into practice, like all educational facilities should, some sort of equipment is required in a laboratory environment to showcase what students are supposed to do with the knowledge given to them in classroom.

To create such an environment the school had aqcuired or received the right equipment that was left to the author to acquaint himself with, install and operate for the first time. The equipment included 9 photovoltaic panels, one solar PV inverter, one off-grid inverter and batteries to store and withdraw energy to/from. The work included the check of the equipment compatibility, initialisation and setup and case studies of the complete system once operational.

The system was built in a classroom on top-floor of the school building with the windows facing SEbS (southeast by south, ~145°). Panels were placed on a wooden frame with the inverters and batteries behind them. External connection to the grid was made from a distribution board across the hall to avoid blackouts to the adjacent computer class in case of a short-circuit etc.

To monitor the validity of the results of panel production there are two pyranometers that connect with LabView. There is also a LabView program to perform tests on panel performance vs. manufacturer specifications by using a source measurement unit.

This text should provide the reader sufficient knowledge on what was done during the build-up, how to operate the system and what can be done in the future to develop it further in educational use.

Key words: photovoltaic, solar, renewable, energy, inverter, off-grid, micro grid, labview, pyranometer, source measurement unit

CONTENTS

ABBREVIATIONS AND TERMS

TAMK	Tampere University of Applied Sciences
KHBO	Katholieke Hogeschool Brugge-Oostende
BOS	Balance of system
PV	Photovoltaic
STC	Standard testing conditions
IEC	International Electrotechnical Commission
AM	Air mass
NOCT	Nominal operating cell temperature
SB	Sunny Boy 2000HF
SI	Sunny Island 2224
MPP	Maximum power point
SRC	Sunny Remote Control
SOC	State of charge
MCB	Miniature circuit breaker
VRLA	Valve-regulated lead-acid
LED	Light emitting diode
Si	Silicone
ISO	International Organisation for Standardization
SMU	Source measurement unit
IEEE	Institute of Electrical and Electronics Engineers
GPIB	General purpose interface bus
RAM	Random access memory
AC	Alternating current
DC	Direct current
V	Volt
A	Ampere
W	Watt
R	Resistance
kWp	kilowatt-peak
C_{10}	Battery capacity in 10°C

1 INTRODUCTION

The world has no shortage of energy. That is quite a statement to make, considering most major armed conflicts, wars and disasters to nature in the last few decades have been caused directly or indirectly due to energy sources, primarily oil, and the future does not look too bright on that matter. The Arctic regions and claims to those made by different North Atlantic Treaty Organization –countries and their opposing force Russian Federation, has the potential to escalate in the coming decades, if no agreement is achieved. Harvesting of those energy sources – natural gas and crude oil – also poses a threat to the environment as the Arctic regions have yet to be exposed to the devastating human effect that can be seen all over the nature where there is or was energy to be harvested – vast open coal mines, empty oil fields with old pumps standing, oil sand mines etc. – the list goes on. So how can such a statement be justified?

The sun. Our solar systems brightly shining star that provides all life on this earth. There is enough solar irradiation on our planet during one hour to provide enough energy for annual global primary energy demand. Solar energy has the potential to not only reduce our current emission levels and let us minimize or stop the use fossil fuels, but also to provide that clean, independent energy to developing countries and bring a stop to famine, lack of fresh water, diseases and human suffering in third-world countries.

There are different approaches and with those different opinions on what is the best and most cost-effective way to utilise that energy. As this thesis is written, the price-per-watt for balance of system (that includes all the capital costs to create a functioning photovoltaic system) is around 3€/Wp, which is about twice that of a coal-fired power plant. However, after the investment, the sun is a free source of energy, where as the other form needs costly fuel. When turning solar energy into electricity, it can be produced at a distance from the consumer, or de-centralized, another words taking the production to the consumption, thus avoiding losses in transfer.

This thesis and the system built and explained in it revolve around the latter. It is about creating a system for a school to educate KHBO students in a practical environment and introduce facts about solar energy and electricity production in a small scale micro-grid, with PV panels as an energy source.

2 DESIGN OF THE MICRO-GRID

The components for the micro-grid had already been selected, ordered and delivered to the college. I will therefore only present the components, explain the theoretical calculations and selection criteria for this type of equipment, and not go into why specifically these brands were chosen.

2.1 Photovoltaic (PV) panels

The primary component in transferring radiating energy from the sun into electricity is of course the photovoltaic panels. There are three mainstream types of PV panels on the market for small-scale consumer micro-grids: Panels that are made up of monocrystalline solar cells, of polycrystalline solar cells or of thin film cells. Mono- and polycrystalline cells are made with a similar technique, by growing a larger crystal using silicone as the main component and then cutting thin wafers, or slices, out of it. However, the process for making polycrystalline cells is much simpler and thus cheaper. It also results in no surplus, as it can be grown to a rectangular form and the cut into square wafers, where as the monocrystalline is grown in cylindrical form and to make panels more effective the edges have to be cut off to save space. Polycrystalline method does result in a lower power-to-area ratio than the monocrystalline, but not by much. Thin film technologies use much less material than the more traditional crystalline cells, and thus save in the amount of material needed. They must be placed between two glass panes, instead of the one used in crystalline panels, so they end up weighing about twice as much. They also have a weaker W/m^2-ratio, but are claimed to have reached a higher performance/price-ratio. Which of the methods is pre-valent is largely decided on the end user power-to-price ratio, not necessarily the W/m^2 ratio. (Wikipedia: Solar cell-article 2012).

2.1.1 Symphony Energy SE6M60 -panels

For this particular micro grid there are nine polycrystalline panels available, all of which are the same type from Symphony Energy (PICTURE 1).

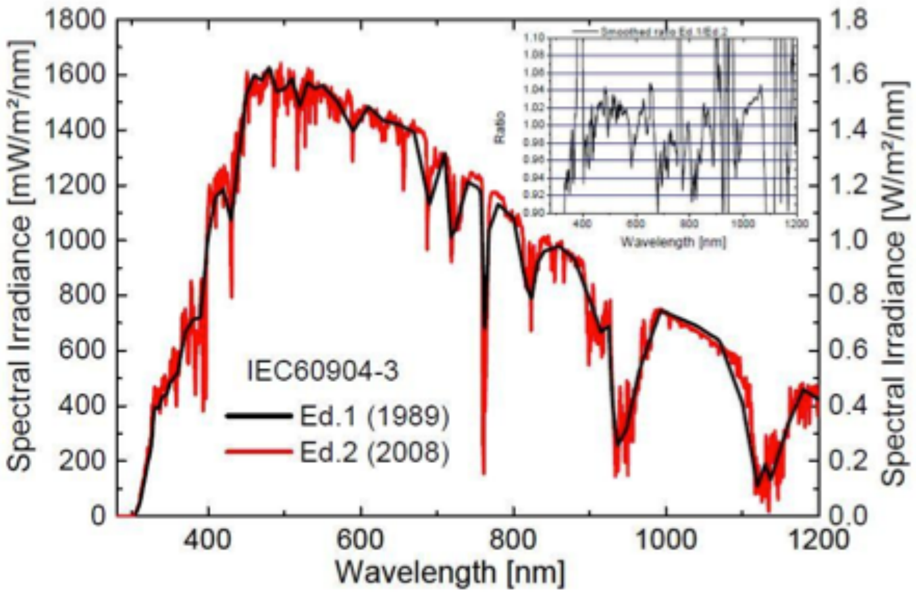
PICTURE 1. PV panels from Symphony Energy (www.symphonyenergy.com/eng, modified)

Each of these panels consists of 6 by 10 cells. Depending on the desired kWp power output, a number of panels must be installed either in series or parallel. The electrical characteristics for these panels can be found below (TABLE 1).

TABLE 1. Characteristics for individual panels

Electrical characteristics/panel	
Peak power (Wp) [W]	230.0
Peak power voltage (Vmpp) [VDC]	30.20
Peak power current (Impp) [A]	7.61
Open circuit voltage (Voc) [VDC]	36.70
Short-circuit current (Isc) [A]	8.16

The manufacturer provides these characteristics. The tests that conclude these variables are standardized testing conditions, STC. In those tests the solar radiation has a standardized spectrum, referred to as AM1.5G (IEC 60904-3), where irradiance is 1000W/m^2, temperature of the cells is 25°C. The AM1.5G is set to present the average conditions in a given place on the Earths surface (PICTURE 2). It considers the tilt of the incidence plane, ground reflectance, atmospheric water and ozone concentration, and turbidity. With the testing conditions strictly standardized, panels can be compared to one another regarding output specifications. (Robinson, J. Pre-construction PV Assessment Qualitative Analysis. 2012)



PICTURE 2. Spectral analysis of AM1.5G conditions (Robinson, J. Pre-consruction.., 2012)

Generally when connecting the panels into an inverter and eventually a 230VAC grid, it is best to place them in series. This raises the voltage to a more useful level without a transformer and also maintains the current in common and reasonable value. As any electrically oriented person knows, this also reduces heat losses in the system (FORMULA 1) and/or enables the use of smaller diameter cables. Calculations for system characteristics are simple multiplying of voltages and power and results are below (TABLE 2).

$$P_{losses} = R_{cables} \cdot {I_{DC}}^2 \qquad (1)$$

Where P_{losses} = Power losses due to heat dissipation in cables

R_{cables} = Resistance in the connection cables

I_{DC} = Direct current in the panels to load/inverter cables

TABLE 2. Characteristics for nine panels connected in series

Electrical characteristics/system	
Peak power (Wp) [W]	2068
Peak power voltage (Vmpp) [VDC]	272
Peak power current (Impp) [A]	7.6
Open circuit voltage (Voc) [VDC]	330
Short-circuit current (Isc) [A]	8.2

One still has to consider that conditions are not always standardized, especially as far as temperatures go. In Belgium, the average air temperature varies between some degrees below 0°C and up to 25°C (http://www.meteovista.be). The panels are also given temperature coefficients, so that the temperature variations can be taken into account in the design of systems. For the SE6M60 panels the coefficients are presented below (TABLE 3). It must also be taken into cosideration, that while the ambient temperature of the cells is something, the actual cell temperature is different. The manufacturer also provides nominal operating cell temperature, NOCT, which is the temperature the cells will reach when open connected, with 800W/m2 irradiance, ambient temperature of 20°C and wind velocity of 1m/s. The panels are to be mounted with open backside to allow cooling (http://pvcdrom.pveducation.org/MODULE/NOCT.htm, 2013).

TABLE 3. Coefficients for SE6M60 panels

Coefficients	
I (%/°C)	0.06
V (%/°C)	-0.35
P (%/°C)	-0.46
NOCT (°C)	46.00

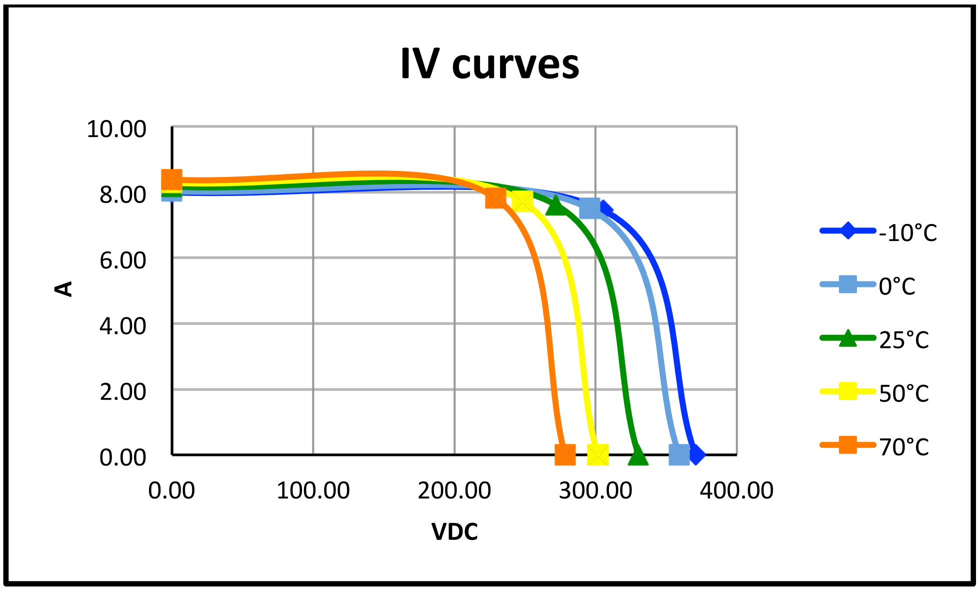
For Belgium, the national standard for evaluating temperature variations states, that calculations must be made in a temperature range of -10°C...70°C. This is to ensure that $V_{OC\text{-}10°C}$, and $V_{MPP70°C}$ are in the range of the inverter. In the

TABLE 4 are calculated the variations in voltage, current and power under the standard condition variations.

