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TREBALL DE FI DE GRAU

DEGREE FINAL PROJECT

MONITORING SYSTEM FOR A SOLAR POWER PLANT

Estudis/Degree Programme: Engineering of Electronic Systems

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Collaborations

LUT Energy, Electrical department.

Lappeenranta University of Technology (LUT).

Appreciation

Specially thankful to Antti Kosonen for the rigorous following and interest with that project.

Resum del Treball

L'ús de les energies renovables a Finlàndia va arribar a subministrar fins a un 46% del consum elèctric el 2012, però l'energia solar té un paper ínfim en aquest destacable percentatge. El 2013, la Universitat Tecnològica de Lappeenranta (LUT), va començar la construcció de la primera etapa d'una central fotovoltaica que arribarà a subministrar una potència nominal de 220 kWp un cop acabada. L'objectiu principal per aquest projecte és dissenyar un software de monitorització per aquesta central basat en LabVIEW®. Aquest software recopila dades de diferents sensors i aparells connectats a una VLAN (Virtual Local Area Network), crea figures per mostrar l'eficiència de la central i desa informació per un ús futur. A més a més, es guarden certs valors en una base de dades que conté informació de la xarxa intel·ligent (smart grid) del projecte "green campus" de la LUT.

En aquesta memòria es fa un petit estudi climatològic de la zona de Lappeenranta, així com un repàs de l'estructura de la central fotovoltaica i de tots els sensors i aparells connectats a la xarxa de comunicació. També es descriuen totes les característiques del software així com les seves utilitats i funcionament. Pel desenvolupament d'aquest software, s'han fet tests al laboratori i, finalment, el seu funcionament ha sigut verificat sobre l'ambient real.

Resumen del Proyecto

El uso de las energías renovables en Finlandia llegó a suministrar hasta un 46% del consumo eléctrico el 2012, pero la energía solar tiene un papel ínfimo en este destacable porcentaje. El 2013, la Universidad Tecnológica de Lappeenranta (LUT), empezó la construcción de la primera etapa de una central fotovoltaica que llegará a suministrar una potencia nominal de 220 kWp una vez terminada. El objetivo principal para este proyecto es diseñar un software de monitorización para esta central fotovoltaica basado en LabVIEW®. Este software recopila datos de diferentes sensores y aparatos conectados a una VLAN (Virtual Local Area Network) crea figuras para mostrar la eficiencia de la central y guarda información para un uso futuro. Además, ciertos valores son guardados en una base de datos que contiene información de la red inteligente (smart grid) del proyecto "green campus" de la LUT.

En esta memoria se hace un pequeño estudio climatológico de la zona de Lappeenranta, así como un repaso de la estructura de la central fotovoltaica y de todos los sensores y aparatos que se utilizan en la red de comunicación. También se describen todas las características de este software así como sus utilidades y funcionamiento. Para el desarrollo de este software, se han hecho test en el laboratorio y, finalmente, su funcionamiento se ha verificado en el ambiente real.

Abstract

The use of the renewable energies in Finland supplied 46% of the electrical needs of the country on 2012, but solar energy has a negligible role in this notable percentage. On 2013, Lappeenranta University of Technology (LUT), started the construction of the first stage of a photovoltaic solar power plant that will provide a rated power of 220 kWp once finished. The main goal for this thesis is to design monitoring software for this solar power plant based on LabVIEW®. This software collects data from different sensors and devices connected to a VLAN (Virtual Local Area Network), plots figures for showing the efficiency of the solar power plant, and stores information for future use. Moreover, certain values are also stored to a database that contains information of the whole LUT's smart grid.

In this report a brief study of the weather at Lappeenranta is made, as well as an overview of the structure of the solar power plant and all the sensors and devices used in the communication network. Also, all the characteristics, utilities and operation for this software are described. For the development, different tests are carried out at the laboratory and, finally, the operation of the software is verified in a real environment.