TABLE 4. Temperature effects in system characteristics

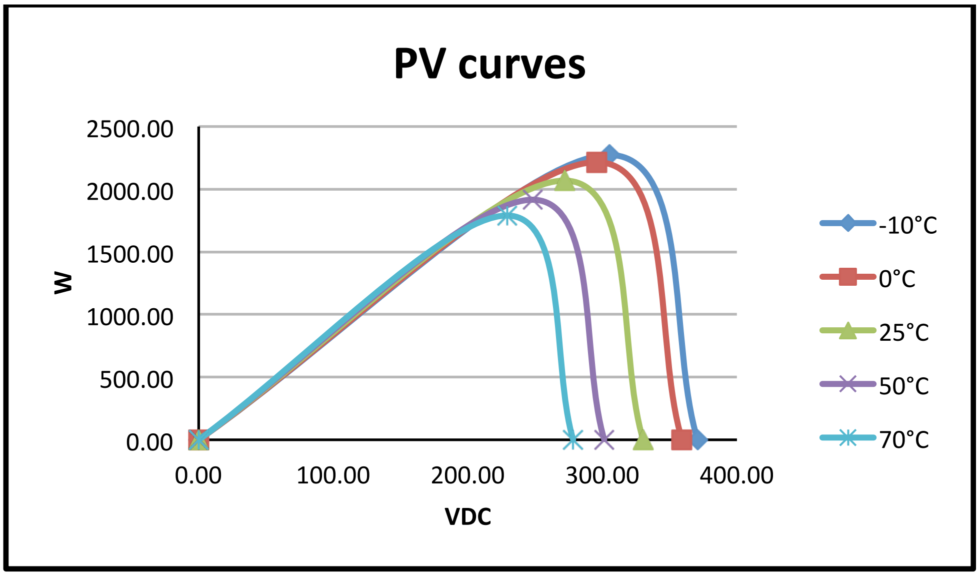
Temperature	-10°C	70°C
Peak power (Wp) [W]	2273	1790
Peak power voltage (Vmpp) [VDC]	305	229
Peak power current (Impp) [A]	7.5	7.80
Open circuit voltage (Voc) [VDC]	371	278
Short-circuit current (Isc) [A]	8.0	8.4

The full table with temperature effects can be found in appendices (Appendice 1). Effects can also be seen in the IV curves for 9 panels in series presented in GRAPH 1. As the table shows, the power output at -10°C is above 2,2kW, but less than 1,8kW at high temperatures. The effects of this in the design of the system will be explained later in this document when considering inverters.



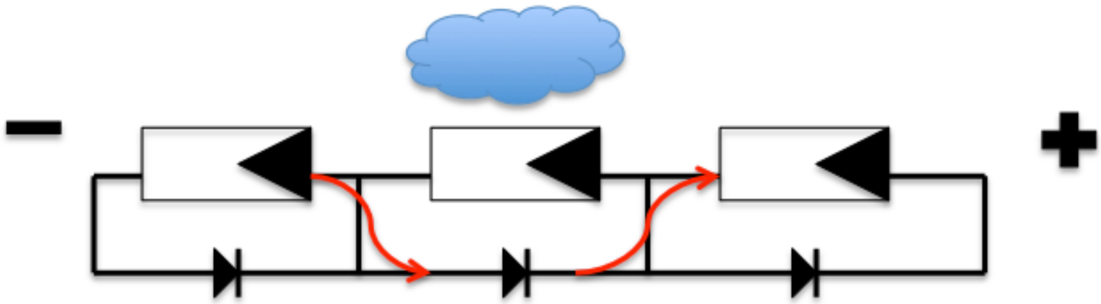
GRAPH 1. IV curves for 9 SE6M60 panels connected in series.

The graph below emphasises the effect of temperature in power output of the panels. Lower temperatures provide a better yield from the panels, as the cells are cooler and more efficient (GRAPH 2). The Maximum Power Point (here on referred to as MPP) is the point where the highest yield is achieved from the entire system. The solar PV inverter searches for that point and adjusts the voltage and current of the panels. Depending on the inverter or type of panel setup, one or more MPP’s can be in use at the same time for a field of panels.



GRAPH 2. PV curves for 9 SE6M60 panels connected in series

To prevent shading in panels or strings, they are fitted with 3 bypass diodes. These diodes further divide the 6x10 cells into 2x10+2x10+2x10 cells. Their function is to redirect the flow of current, if a certain part of a panel becomes shaded and the voltage drops. This does not only result in power drop, but also in powerloss. The illustration (PICTURE 3) shows the connection of the diodes and flow of current in case of shading.



PICTURE 3. Flow of current in case a cell or string becomes shaded or dirty

2.2 Inverters

In this project, there were two different inverters. Firstly, there is the solar inverter. This inverter is connected directly to the panels, and converts the DC-voltage supplied by the panels into AC-voltage and feeds the solar power to the grid it is also connected. Secondly, there is the off-grid inverter. This enables us to use the micro-grid in an island mode, completely self-sustainable and disconnected from the grid, powered completely from the main grid as well as the combination of these two. Both inverters and their functions are explained in the next chapters.

2.2.1 Dimensioning and design

When dimensioning a system, it is well possible that the power outputs of suitable inverters are some hundred watts above or below the nominal kWp of planned panels to be installed. Due to the very small time when conditions are optimal and when that kWp could be achieved, calculations need to be made whether that extra investment of a larger inverter can be received from that extra power in a reasonable timeframe. A larger inverter than installed $kWp_{0°C}$ is not considered a good investment. The solar irradiation at those temperatures is significantly lower due to the larger inclination and the reduced temperature losses are therefore not compensated. Depending on the installations yearly irradiation, inclination and azimuth of the panels, the installed $kWp_{25°C}$ might never be achieved during the lifespan of the inverter. As a rule of thumb, inverter input power should be between 80%...90% of the panel power output.

Data from other functioning systems can be found online on different organizational and corporate websites and was also used as a reference for this document. Condensed reference data from a very good day in May 2012 can be found in appendice 2. System in question has 48 x 235Wp = 11,280kWp, placed 19° over horizon and facing 54° due east of south, or a true heading of 126°. As an example of the Wp vs inverter power in design, a data sample was taken of a sunny day in late May, when the solar angle is highest at approximately 60° above horizon and rising at 55° azimuth at 04.40. (http://aa.usno.navy.mil/cgi-bin/aa_altazw.pl). Best yield is achieved not when azimuth is direct but when inclination is the smallest. That means to say that the sun at highest point is only 11° off from direct angle. Even then, the panels were not able to produce more than 9.6kW at best. Unfortunately no temperature data for panels is available, but it can be assumed to be above the STC conditions (panel ambient temperature 25°C).

Most time of the lifespan of the inverter it works in the lower percentages of it's output, and thus the aforementioned rule of thumb enables a higher efficiency rate, and can also save in the investment costs when purchasing the inverter. Each design is unique with regard to expected yield and weather conditions and care should be taken when considering different inverters.

2.2.3 Solar inverter Sunny Boy 2000HF

PICTURE 4. Sunny Boy 2000HF (http://www.sma.de/en/products/solar-inverters-with-transformer.html)

The Sunny Boy 2000HF (here on referred to as SB) is a high-frequency inverter with an in-built transformer. Key technical data is presented in table below (TABLE 5). It has a maximum DC power input close to the maximum output of the panel group, although only at very low panel temperatures.

TABLE 5. Sunny Boy 2000HF technical data (Sunny Boy HF manual, 2012)

Technical Data	Sunny Boy 2000HF
Input (DC)	
Max. DC power (@ cos φ=1)	2100 W
Max. input voltage	700 V
MPP voltage range / rated input voltage	175 V - 560 V / 530 V
Min. input voltage / initial input voltage	175 V / 220 V
Max. input current	12 A
Max. input current per string	12 A
Number of independent MPP inputs / strings per MPP input	1 / 2
Output (AC)	
Rated output power (@ 230 V, 50 Hz)	2000 W
Max. apparent AC power	2000 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V - 280 V
AC power frequency / range	50 Hz, 60 Hz / −4.5 Hz ... +4.5 Hz
Rated power frequency / rated power voltage	50 Hz / 230 V
Max. output current	11.4 A
Power factor at rated power	1
Adjustable displacement factor	–
Feed-in phases / connection phases	1 / 1
Efficiency	
Max. efficiency / European efficiency	96.3 % / 95 %

As the table above shows us, the input DC voltage range is quite broad and the panel voltage is well within those limits. Also the input current is lower, even with short-circuit current from the panels at low temperatures. The number of independent MPP inputs gives us the number of MPP the inverter is able to find. In this case, the inverter can look for one MPP in two strings of panels, another words all the panels connected to this inverter will have the same current flowing through them, and voltage varies according to panel by-passes caused by shading (PICTURE 3).

Output of the inverter can be selected from three different nominal voltages 220VAC, 230VAC and 240VAC respectively. The actual feed-in voltage varies according to the grid-voltage the panel is connected to. The SB cannot function without an AC voltage connected to it. That is why it must always be either grid-connected or used with an off-grid inverter. Output voltage of the inverter must be slightly larger than that of the grid it is connected to for the power to be fed to the grid as opposed to the panels. Maximum output is at 2000W/2000VA and 11.4A. The Sunny Boy 2000HF is a 1-phase inverter. If a 3-phase grid is necessary to create, a specific 3-phase inverter must be connected to the panels, or three 1-phase inverters must be used together with three 1-phase off-grid inverters.

2.2.4 Sunny Island 2224

PICTURE 5. Sunny Island 2224 (http://www.sma.de/en/products/off-grid-inverters.html)

The Sunny Island 2224 (here on referred to as SI) is an off-grid inverter. In this case the off-grid inverter means that loads connected to the SI can be powered straight from a generator or grid and/or from an alternate power source, such as solar panels or windmills or similar, not on-demand energy sources, or from the batteries. The SI has to be connected to a set of batteries, which can be of different type, in order for it to function. The operation will be explained in further detail later in chapter 3, operation.

TABLE 6. Sunny Island 2224 technical data (Sunny Island manual, 2012)

	SI 2224
Output Values	
Nominal AC voltage ($U_{AC,\ nom}$) (adjustable)	230 V (202 to 253 V)
Nominal frequency (f_{nom})	50 Hz (45 to 65 Hz)
Continuous AC output power (P_{nom}) at 25 °C	2200 W
Continuous AC output power (P_{nom}) at 45 °C	1600 W (-27 %)
AC output power for 30 min at 25 °C	2900 W
AC output power for 5 min at 25 °C	3800 W
AC output power for 1 min at 25 °C	3800 W
Nominal AC current ($I_{AC,\ nom}$)	9.6 A
Max. stand-alone grid current (limitations based on hardware)	25 A_{peak} (500 ms)
Max. stand-alone grid current (limitations based on software)	17 A_{eff} (2.5 s)
Harmonic distortion of output voltage (K_{VAC})	< 4 %
Power factor (cos j)	- 1 to +1
Input Values	
Input voltage ($U_{AC,\ ext}$) (adjustable)	230 V (172.5 to 264.5 V)
Input frequency (f_{ext}) (adjustable)	50 Hz (40 to 70 Hz)
Max. AC input current ($I_{AC,\ ext}$) (adjustable)	25 A
Max. input power ($P_{AC,\ ext}$)	5.75 kW
Battery Data	
Battery voltage ($U_{Bat,\ nom}$) (range)	24 V (16.8 to 31.5 V)

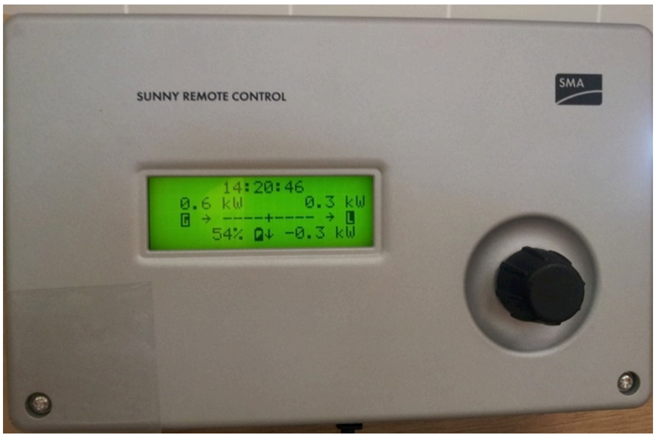
The continuous AC output power at 25°C is 2200W, which is almost the same as the power output of the SB connected to it. SMA notes that no larger (SB) nominal output than twice the nominal output of the SI should be connected together (2).

$$P_{AC\max SB} = 2\ x\ P_{AC\ nom\ SI} \qquad (2)$$

Nominal output current I_{AC} is just below 10A, so a 10A load breaker could be used. Momentarily the SI can have peak current in the stand-alone grid of 25A (for 500ms) in a motor start etc. and an effective momentary current of 17A (2,5s). SI can feed reactive and capasitive loads with a PF varying between -1 and 1.

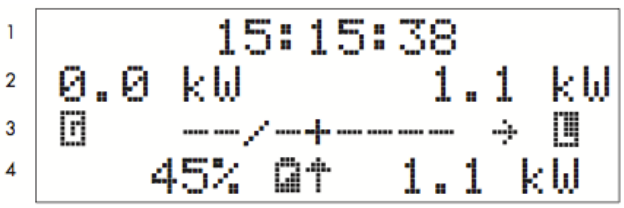
The battery voltage to be connected must be 24V. The batteries in this system are presented in the next chapter. In stand-alone mode, SI generates the AC voltage from the DC voltage of the batteries. It can feed loads in the stand-alone grid from an external power source such as SB, directly from the batteries, or both.

SI is controlled and monitored with a control panel, Sunny Remote Control (here on referred to as SRC) (PICTURE 6). There is a turn-push -switch that works as a navigator and selector of different functions in the menus. Turning the knob navigates up and down in the menu, and pushing it selects them. The SRC connects to the SI with a CAT5e-FTP patch cable, and it has a SD/MMC –memory card slot for saving events and preferences. To set the password for SRC-1, simply calculate the operating hours and enter the value in the field ie. 243 running hours equal “09” as the password.



PICTURE 6. Sunny Remote Control

The SRC standard view 1, or home screen (PICTURE 7), shows what is happening in the stand-alone grid regarding power consumption by the load, the batteries, and the feed power of the grid or generator.

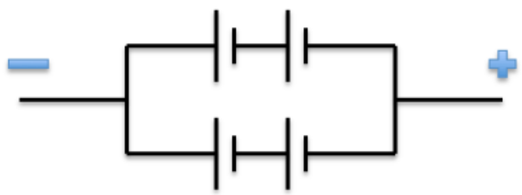


PICTURE 7. Standard view 1, or home screen, of the Sunny Remote Control (SI manual, 2012)

First line shows the time of day. Second row shows the power of grid (left) and load. Third line is a visualisation of the direction of power and internal breaker status. Here the grid/generator is not connected and the load is fed by the batteries with 1,1kW. Line 4 shows the SOC and power to/from the batteries. Below is a situation, where everything is disconnected.

2.2.5 DynoEurope EV Batteries

SI can be connected to three types of batteries; VRLA, FLA and Ni-Cd. SMA recommends that at least 175Ah (C_{10}) battery capacity to be connected to ensure a faultless operation of the system. In addition, if an AC-coupled PV plant is connected, 200Ah/installed kWp should be connected (SI manual, 2012). In this case that would mean 400Ah. Battery capacity installed here is only 100Ah, with 2x2x50Ah. Two sets of two series-connected batteries connected in parallel (PICTURE 8). For testing purposes the capacity is sufficient, but if any realistic household loads were connected to it, the batteries would be depleted during the course of night. The Electric Vehicle batteries currently installed provide several charges and discharges, and allow for fast charge times. From 20% to 95% in less than two hours when connected to the feed grid and charged with a maximum momentary power of 1,5kW, which the solar panels in good outdoors conditions could yield.



PICTURE 8. Battery connections in Sunny Island 2224

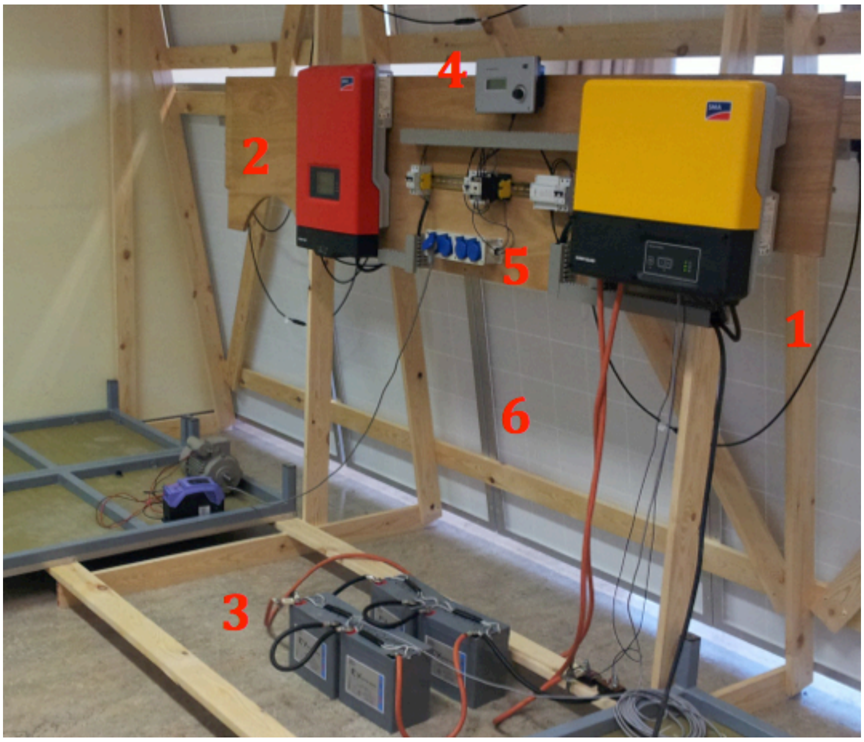
The SI also features a battery current and temperature sensor, which enable it to monitor and adjust the charging process more thoroughly if necessary. For the current measurement, a specific current shunt was installed, that converts the charge current into mV signal. Here, a 200A current corresponds to 60mV. The current sensor is not mandatory, as no DC loads ar generators are connected to the SI (SI manual, 2012).

Battery temperature sensor is a simple thermoelement that is place on the side of a battery, here put between two batteries. As the batteries are simply layed on the floor in an open place, a sufficient airflow keeps the battery surface temperature close to the room temperature. In a separate battery compartment, where the temperature raises more, the temperature sensor is crucial device, as the optimal charging current is heavily dependent on the battery temperature. The SI manual provides sufficient information regarding airflow demand for batteries located in a closed space.

2.3 Other hardware

Other hardware consists of cables, wires, miniature circuit breakers (MCB's), power outlets, cable trays, junction box and a load shedding contactor. The contactor is powered and controlled by the batteries and SI, and different scheduled events can be customised to disconnect loads when there is not enough power available. Cables and wires were chosen to correspond the MCB's 10A and 16A, so all have a diameter of 2,5mm^2.

2.4 Complete system



PICTURE 9. Complete installation

1. Off-grid inverter Sunny Island 2224
2. PV inverter Sunny Boy 2000HF
3. Batteries DynoEurope EV
4. Sunny Remote Control
5. Other hardware
6. PV panels (backside facing) (PICTURE 10)

As shown in PICTURE 9, the entire installation is set inside a classroom to a wooden frame. Conditions are not entirely up to standards of fixed installations, but the main goal was simply to set up the equipment to gain a testbed for students to investigate and study PV panels and the related equipment. There is reason to believe that the panels will be permanently installed to a different location in a few years.

The panels are pictured below. They are set up so that 6 panels are put long side vertically and 3 horizontally. Due to the by-pass diode set-up and the limited solar irradiation through the windows, this has effects that will be covered later in chapter 3 OPERATION.

PICTURE 10. SE6M60 Monocrystalline panels installed in the classroom testbed

The angle of the panels is very steep, but this is not necessarily a bad thing for this purpose. When the school year begins in September, the angle of the sun is already lower than during summer months, approximately 40° above horizon. The highest angle is of course during summer solstice around 20th of June, when the sun reaches over 62° above horizon for this location. Because of the windows, the optimal angle is in fact in November through January, when the height of the sun is between 20° and 15° (15th of each month respectively) above horizon (http://aa.usno.navy.mil/cgi-bin/aa_altazw.pl).

3 OPERATION

3.1 Initialisation of Sunny Island 2224

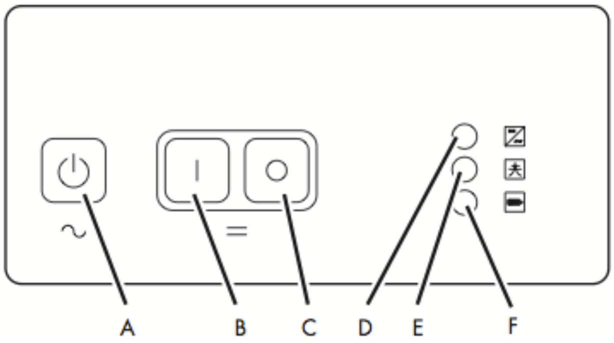
When operating the SI for the first time, all settings are in the default mode as it was ordered from the manufacturer. The menus are numbered with a # separating each submenu eg. 001#01 for Start Menu; Start System. The manual guides the installer through first commissioning in chapter 9. The key points to check/set when starting a new system are (defaults in bold):

- 003#01 Number of phase(s) (**1/1**, x/3)
- 003#03 Voltage/Frequency type (**230V, 50Hz**)
- 003#04 Date (dd.mm.yyyy)
- 003#05 Time (hh:mm:ss)
- 003#06 Battery type (**VRLA**, FLA, Ni-CD)
- 003#08 Nominal Battery Voltage (**24V**)
- 003#09 Nominal Battery Capacity (**100Ah** to 10000Ah)
- 003#10 External Source (**PVonly**, Generator, Grid, Generator and Grid)
- 003#11 Maximal Grid Current (0 to 25A, **16A**)
- 003#12 Maximal Generator Current (0 to 25A, **16A**)
- 003#13 Generator Interface (Manual, GenManual, **Autostart**)

For this system the parameter 003#10 was changed to Grid-mode. That means the batteries are being charged when ever there is grid voltage present, as well as PV panel voltage from SB.

Once the initialization has been done, the inverter goes into stand-by mode and asks the operator to start the system. Pushing and holding the SRC turn-knob now starts the system and it is running. Depending on the conditions, different LED's show different colors in the front panel of the SI. These conditions are covered in the next chapters.

The front of SI has three pushbuttons and three LED's. They are presented in the picture below (PICTURE 11).

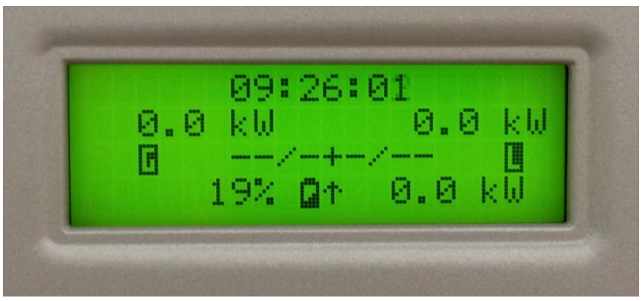


A	Start / Stop button
B	DC start button
C	DC stop button
D	Inverter LED
E	Grid LED
F	Battery LED

PICTURE 11. Control panel on the enclosure (SI manual 2012)

Button A starts the inverter operation. Buttons B and C start and stop the DC function, ie. Charging the batteries or creating the AC voltage from the DC side. The LED's have three different colours each, green, red and orange, to indicate different situations.

After the SI has been turned on and initialised, and the inverter function has been started, the standard view 1 on SRC shows, that all breakers are open and no power is transferred, (PICTURE 12). It is also showing a breaker opened towards the load, this function will be explained later in this document.



PICTURE 12. Standard view 1 after initialisation

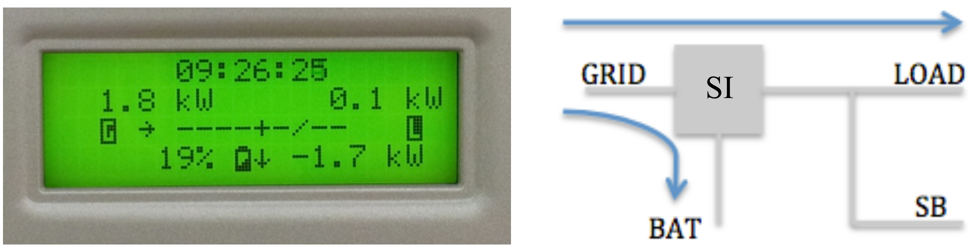
The next chapters describe what happens, when the grid is connected to the system, when it is not connected, and when the PV panels are producing power.

3.2 Operation with grid connection

When the SI is started after the initialization and the grid is connected and a voltage is present, it shows that inverter is in operation (D is green), grid is connected and synchronized (E is green) and a state of charge that batteries have, here between 0%-20% (F is red).

PICTURE 13. SI enclosure after startup with grid connected

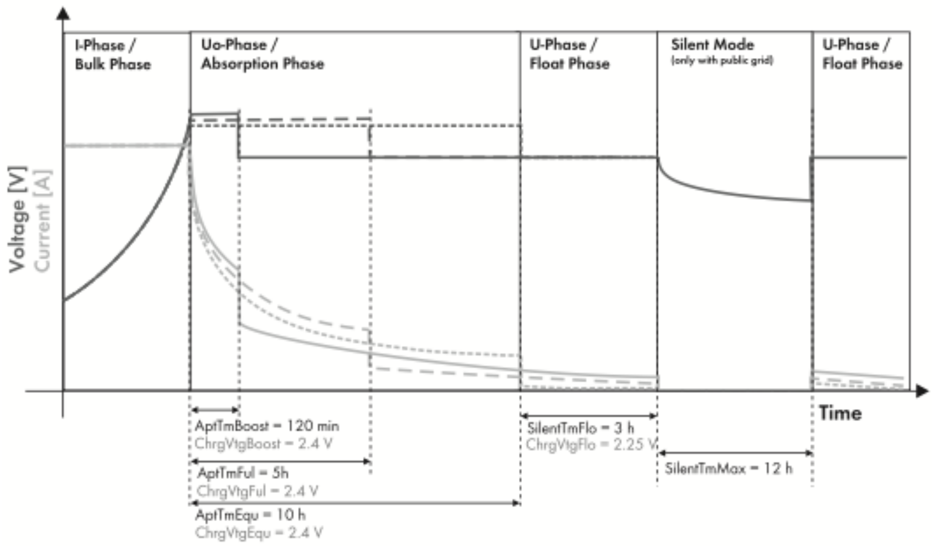
With no other load present, practically all power is directed in to the batteries. Standard view 1 shows a 1,8kW power taken from the grid. 1,7kW is fed to the batteries and 0,1kW is used to maintain the stand-alone grid voltage. The negative marking in front of battery power indicates the charging process. In actual fact, the power fed to the batteries varies between 1,7kW...1,8kW, when the power going to the load goes to zero. This is no doubt due to inaccuracies in the scale and round-up function. Apparently the inverter does not count for own losses (PICTURE 14).



PICTURE 14. Introduction of grid voltage with low battery power

3.2.1 Charging the batteries

When the batteries are at a low SOC and the grid is connected, the SI begins to charge the batteries according to its proprietary battery management and charge control system. It is essentially a 3-phase charging process described in the graph below (PICTURE 15).