Abbreviations and symbols

Roman letters

E_{I}	Energy imported (absolute value)
E_{E}	Energy exported (absolute value)
E_{rI}	Energy imported (relative value)
E_{rE}	Energy exported (absolute value)
E_{D}	Energy difference (absolute value)
E_{rD}	Energy difference (relative value)
E_{1h}	Energy produced in one hour
M_{s}	Money saved
M_{D}	Euro values difference
M_{AM}	Economic amortization
M_{E}	Energy cost
M_{I}	Investment
P	Power
$P_{\%}$	Percentage of power
P_{rtd}	Rated power
$P_{\mathrm{avg,1min}}$	Averaged power value over one minute
$P_{\mathrm{avg,1h}}$	Averaged power value over one hour
$P_{\mathrm{avg,24h}}$	Averaged power value over 24 hours
p	Power sample
t	Time
T	Time period
V	Voltage

Acronyms

AC	Alternating current
DC	Direct current
VLAN	Virtual Local Area Network
I2I	Inverter to inverter

1 Introduction

In this introduction chapter, it is first exposed the context of the solar energy in Finland and LUT's work to promote this kind of technology in the energy production. Finally, all the objectives for this project are presented.

1.1 Context

Finland is the country in the 3rd position in percentage of renewable energy production of the European Union with a 46% on 2012 (OSF, 2013). This high ratio is reached by means of use a lot of different resources, such as black liquor and other concentrated liquors, wood combustion, wind power, hydroelectric, etc. Table 1.1 shows the share of the renewable energy in 2011.

Table 1.1, Share of renewable energy in 2011 (OSF, 2013).

Energy Source	**2011 (PJ[1])**	**%**
Black liquor and other concentrated liquors	135.110	34.270
Wood fuels of industry and energy production	121.810	30.897
Small combustion of wood (e.g. homes and saunas)	59.370	15.059
Hydro power	44.200	11.211
Ambient-source heat pumps	12.460	3.160
Bioliquids in traffic and space heating	9.800	2.486
Solid recovered fuels (organic fraction)	5.840	1.481
Biogas	2.230	0.566
Wind power	1.740	0.441
Other biofuels	1.630	0.413
Solar energy	0.060	0.015
Totals	394.25	100.00

Observing a little closer, it is possible to notice that the solar energy is the last of those renewable resources used in Finland, the reason of that is something easy to understand: Finland's weather conditions are strictly characterized for its cold temperatures and low average sun irradiation.

[1] PJ, Energy unit. 1 PJ = 10^{15} Joules = 277.78 GWh

The second fact makes it a place where at first it seems not the best idea making any investment for solar energy. Figure 1.1 shows the yearly sum of global irradiation at Finland for optimally inclined surfaces.