PICTURE 15. Charging process of the batteries (SI manual, 2012)

The SI begins to charge the batteries with a steady current that should not exceed 90A under any circumstances according to the manual. The battery cables are 50mm^2 in cross-section and protected with a 135A blow-fuse. The manufacturer recommends the use of NH disconnecting fuses rated at 100A, but such were not available at this time. Once the absorption phase is achieved, the charging current drops to the intermittent level. The SRC reports the time left until full charge is achieved, which is 5h after the absorption phase is achieved. PICTURE 16 shows the SOC being full in 2 hours and 20 minutes.

PICTURE 16. Absorption phase of battery charging

3.2.2 Feeding the stand-alone grid from the feed grid

When the main grid is connected to the stand-alone side the load is fed directly from it. The maximum permissible load is presented in the manual and in

TABLE 6. Maximum continuous load at 25°C is 2200W and a 20°C increase in temperature results in a 27% decrease in power output (1600W). Momentarily the SI can pass larger power and current, for instance when a motor is started in the stand-alone side. When 1,8kW of lights were connected and the batteries were charged with 1,1kW, a total of 2,9kW was taken from the feeding grid for some minutes, and no problems occurred.

PICTURE 17. Momentary overload of SI

PICTURE 17 shows the readings in SRC when this was tested. According to the manual, this situation could have been kept for 30 minutes, as the room temperature was close to 25°C. It also shows the flow of power to both the load and the batteries.

3.3 Operation without grid connection

The SI can also be operated without feed grid present, or without a generator running. In this test equipment there is a breaker switch that simulates the loss of voltage that is a common occurrence especially in developing countries. The middle LED in the front cover of SI indicates the lack of grid or generator voltage by going from green to red to dark. Red indicates a disturbance or fault.

If voltage is restored, the SI synchronises the feed voltage with the stand-alone grid. This is indicated with an orange light (PICTURE 18).

PICTURE 18. Synchronisation of feed grid or generator

Once the voltage and phase are synchronised the SI closes the inner breaker and depending on the power demand and supply, starts to feed power to the stand-alone side or back to the grid from the SB.

3.3.1 Feeding the stand-alone grid from batteries

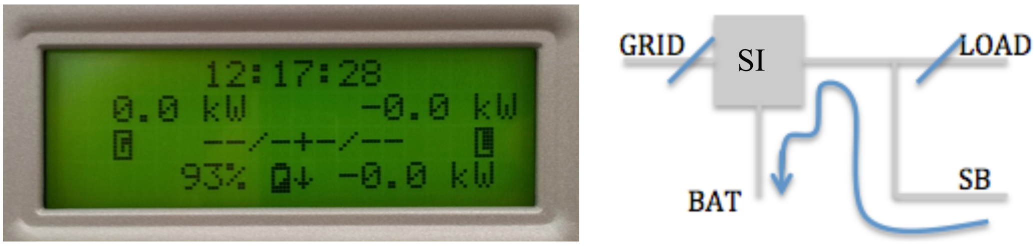
When the grid is disconnected or voltage in feed grid drops, the SI seamlessly starts to feed the load from the batteries. No disruption in power output occurs. The SRC shows the inner breaker being open from the feeding grid and the direction of power from batteries to the load in stand-alone grid side (PICTURE 19).

PICTURE 19. Feeding stand-alone grid from the batteries

The SI does not know if the PV panels feed the load as well, as long as the load is larger than the power output from the SB. It simply reduces the output to correspond with the demand left from the SB fed load. The SB functions will be covered in following chapters.

3.3.2 Charging the batteries from stand-alone grid

When the output power from SB exceeds the load, or in this case the load is disconnected due to small output of panels, the SI begins to load the batteries from the stand-alone grid side. Because the panels are located inside a classroom, and are largely shaded, the output remains very small and does not show in the numeral value. The arrow however indicates the direction of power to the batteries (PICTURE 20).

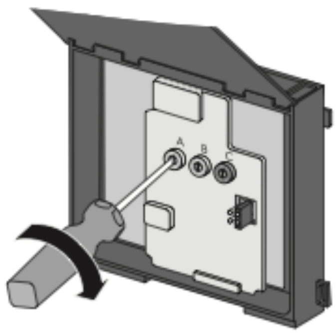


PICTURE 20. Charging batteries from Sunny Boy

Maintaining the voltage and frequency in the stand-alone grid also consumes power. When no feeding grid is connected, and only the SB produces power, the direction of power to or from the batteries varies when the production from SB is around 30W. This is with the batteries charged above 80%.

3.4 Sunny Boy 2000HF

The Sunny Boy requires very little changes in parameters to start operating. It is sent configured from the factory, and simply needs to be setup to match the country of installation. The country setup can be adjusted in the communication module supplied with the inverter (PICTURE 21). Further instructions are in the SB manual.



PICTURE 21. Communication module for Sunny Boy 2000HF

Inside the communication module there are three rotary switches. The country setup is done via switches A and B. For this setup the switches are set to A-7 and B-9. That is the country data set for Belgium with English as display language (TABLE 7).

TABLE 7. Rotary switch position equivalence

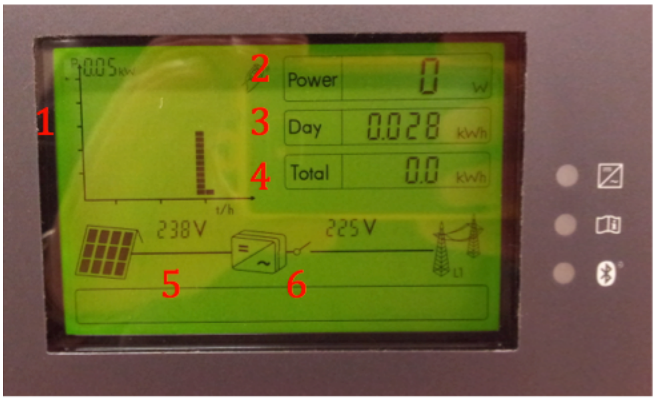
(A)	(B)	Country data set	Display language	Grid Guard protection	Country
7	9	C10/11	English	yes	Belgium
7	A	C10/11	German	yes	Belgium
A	C	SI4777-2	English	no	Israel
B	8	IEC61727/MEA	English	no	Thailand
B	C	IEC61727/PEA	English	no	Thailand
D	0	Off-Grid 60Hz	English	no	Flexible
D	1	Off-Grid 60Hz	German	no	Flexible

If desired, for testing purposes or otherwise, the setup could be put for off-grid use, but this would require a laptop with *Bluetooth* interface and Sunny Explorer software. This way the SB could be set to connect faster to the off-grid and even without the presence of grid voltage. This would result in a more intermittent connection-disconnection during cloudy days, but would enable a better view to study the equipment. To change the parameters after 10 working hours, a SMA Grid Guard Code needs to be applied from the manufacturer. This can be done with an application form available in the manufacturers website and in the appendix 5 of this thesis.

3.4.1 Feeding the stand-alone grid with solar power

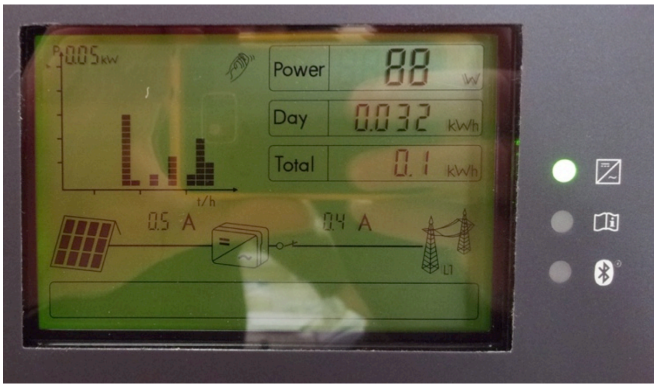
Once the connections from PV panels are made, communication module is in place, and the SB is connected to set voltage and frequency, it begins to seek for DC power output, MPP. MPP is the point where DC voltage and current yield the best attainable AC power output. The DC voltage is lowered or raised, and the current sets accordingly. The AC voltage is always a little higher than on the stand-alone grid for correct power direction.

In the front panel (PICTURE 22), the SB shows a histograph of produced power output in the upper left corner (1). Next to that on the right is the momentary power output (2), past 1-day output (3) and total power output since last reset (4). There is also a visual display showing the DC voltage (5) and status of the breaker (6), which is also shown with the top LED. The other LED's indicate disturbance in the function (middle LED, red) and an established *Bluetooth* connection (bottom LED, blue).



PICTURE 22. Sunny Boy 2000HF front cover display

When there is sufficient power available from the PV panels, SB makes the connection with the stand-alone grid. The top LED then goes green and the indicating switch shows closed connection (6). Momentary power output is shown as a numerical value (2).



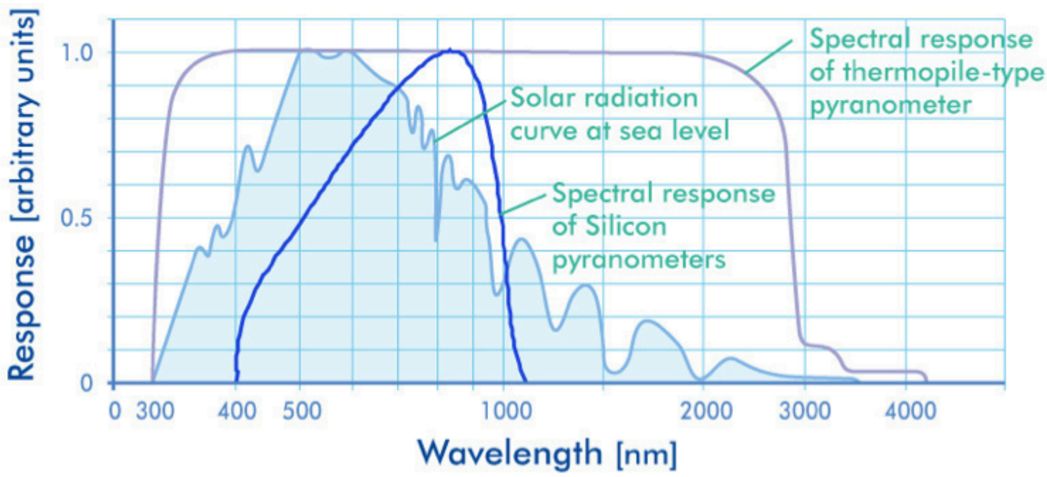
PICTURE 23. Sunny Boy 2000HF connected to the stand-alone grid

3.4.2 Artificial light assisted solar

Placement of the panels, windows and shading all result in a very poor produced to nominal power output ratio. At best less than 100W was produced during these tests, even when assisted with artificial light. When effects of artificial light was tested, halogen worklights were put to luminate the shaded areas. The effects due to poor light spectrum were limited to around 20..25W. Proportional effect seemed large at first, but when the result was almost constant regardless of power output without the lights, the effects were considered weak.

4 MEASUREMENT

There are different methods and hardware for measuring the irradiation of the sun. Main categories are PV reference cells and pyranometers. PV reference cells are not considered very reliable method for measuring the irradiation of the sun, as they require a much more direct irradiance compared to pyranometers and give a greater error value. PV reference cells also have a much more narrow spectral response, which gives more inaccurate results. Even within pyranometers there is great difference in accuracy. Graph below shows the different spectral responses of two types of pyranometers (GRAPH 3).



GRAPH 3. Spectral responses of different pyranometers (Pasquini, F. Solar Radiation Measurement, 2012.)

For this project there were two different pyranometers aqcuired that are presented in this chapter.

4.1 Pyranometer classification

There are two types of sensing elements in pyranometers: Si-pyranometer (conventional photodiode) and thermopile pyranometers. According to the ISO-9060 standard, that among other things defines the specifications for pyranometers, the Si-pyranometer has no classification and is therefore not considered an accurate testing device. The thermopile pyranometers are divided into three categories and requirements accordingly: Secondary standard, First Class and Second Class (TABLE 8). Furthermore, the standard appreciates the different uses for each classification.

TABLE 8. ISO-9060 Pyranometer specifications (Hukseflux USA, 2011)

Ref No.	ISO-9060 Pyranometer Specifications	Secondary Standard	First Class	Second Class
1	**Response time:** time to reach 95% response	< 15 sec.	< 30 sec.	< 60 sec.
2	**Zero-offset:** Offset-A: response to 200 W/m² net thermal radiation, ventilated Offset-B: response to 5 K/h change in ambient temperature	+ 7 W/m² ± 2 W/m²	+ 7 W/m² ± 2 W/m²	+ 7 W/m² ± 2 W/m²
3a	**Non-stability:** % change in responsivity per year	± 0.8%	± 1.5%	± 3%
3b	**Non-Linearity:** % deviation from responsivity at 500 W/m² due to change in irradiance from 100 – 1000 W/m²	± 0.5%	± 1%	± 3%
3c	**Directional response (for beam irradiance):** the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring from any direction, a beam radiation whose normal incidence irradiance is 1000 W/m²	± 10 W/m²	± 20 W/m²	± 20 W/m²
3d	**Spectral Selectivity:** % deviation of the product of spectral absorbance and transmittance from the corresponding mean, from 0.35 – 1.5 µm	± 3%	± 5%	± 10%
3e	**Temperature response:** % deviation due to change in ambient within an interval of 50K, *(e.g. -10 to +40º C typical)*	2%	4%	8%
3f	**Tilt response:** % deviation in responsivity relative to 0º tilt, due to change in tilt from 0º to 90º tilt at 1000 W/m² beam irradiance	± 0.5%	± 2%	± 5%

Secondary Standard devices are labeled individually and each instrument must pass the given criteria. These devices can be used for research grade measurement applications and must meet the most stringent specifications.

First and Second Class devices can be labeled as a single instrument or a type of pyranometer, if they are identical in design. They must still meet the respective specifications in all cases. In addition, if a First Class measurement device is to be used in solar energy test applications, a directional error validation from the manufacturer is required. This means that the cosine and azimuthal errors need to be validated for single instruments. (Hukseflux USA, 2011.)

4.2 Si-Pyranometer SP Lite2

The Si-pyranometer is a very simple construction. It only comprises of a photodiode that reacts to light, in this case mostly by creating a voltage between positive and negative pole. This can then be read with mV-meter or amplified to desired scale before taking a reading. Due to the simplicity of these sensors they are very cheap compared to thermopile sensors, but also lack in accuracy and unison among other sensors of the same type. Because there is no standard to define different attributes of these sensors, two photodiode sensors of the same type but different manufacturer can produce different solar irradiation readouts, thus voiding the purpose.

For this project there is a Si-Pyranometer made by Kipp&Zonen, model SP Lite2 (PICTURE 24). It is a very compact sensor intended for routine measurements, for instance to estimate panel or plant performance in small scale.

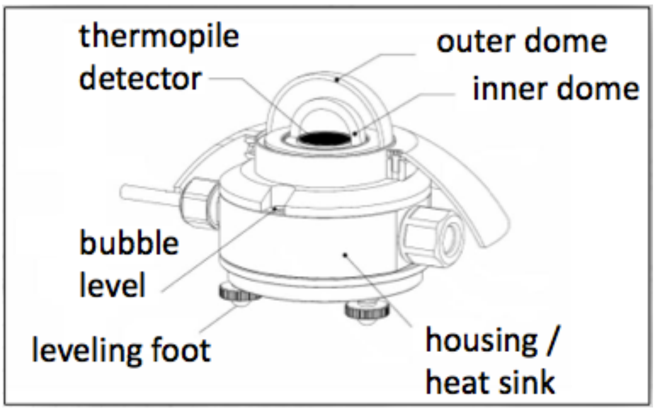
SPECIFICATIONS SPEZIFIKATIONEN • SPÉCIFICATIONS • ESPECIFICACIONES		
Spectral range Spektralbereich • Gamme spectrale • Rango espectral		400 to 1100 nm
Response time Ansprechzeit • Temps de réponse • Tiempo de respuesta	@ 95 %	< 500 ns
Non-linearity Nichtlinearität • Non-linéarité • No - linealidad	0 to 1000 W/m²	< 1 %
Temperature dependence Temperaturabhängigkeit Dépendance en température Dependencia de la temperatura	-30°C to +70°C	-0.15 % /°C
Directional error Richtungsfehler • Erreur directionnelle • Error direccional	Up to 80 ° (with 1000 W/m² beam)	< 10 W/m²
Sensitivity Empfindlichkeit • Sensibilité • Sensibilidad		60 to 100 µV/W/m²
Non-stability (change/year) Jährliche Stabilitätsabweichung Instabilité par an Variación anual de la estabilidad		< 2 %

PICTURE 24. SP Lite2 Si-Pyranometer and specifications (Kipp&Zonen, SP Lite2 instruction sheet, 2012.)

The SP Lite2 connects with two wires and needs to be ground shielded against disturbance in the signal. The signal measured is mV-signal with a sensitivity given from 60 to 100µV per W/m^2. This means that at STC irradiance it should yield approximately 60 to 100mV. This is a very large possible error and inaccuracy. Also the spectral range is very narrow compared to the thermopile pyranometers (GRAPH 3).

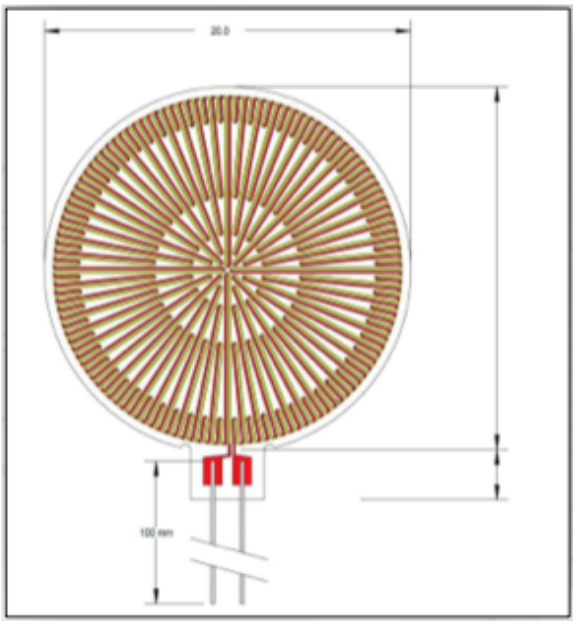
4.3 Thermopile Pyranometer CMP 6

Thermopile pyranometers are classified in ISO-9060 standard, as mentioned in chapter 4.1. Basic design in a thermopile pyranometer is more or less the same regardless of the manufacturer, thanks to standardisation. It consists of the thermopile element, dome(s), and a heat sink (housing). Usually it also includes a bubble level and adjustable feet for leveling (PICTURE 25). The CMP 6 from Kipp & Zonen is the other pyranometer for this project. It is a typical First Class sensor but lacks the directional error certification thus excluding use for solar energy applications.



PICTURE 25. Thermopile pyranometer construction (Hukseflux USA, 2011.)

The thermopile element, which converts thermal heat energy into voltage potential linearly, is comprised of 64 series connected thermocouple junctions (PICTURE 26). It is also connected with two wires and needs to be ground shielded. It produces a mV signal, but has a much smaller sensitivity than the SP Lite2, yielding 5 to 20μV per W/m^2.



PICTURE 26. Thermocouples in thermopile element

The CMP 6 also includes a screw-in drying cartridge with changeable desiccant, to remove humidity and reduce error. It is recommended, that the CMP 6 be installed leveled with horizon to gain accurate readings. As the directional error is not given as a function of tilt angle, it is impossible to get accurate readings from a tilted pyranometer. TABLE 9 shows the specifications for CMP 6 sensor.

TABLE 9. CMP 6 pyranometer specifications

Specification	Unit	CMP 6/ CMA 6
Spectral range	nm	285 - 2800
Sensitivity	μV/W/m²	5 to 20
Impedance	Ω	20 to 200
Response time	s	< 18
		< 6
Non-linearity	%	< 1
Temperature dependence of sensitivity	%	< 4
Tilt error	%	< 1
Zero offset A	W/m²	< 15
Zero offset B	W/m²	< 4
Operating temperature	°C	-40 to +80
Field of view		180°
Directional error	W/m^2	< 20
Maximum irradiance	W/m^2	2000
Non-stability	%	< 1
Humidity	% RH	0 - 100
Uncertainty in daily total	%	< 5

4.4 Connecting pyranometers with LabView

For connecting pyranometers to a PC to get readings, National Instruments LabView-program was used in conjuction with a multifunction signal aqcuiring unit NI-DAQmx (PICTURE 27). The DAQmx connects to a PC via USB, and thus enables the use of any simple laptop. It does require the LabView software and/or National Instruments Measurement & Automation software MAX. The DAQ comes in 12- or 14-bit versions, and has analog inputs and outputs as well as digital inputs and outputs, and is configurable. To receive more practical results, an additional operation amplifier should be used. With the SPLite2 directly connected, there was so much variation in the signal, that when converted to W/m^2 results in tens of percents of inaccuracy.

PICTURE 27. Multifunctional signal aqcuiring unit NI-DAQmx (NI website, 2013.)

4.5 Yokogawa GS610 SMU

The Yokogawa GS610 Source Measurement Unit (here on referred to as SMU) was used to verify the characteristics of a given solar panel. To retrieve and analyse data from the SMU (PICTURE 28) it needed to be connected to a PC. When connecting hardware with a PC a General Purpose Interface Bus (here on referred to as GPIB) was used, which is also known as IEEE-488 interface bus originally developed by Hewlett-Packard. This interface is known and used all over the world and most manufacturers provide this connection for their measurement and source units (National Instruments, 2013).

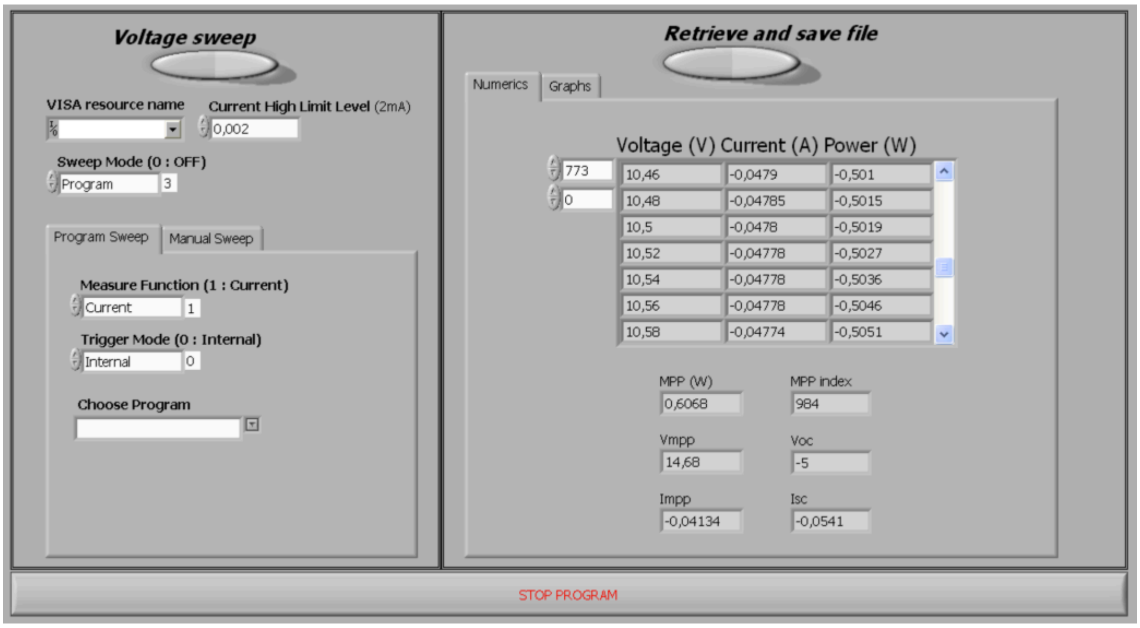
PICTURE 28. Yokogawa GS610 Source Measurement Unit (Yokogawa Electric Corporation. 2013.)

A panel can be connected to the poles of the SMU and according to the specifications given for a panel to correspond with the positive and negative pole. Then a voltage sweep program can be run to verify the given specifications for the panel. These specifications include V_{OC}, I_{SC} and MPP. Given that the testing conditions for this sweep cannot be verified to be according to the standard (IEC 60904-3), they have to be seen as relations to one another and if necessary, multiplied to correspond with the amplitudes given for the panel.

The SMU can feed a voltage and measure current at the same time. When a voltage sweep is done, the SMU is given a starting voltage, step size and end voltage. For safety measures also the current can be limited. Once the sweep is done, the results are saved to a Comma Separated Value –file, or .csv-file, in the GS610 volatile memory. Because they are stored in the volatile memory, the files are lost every time there is a powerout or if someone turns off the SMU. The GS610 can have up to 33 files in the RAM memory, however, if it runs out of memory before the count is achieved due to large file sizes, it will begin to write on the oldest files. It is therefore important that the files are saved to another location on the PC before the SMU runs out of memory.

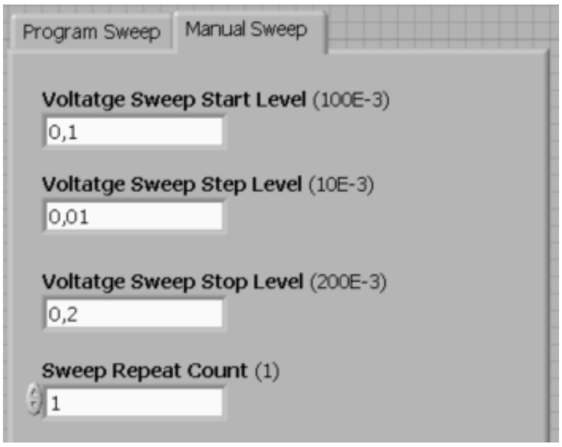
4.6 GS610 LabView front panel

LabView software from National Instruments is a graphical programming tool capable of a multitude of tasks. For the use of GS610 a program was built using LabView 2011. It provides the user with a front panel (PICTURE 29) to operate the SMU as with the buttons, but with ease and single button multifunctions.



PICTURE 29. LabView Front panel for the SMU

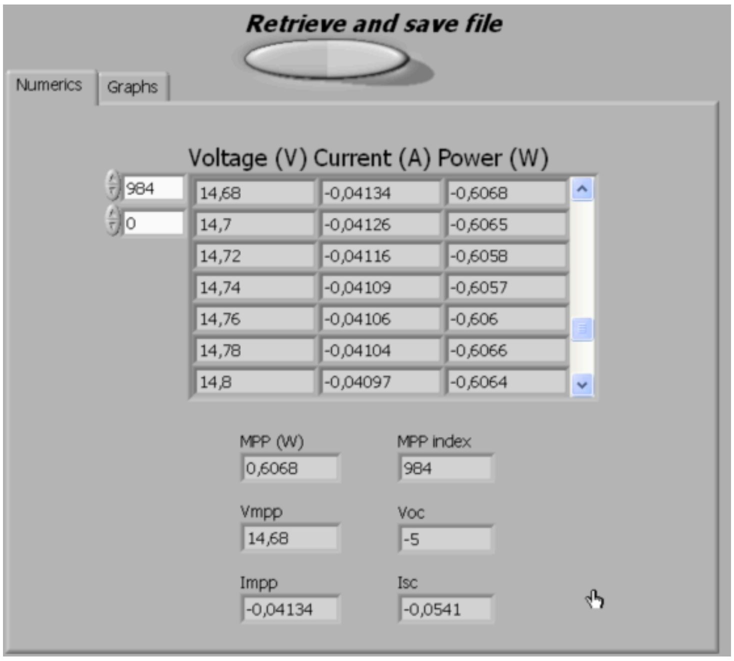
In the front panel the operator first selects the correct VISA resource name. In this case the GS610 appears as a device connected with the GPIB address 15. GS610 could be assigned another address number as well. If it needs to be changed, this has to be done manually from the SMU. Then the operator sets the current limit during sweep according to panel specifications if available. Default is set at 2mA. Sweep mode determines whether to choose a pre-installed sweep program or to set initial voltage, step size and final voltage in the “Manual Sweep”-tab (PICTURE 30). The sweep can also be done several times in a row. Once the selection is made clicking the “Voltage Sweep”-button starts the sweep.



PICTURE 30. Manual Sweep-tab in front panel

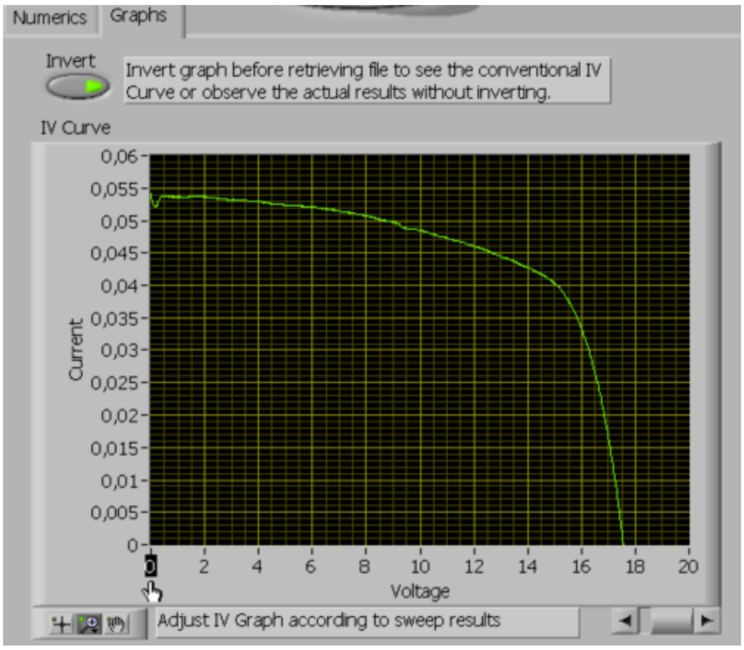
Once the sweep is done, the results are stored in the RAM memory of the GS610. The operator can then view those results by clicking ”Retrieve and save file”-button. The program asks the user then which file to open. Result files are numbered each time a sweep is done, and the latest sweep is always result.csv-file and previous sweeps numbered consecutively result1.csv, result2.csv etc. When the user clicks to open, the program also prompts to save that file in another location. As mentioned before, the RAM is volatile memory and a power loss or unintentional shut-down both result in lost files. Space limitation can also happen in large data point sweeps, although unlikely.

After the file has been retrieved the program shows the results in a table with voltage, current and power. Under the table it automatically retrieves the MPP and corresponding voltage and current and gives the row number in the table. It also shows the I_{SC} and V_{OC} (PICTURE 31).



PICTURE 31. Table of results and key elements in front panel

In the ”Graphs”-tab the user can see the graphical presentation of the sweep. As the sweep returns a negative current and a positive voltage when the panel is feeding power to the SMU, it can be confusing to relate to the resulting graph. The ”Invert”-button negates the current results and provides a similar IV curve as some manufacturers provide with their panels. To adjust the curve, the user can simply click the ends of X- or Y-axis and type the desired scale (PICTURE 32), usually 0...U_{max}.



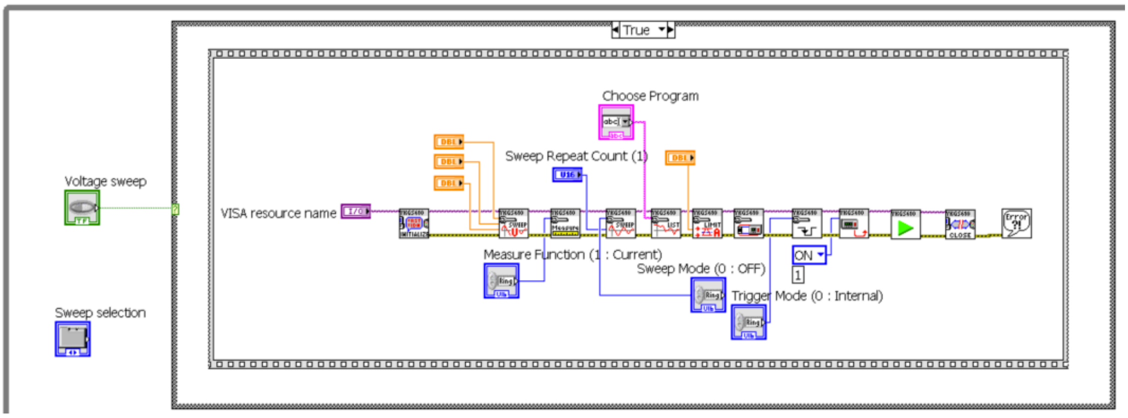
PICTURE 32. Inverted IV curve of the results

4.7 GS610 LabView block diagram

With LabView, the actual program is in the block diagram. There you can program with a graphic interface using ”building blocks” of code and connect them with ”wires” to each other. This way of programming is very simple and does not require the user to memorise extensive lists of commands and different programming languages. For the GS610 front panel presented in the previous chapter there is a block diagram that performs all the tasks given by the user in the front panel. As with normal programs, the user does not have access or see the block diagram, he simply sees the results of commands etc.

4.7.1 Voltage sweep

The block diagram is divided into two main structures, just as the front panel but these have no correlation. There is a case structure for the execution voltage sweep, initiated by the true-false signal from the ”Voltage Sweep”-button. The program then goes into a sequence where it aqcuires the VISA resource name and then goes through the different sub-VI’s from left to right with the resource name and possible errors. Along the way it picks up different settings selected or typed in the front panel and finally starts the sweep accordingly. In each sub-VI seen in the sequence the program communicates with the SMU. Third to last is the sub-VI that starts the sweep, the next one closes the connection between program and SMU and the last one reports an error if such occurs (PICTURE 33). These sub-VI’s were retrieved from NI and supplied by the manufacturer in accordance with the drivers for GS610 and are accessible to all. This made the programming significantly faster.

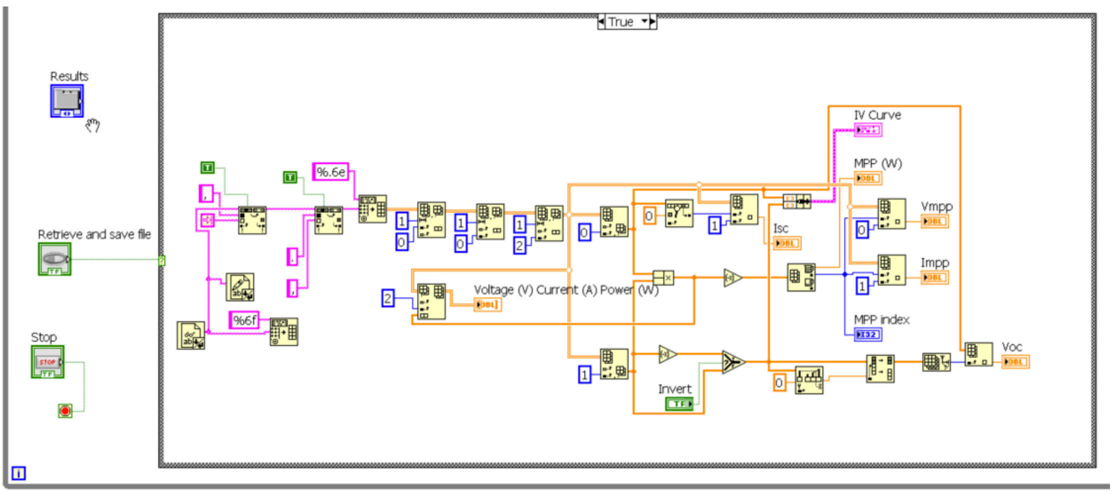


PICTURE 33. Voltage Sweep case structure in the block diagram

”Voltage sweep”-button and ”Sweep selection”-tab are inside the main While-loop, which enables the program to run as long as the ”Stop”-button in the front panel bottom is clicked (PICTURE 34).

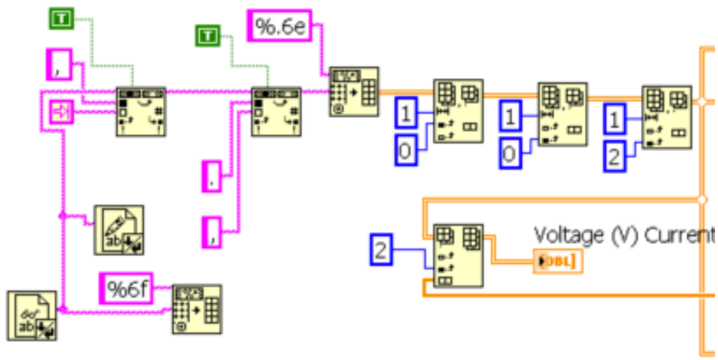
4.7.2 Retrieving results

The other main structure handles the result files. It contains a case structure, that is executed everytime the ”Retrieve and save file”-button is clicked.



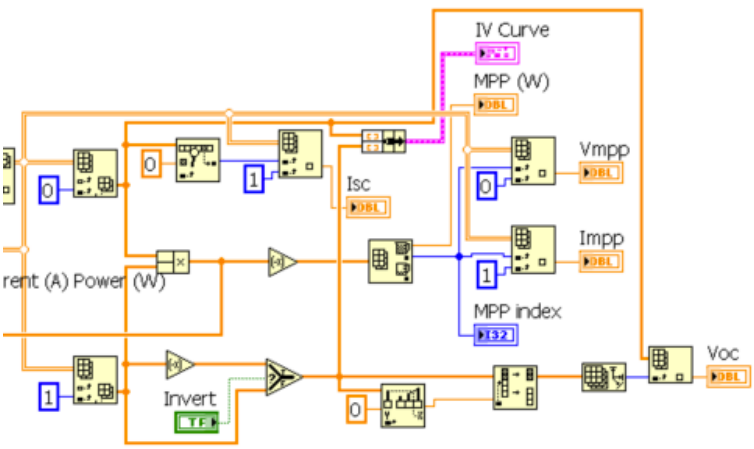
PICTURE 34. Case structure for retrieving, handling and showing the results

The case structure for retrieving the files and saving it in another location, handling the .csv-file and presenting the results in the table and graph is shown in picturePICTURE 34. The original file is a string of text, with periods separating decimals. LabView cannot handle these in an array, so the first the string is edited by changing commas into tabs, and then replacing all periods with commas. Then the string is changed into a two-dimensional array with 6-digit scientific notation according to the syntax %.6e. As the top row contains text, it is deleted from the array. So is the time and setup column, as they are irrelevant results (PICTURE 35). In the bottom right is the block used to add a third column containing the results of multiplication of the voltage and current columns resulting in respective power for each voltage.



PICTURE 35. Reshaping the string, converting it to an array and deleting top row and exterior columns

After the two-dimensional array is created, it is divided into 1-dimension arrays, voltage and current respectively. The current-array results can be then negated and it is bundled to the XY-graph. Results are also multiplied to create the power-array. The arrays are also searched for key points as mentioned in chapter 4.6. I_{SC} is where the voltage is zero, but for the V_{OC} it required a more complicated construction. As the current has a value ≠0 throughout the sweep, the array is searched for a point with a previous value under and next value over zero, then the array is split and the last element is shown.



PICTURE 36. Editing arrays and locating key points

5 DISCUSSION

This project provided a good insight into solar energy with emphasis on photovoltaic panels and solar electricity on many levels: Hardware selection on both engineering and economical scale point of view, although the latter is not really reflected in the final product, as the hardware was already selected. Throughout this project different sources of insight arose in the web, judging by which it is clear that the energy revolution is coming. Speaking from a European point of view, the financial situation has hindered current development, but luckily some major investments have already taken place especially in Germany, and some larger projects are constantly being planned. As the decisionmakers are inclined by the public to shift weight in energy policies towards both economically and environmentally sound direction, new generations of engineers need to be ready for the increasing demand by employers to have basic familiarity with renewable energy sources, such as solar PV panels.

The learning platform created here is going to give just that extra edge in job market to current and future students. Belgium is in the top-6 of Europes PV tables in every category as surveyed by the EurObserv'ER in 2012 (Photovoltaic barometer 2011). There is new Wp installed every year and the already installed capacity requires people who understand how it works and how it is connected to the grid and what repercussions each Wp has to the existing grid.

When new locations are considered for installments, it is crucial that all parties involved understand the real potential such systems have, as they are as dependent on the location as they are of correct design. This is where the pyranometers step in, as well as in assessing the yield of an existing system. The use of LabView for aqcuainting students with the hardware, gives them the power to shape the software to their own preferences and possibly create superior products to the existing ones on the market.

As with all good learners thinking for your self is crucial and a healthy amount of criticism to what we are told is an absolute demand for any engineer. The LabView software created is an example of how that could be done when measuring the panels. The hardware provides also a great platform to be re-invented by each student, as there are more functions with the SMU unused than there are used, and in a few years it could be completely run from a laptop with an intuitive and userfriendly "operating system."

5.1 Developments

From the current system the very first thing I would change is the panel setup. The way they are now on the wooden rack in the classroom is very unpractical. The windows prevent sunlight most of the time to the toprow completely, and this just results in unnecessary losses. Also the movement of the rack takes a lot of physical effort and it could topple over at worst breaking the expensive panels or inverters. Best approach would be to take the remaining six panels from the bottom row and mount them just in front of the windows. This way the equipment can achieve a better yield than with poorly located nine panels and enables the year round use and study. Or both possibilities could be left, to emphasise the locations significance.

Also, the connection to the feeding grid should be extended to the classroom. Current setup with long extension cables is both inconvenient and potentially unsafe in the corridor.

Of course, this is likely a temporary setup if the location of the entire education facilities is moved to the city of Brugge, but apart from the grid connection, should not be of great effort to execute if so desired.

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APPENDICES

Appendix 1. Effects of temperature variation in output of 8 SE6M60 panels connected in series.

-10°C	I	V	P
Short circuit	7.99	0.00	0.00
Mpp	7.45	271.20	2020.46
Open circuit	0.00	329.57	0.00
0°C	I	V	P
Short circuit	8.04	0.00	0.00
Mpp	7.50	262.74	1969.46
Open circuit	0.00	319.29	0.00
25°C	I	V	P
Short circuit	8.16	0.00	0.00
Mpp	7.61	241.60	1838.58
Open circuit	0.00	293.60	0.00
50°C	I	V	P
Short circuit	8.28	0.00	0.00
Mpp	7.72	220.46	1702.87
Open circuit	0.00	267.91	0.00
70°C	I	V	P
Short circuit	8.38	0.00	0.00
Mpp	7.82	203.55	1590.82
Open circuit	0.00	247.36	0.00

Appendix 2. Data from a sunny day in May.

Installed panels: 48*235Wp = 11.280kWp (±3%)

Inclination and azimuth: 19° over horizon, 54° from south to east

Coordinates:

Date and time	Total kWh	kW	Date and time	Total kWh	kW
25/05/2012 04:50:00	3,931,427	0,000	25/05/2012 08:35:00	3,942,828	6,804
25/05/2012 04:55:00	3,931,427	0,000	25/05/2012 08:40:00	3,943,413	7,020
25/05/2012 05:00:00	3,931,433	0,072	25/05/2012 08:45:00	3,943,916	6,036
25/05/2012 05:05:00	3,931,440	0,084	25/05/2012 08:50:00	3,944,392	5,712
25/05/2012 05:10:00	3,931,450	0,120	25/05/2012 08:55:00	3,945,023	7,572
25/05/2012 05:15:00	3,931,461	0,132	25/05/2012 09:00:00	3,945,656	7,596
25/05/2012 05:20:00	3,931,474	0,156	25/05/2012 09:05:00	3,946,292	7,632
25/05/2012 05:25:00	3,931,489	0,180	25/05/2012 09:10:00	3,946,933	7,692
25/05/2012 05:30:00	3,931,506	0,204	25/05/2012 09:15:00	3,947,584	7,812
25/05/2012 05:35:00	3,931,524	0,216	25/05/2012 09:20:00	3,948,241	7,884
25/05/2012 05:40:00	3,931,545	0,252	25/05/2012 09:25:00	3,948,907	7,992
25/05/2012 05:45:00	3,931,567	0,264	25/05/2012 09:30:00	3,949,583	8,112
25/05/2012 05:50:00	3,931,593	0,312	25/05/2012 09:35:00	3,950,271	8,256
25/05/2012 05:55:00	3,931,633	0,480	25/05/2012 09:40:00	3,950,964	8,316
25/05/2012 06:00:00	3,931,706	0,876	25/05/2012 09:45:00	3,951,658	8,328
25/05/2012 06:05:00	3,931,792	1,032	25/05/2012 09:50:00	3,952,360	8,424
25/05/2012 06:10:00	3,931,919	1,524	25/05/2012 09:55:00	3,953,073	8,556
25/05/2012 06:15:00	3,932,078	1,908	25/05/2012 10:00:00	3,953,789	8,592
25/05/2012 06:20:00	3,932,254	2,112	25/05/2012 10:05:00	3,954,513	8,688
25/05/2012 06:25:00	3,932,445	2,292	25/05/2012 10:10:00	3,955,242	8,748
25/05/2012 06:30:00	3,932,653	2,496	25/05/2012 10:15:00	3,955,973	8,772
25/05/2012 06:35:00	3,932,876	2,676	25/05/2012 10:20:00	3,956,706	8,796
25/05/2012 06:40:00	3,933,116	2,880	25/05/2012 10:25:00	3,957,450	8,928
25/05/2012 06:45:00	3,933,372	3,072	25/05/2012 10:30:00	3,958,195	8,940
25/05/2012 06:50:00	3,933,643	3,252	25/05/2012 10:35:00	3,958,943	8,976
25/05/2012 06:55:00	3,933,931	3,456	25/05/2012 10:40:00	3,959,705	9,144
25/05/2012 07:00:00	3,934,235	3,648	25/05/2012 10:45:00	3,960,474	9,228
25/05/2012 07:05:00	3,934,556	3,852	25/05/2012 10:50:00	3,961,247	9,276
25/05/2012 07:10:00	3,934,893	4,044	25/05/2012 10:55:00	3,962,025	9,336
25/05/2012 07:15:00	3,935,245	4,224	25/05/2012 11:00:00	3,962,803	9,336
25/05/2012 07:20:00	3,935,612	4,404	25/05/2012 11:05:00	3,963,585	9,384
25/05/2012 07:25:00	3,935,996	4,608	25/05/2012 11:10:00	3,964,370	9,420
25/05/2012 07:30:00	3,936,395	4,788	25/05/2012 11:15:00	3,965,156	9,432
25/05/2012 07:35:00	3,936,809	4,968	25/05/2012 11:20:00	3,965,942	9,432
25/05/2012 07:40:00	3,937,238	5,148	25/05/2012 11:25:00	3,966,733	9,492
25/05/2012 07:45:00	3,937,681	5,316	25/05/2012 11:30:00	3,967,520	9,444
25/05/2012 07:50:00	3,938,138	5,484	25/05/2012 11:35:00	3,968,309	9,468
25/05/2012 07:55:00	3,938,608	5,640	25/05/2012 11:40:00	3,969,095	9,432
25/05/2012 08:00:00	3,939,091	5,796	25/05/2012 11:45:00	3,969,884	9,468
25/05/2012 08:05:00	3,939,587	5,952	25/05/2012 11:50:00	3,970,674	9,480
25/05/2012 08:10:00	3,940,096	6,108	25/05/2012 11:55:00	3,971,465	9,492
25/05/2012 08:15:00	3,940,618	6,264	25/05/2012 12:00:00	3,972,260	9,540
25/05/2012 08:20:00	3,941,153	6,420	25/05/2012 12:05:00	3,973,053	9,516
25/05/2012 08:25:00	3,941,703	6,600	25/05/2012 12:10:00	3,973,843	9,480
25/05/2012 08:30:00	3,942,261	6,696	25/05/2012 12:15:00	3,974,637	9,528

	Total kWh	kW	Date and time	Total kWh	kW
25/05/2012 12:20:00	3,975,435	9,576	25/05/2012 16:05:00	4,005,254	5,424
25/05/2012 12:25:00	3,976,225	9,480	25/05/2012 16:10:00	4,005,694	5,280
25/05/2012 12:30:00	3,977,018	9,516	25/05/2012 16:15:00	4,006,120	5,112
25/05/2012 12:35:00	3,977,799	9,372	25/05/2012 16:20:00	4,006,532	4,944
25/05/2012 12:40:00	3,978,578	9,348	25/05/2012 16:25:00	4,006,932	4,800
25/05/2012 12:45:00	3,979,353	9,300	25/05/2012 16:30:00	4,007,317	4,620
25/05/2012 12:50:00	3,980,131	9,336	25/05/2012 16:35:00	4,007,687	4,440
25/05/2012 12:55:00	3,980,907	9,312	25/05/2012 16:40:00	4,008,043	4,272
25/05/2012 13:00:00	3,981,678	9,252	25/05/2012 16:45:00	4,008,382	4,068
25/05/2012 13:05:00	3,982,444	9,192	25/05/2012 16:50:00	4,008,708	3,912
25/05/2012 13:10:00	3,983,203	9,108	25/05/2012 16:55:00	4,009,020	3,744
25/05/2012 13:15:00	3,983,959	9,072	25/05/2012 17:00:00	4,009,314	3,528
25/05/2012 13:20:00	3,984,707	8,976	25/05/2012 17:05:00	4,009,594	3,360
25/05/2012 13:25:00	3,985,453	8,952	25/05/2012 17:10:00	4,009,858	3,168
25/05/2012 13:30:00	3,986,191	8,856	25/05/2012 17:15:00	4,010,109	3,012
25/05/2012 13:35:00	3,986,925	8,808	25/05/2012 17:20:00	4,010,345	2,832
25/05/2012 13:40:00	3,987,660	8,820	25/05/2012 17:25:00	4,010,566	2,652
25/05/2012 13:45:00	3,988,384	8,688	25/05/2012 17:30:00	4,010,772	2,472
25/05/2012 13:50:00	3,989,104	8,640	25/05/2012 17:35:00	4,010,963	2,292
25/05/2012 13:55:00	3,989,819	8,580	25/05/2012 17:40:00	4,011,138	2,100
25/05/2012 14:00:00	3,990,529	8,520	25/05/2012 17:45:00	4,011,299	1,932
25/05/2012 14:05:00	3,991,231	8,424	25/05/2012 17:50:00	4,011,445	1,752
25/05/2012 14:10:00	3,991,929	8,376	25/05/2012 17:55:00	4,011,578	1,596
25/05/2012 14:15:00	3,992,618	8,268	25/05/2012 18:00:00	4,011,695	1,404
25/05/2012 14:20:00	3,993,295	8,124	25/05/2012 18:05:00	4,011,801	1,272
25/05/2012 14:25:00	3,993,963	8,016	25/05/2012 18:10:00	4,011,893	1,104
25/05/2012 14:30:00	3,994,626	7,956	25/05/2012 18:15:00	4,011,973	0,960
25/05/2012 14:35:00	3,995,279	7,836	25/05/2012 18:20:00	4,012,043	0,840
25/05/2012 14:40:00	3,995,921	7,704	25/05/2012 18:25:00	4,012,104	0,732
25/05/2012 14:45:00	3,996,557	7,632	25/05/2012 18:30:00	4,012,157	0,636
25/05/2012 14:50:00	3,997,187	7,560	25/05/2012 18:35:00	4,012,202	0,540
25/05/2012 14:55:00	3,997,806	7,428	25/05/2012 18:40:00	4,012,241	0,468
25/05/2012 15:00:00	3,998,413	7,284	25/05/2012 18:45:00	4,012,276	0,420
25/05/2012 15:05:00	3,999,008	7,140	25/05/2012 18:50:00	4,012,307	0,372
25/05/2012 15:10:00	3,999,594	7,032	25/05/2012 18:55:00	4,012,336	0,348
25/05/2012 15:15:00	4,000,167	6,876	25/05/2012 19:00:00	4,012,361	0,300
25/05/2012 15:20:00	4,000,729	6,744	25/05/2012 19:05:00	4,012,386	0,300
25/05/2012 15:25:00	4,001,281	6,624	25/05/2012 19:10:00	4,012,410	0,288
25/05/2012 15:30:00	4,001,821	6,480	25/05/2012 19:15:00	4,012,433	0,276
25/05/2012 15:35:00	4,002,348	6,324	25/05/2012 19:20:00	4,012,455	0,264
25/05/2012 15:40:00	4,002,863	6,180	25/05/2012 19:25:00	4,012,475	0,240
25/05/2012 15:45:00	4,003,368	6,060	25/05/2012 19:30:00	4,012,495	0,240
25/05/2012 15:50:00	4,003,859	5,892	25/05/2012 19:35:00	4,012,513	0,216
25/05/2012 15:55:00	4,004,337	5,736	25/05/2012 19:40:00	4,012,530	0,204
25/05/2012 16:00:00	4,004,802	5,580	25/05/2012 19:45:00	4,012,546	0,192
Date and time	Total kWh	kW			
25/05/2012 19:50:00	4,012,559	0,156			
25/05/2012 19:55:00	4,012,572	0,156			
25/05/2012 20:00:00	4,012,582	0,120			
25/05/2012 20:05:00	4,012,592	0,120			
25/05/2012 20:10:00	4,012,599	0,084			
25/05/2012 20:15:00	4,012,605	0,072			
25/05/2012 20:20:00	4,012,610	0,060			
25/05/2012 20:25:00	4,012,616	0,072			
25/05/2012 20:30:00	4,012,618	0,024			
25/05/2012 20:35:00	4,012,618	0,000			
25/05/2012 20:40:00	4,012,618	0,000			

Appendix 3. Solar angle and azimuth in Oud-Tornhout

Astronomical Applications Dept.
U.S. Naval Observatory
Washington, DC 20392-5420

OUD-TURNHOUT

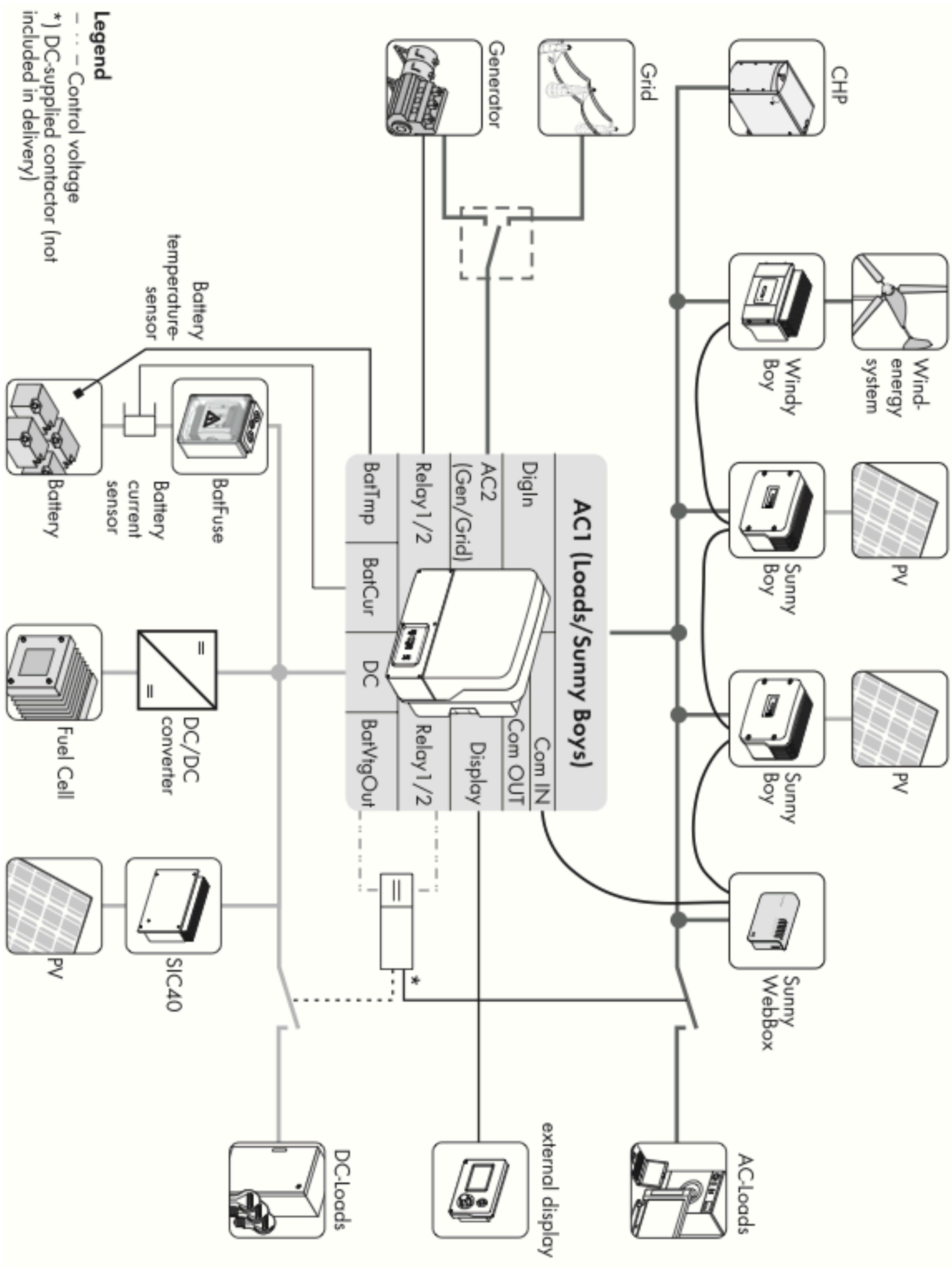
E 5° 00', N51° 17'

Altitude and Azimuth of the Sun
May 25, 2012
Zone: 1h East of Greenwich

h m	Altitude °	Azimuth (E of N) °	h m	Altitude °	Azimuth (E of N) °	h m	Altitude °	Azimuth (E of N) °
02:55	-11.6	32.7	05:45	8.6	66.9	08:35	34.6	99.4
03:00	-11.2	33.8	05:50	9.4	67.8	08:40	35.4	100.4
03:05	-10.8	34.9	05:55	10.1	68.8	08:45	36.1	101.5
03:10	-10.3	36.0	06:00	10.8	69.7	08:50	36.9	102.6
03:15	-9.8	37.1	06:05	11.5	70.6	08:55	37.7	103.7
03:20	-9.4	38.2	06:10	12.3	71.5	09:00	38.4	104.9
03:25	-8.9	39.2	06:15	13.0	72.4	09:05	39.2	106.0
03:30	-8.4	40.3	06:20	13.8	73.4	09:10	39.9	107.2
03:35	-7.9	41.4	06:25	14.5	74.3	09:15	40.7	108.3
03:40	-7.3	42.4	06:30	15.3	75.2	09:20	41.4	109.5
03:45	-6.8	43.5	06:35	16.0	76.1	09:25	42.2	110.7
03:50	-6.3	44.5	06:40	16.8	77.0	09:30	42.9	112.0
03:55	-5.7	45.5	06:45	17.5	78.0	09:35	43.6	113.2
04:00	-5.1	46.6	06:50	18.3	78.9	09:40	44.3	114.5
04:05	-4.6	47.6	06:55	19.1	79.8	09:45	45.0	115.8
04:10	-4.0	48.6	07:00	19.8	80.7	09:50	45.7	117.2
04:15	-3.4	49.6	07:05	20.6	81.7	09:55	46.4	118.5
04:20	-2.8	50.6	07:10	21.4	82.6	10:00	47.1	119.9
04:25	-2.2	51.6	07:15	22.2	83.5	10:05	47.8	121.3
04:30	-1.6	52.6	07:20	22.9	84.5	10:10	48.4	122.7
04:35	-0.9	53.6	07:25	23.7	85.4	10:15	49.1	124.2
04:40	0.2	54.6	07:30	24.5	86.4	10:20	49.7	125.7
04:45	0.8	55.5	07:35	25.3	87.3	10:25	50.4	127.2
04:50	1.3	56.5	07:40	26.0	88.3	10:30	51.0	128.8
04:55	1.9	57.5	07:45	26.8	89.3	10:35	51.6	130.4
05:00	2.6	58.4	07:50	27.6	90.2	10:40	52.2	132.0
05:05	3.2	59.4	07:55	28.4	91.2	10:45	52.7	133.7
05:10	3.8	60.3	08:00	29.2	92.2	10:50	53.3	135.4
05:15	4.5	61.3	08:05	30.0	93.2	10:55	53.8	137.1
05:20	5.2	62.2	08:10	30.7	94.2	11:00	54.4	138.9
05:25	5.9	63.2	08:15	31.5	95.2	11:05	54.9	140.7
05:30	6.5	64.1	08:20	32.3	96.2	11:10	55.4	142.6
05:35	7.2	65.0	08:25	33.1	97.3	11:15	55.8	144.5
05:40	7.9	66.0	08:30	33.8	98.3	11:20	56.3	146.4

11:25	56.7	148.4	15:35	44.2	245.8	19:45	6.5	296.2
11:30	57.1	150.4	15:40	43.5	247.1	19:50	5.8	297.1
11:35	57.5	152.4	15:45	42.8	248.3	19:55	5.1	298.0
11:40	57.8	154.5	15:50	42.0	249.5	20:00	4.4	299.0
11:45	58.1	156.6	15:55	41.3	250.8	20:05	3.8	299.9
11:50	58.4	158.7	16:00	40.6	252.0	20:10	3.1	300.9
11:55	58.7	160.9	16:05	39.8	253.1	20:15	2.5	301.8
12:00	58.9	163.1	16:10	39.1	254.3	20:20	1.9	302.8
12:05	59.2	165.3	16:15	38.3	255.4	20:25	1.3	303.8
12:10	59.3	167.6	16:20	37.6	256.5	20:30	0.7	304.7
12:15	59.5	169.9	16:25	36.8	257.7	20:35	0.2	305.7
12:20	59.6	172.2	16:30	36.0	258.7	20:40	-1.0	306.7
12:25	59.7	174.5	16:35	35.3	259.8	20:45	-1.6	307.7
12:30	59.8	176.8	16:40	34.5	260.9	20:50	-2.2	308.7
12:35	59.8	179.1	16:45	33.7	261.9	20:55	-2.8	309.7
12:40	59.8	181.4	16:50	32.9	263.0	21:00	-3.4	310.7
12:45	59.8	183.7	16:55	32.2	264.0	21:05	-4.0	311.7
12:50	59.7	186.0	17:00	31.4	265.0	21:10	-4.6	312.7
12:55	59.6	188.3	17:05	30.6	266.1	21:15	-5.2	313.7
13:00	59.5	190.6	17:10	29.8	267.1	21:20	-5.7	314.8
13:05	59.3	192.9	17:15	29.1	268.1	21:25	-6.3	315.8
13:10	59.1	195.1	17:20	28.3	269.0	21:30	-6.8	316.8
13:15	58.9	197.4	17:25	27.5	270.0	21:35	-7.3	317.9
13:20	58.7	199.6	17:30	26.7	271.0	21:40	-7.9	318.9
13:25	58.4	201.7	17:35	25.9	272.0	21:45	-8.4	320.0
13:30	58.1	203.9	17:40	25.2	272.9	21:50	-8.9	321.1
13:35	57.7	206.0	17:45	24.4	273.9	21:55	-9.3	322.1
13:40	57.4	208.0	17:50	23.6	274.8	22:00	-9.8	323.2
13:45	57.0	210.1	17:55	22.8	275.8	22:05	-10.3	324.3
13:50	56.6	212.1	18:00	22.0	276.7	22:10	-10.7	325.4
13:55	56.2	214.0	18:05	21.3	277.6	22:15	-11.2	326.5
14:00	55.7	216.0	18:10	20.5	278.6	22:20	-11.6	327.6
14:05	55.3	217.8	18:15	19.7	279.5			
14:10	54.8	219.7	18:20	19.0	280.4			
14:15	54.3	221.5	18:25	18.2	281.4			
14:20	53.7	223.3	18:30	17.4	282.3			
14:25	53.2	225.0	18:35	16.7	283.2			
14:30	52.6	226.7	18:40	15.9	284.1			
14:35	52.1	228.4	18:45	15.2	285.1			
14:40	51.5	230.0	18:50	14.4	286.0			
14:45	50.9	231.6	18:55	13.7	286.9			
14:50	50.3	233.1	19:00	12.9	287.8			
14:55	49.6	234.7	19:05	12.2	288.7			
15:00	49.0	236.1	19:10	11.5	289.7			
15:05	48.3	237.6	19:15	10.7	290.6			
15:10	47.7	239.0	19:20	10.0	291.5			
15:15	47.0	240.4	19:25	9.3	292.4			
15:20	46.3	241.8	19:30	8.6	293.4			
15:25	45.6	243.2	19:35	7.9	294.3			
15:30	44.9	244.5	19:40	7.2	295.2			

Appendix 4. Schematics of the Sunny Island connections (Sunny Island manual. 2012.)



Appendix 5. Application form for SMA Grid Guard Code (SMA website. 2013. https://www.sma.de/en/service/downloads.html)

APPLICATION FOR
SMA GRID GUARD-CODE

The SMA Grid Guard-Code is your personal access code for changing parameters of the automatic disconnection unit typer SMA Grid Guard®.

Additional information concerning this application

Sunny Boy, Sunny Mini Central, Sunny Tripower and Windy Boy inverters from SMA Solar Technology AG are equipped with the automatic disconnection device SMA Grid Guard®. This disconnection device continuously monitors the low voltage grid into which electricity is fed and automatically stops feeding if an interruption or separation from the grid is detected. The monitoring criteria can be modified according to the applicable regulations of different countries and can therefore be used all over the globe.
SMA Grid Guard® ensures that the low voltage grid can be disconnected by the utility operator any time and thus allows e.g. maintenance and repair work. Any manipulation of this facility can cause malfunctions and therefore directly endanger the life of people, in the case electricity is fed to grid that was disconnected by the utility operator. Therefore changes of the monitoring criteria are exclusively reserved for trained qualified staff.

Parameter changes to SMA Grid Guard®

In certain cases it can be necessary to modify the monitoring criteria preset ex-works in order to comply with the local grid conditions. Trained qualified staff can do this with a personal access code.
The modification of a threshold value is logged in the device by recording the access code that was entered. In case the marking VDE0126 (4.99), VDE0126-1-1 or DK 5940 is included on the type label, this marking must be removed permanently. Furthermore, the changes should be documented and passed on to the system operator so the system documentation can be supplemented.

Declaration of the applicant

I hereby apply for a personal access code for the permanent modification of the threshold values of the grid monitoring. I am aware of the importance of this as described here and am aware of the function of the automatic disconnection device SMA Grid Guard® and assure that

- I will use the access code confidentially,
- will only modify threshold values after consulting the utility operator and
- that any modification of the threshold values will be clearly documented on the type label as well as on any other documentation related to the system.

APPLICATION FOR
SMA GRID GUARD-CODE

Please fill in the form legibly (preferably digital, otherwise hand-written and in block capitals). Please note that your signature must be entered hand-written. Afterwards print out the form and return it duly signed. You may also send the form by fax or e-mail. Please enter "Grid Guard" into the reference line.

Last name/First name*

Company

Street and No.*

ZIP code and city*

Country*

E-mail*

Telephone* Fax

Place, date* Signature*

*Mandatory field which must be filled out.

Service Line
Tel. +49 561 9522-1499
Fax +49 561 9522-4699
E-mail: Inst-Code@SMA.de

GRIDGUARD-ZEN124411