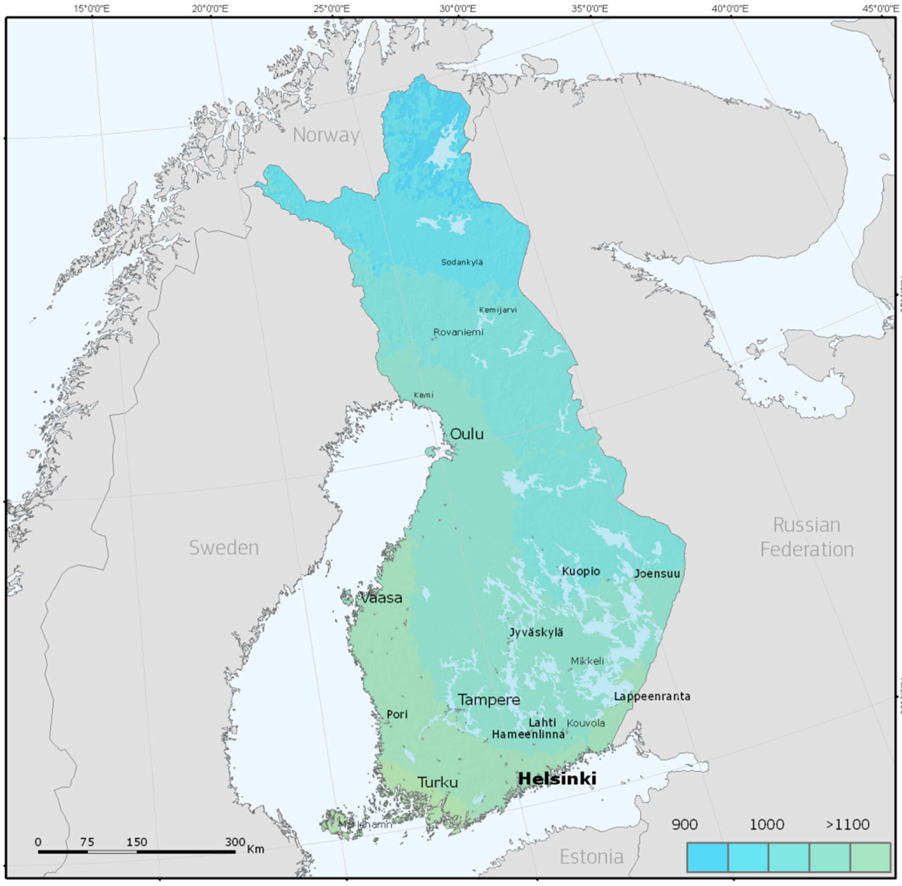

Figure 1.1, Yearly sum of global irradiation [kWh/m^2] at Finland for optimally inclined surfaces (Šúri M., 2012).

Figure 1.2 to Figure **1.4** show the monthly average of the weather conditions that affect the most at the solar power production in Barcelona (Spain), Frankfurt (Germany), and Lappeenranta averaged over the last 22 years. In this way, it is possible to compare the local values with the ones measured at some other European countries where solar power energy is already an extended source. At Lappeenranta, the production of solar energy is possible from March to the end of October because during the cold season, the few hours of sunlight and the fact that the solar panels are covered by snow that disables their operation in practice. On the other hand, in summer, the longer days compensate the bad winter conditions facilitating high production values. So although the solar distribution is different, in average, the conditions for solar energy production in Lappeenranta are quite similar to the ones in Frankfurt.

It is important to take into account that the efficiency of solar panels is temperature dependent. The maximum power value given by a solar panel can drop −0.5% per Celsius degree. This parameter favors a better efficiency for the solar panels in Finland than in some other warmer locations and may compensate a little bit the lack of solar radiation.

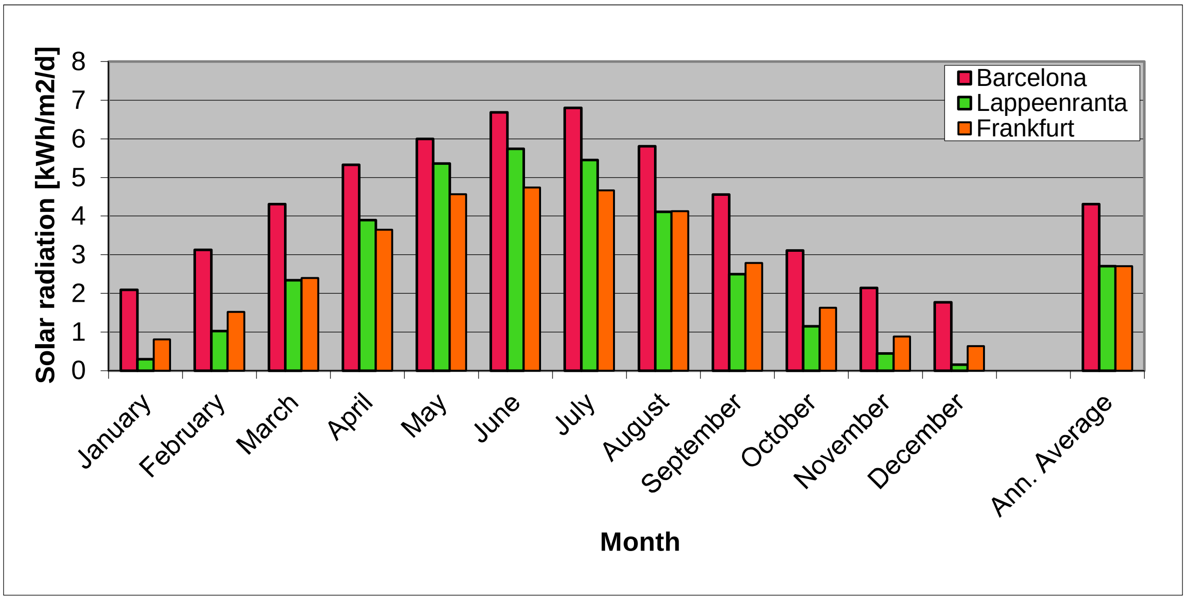

Figure 1.2, Monthly average daily solar irradiation comparison for horizontal planes between Barcelona, Lappeenranta, and Frankfurt (NASA, 2013).

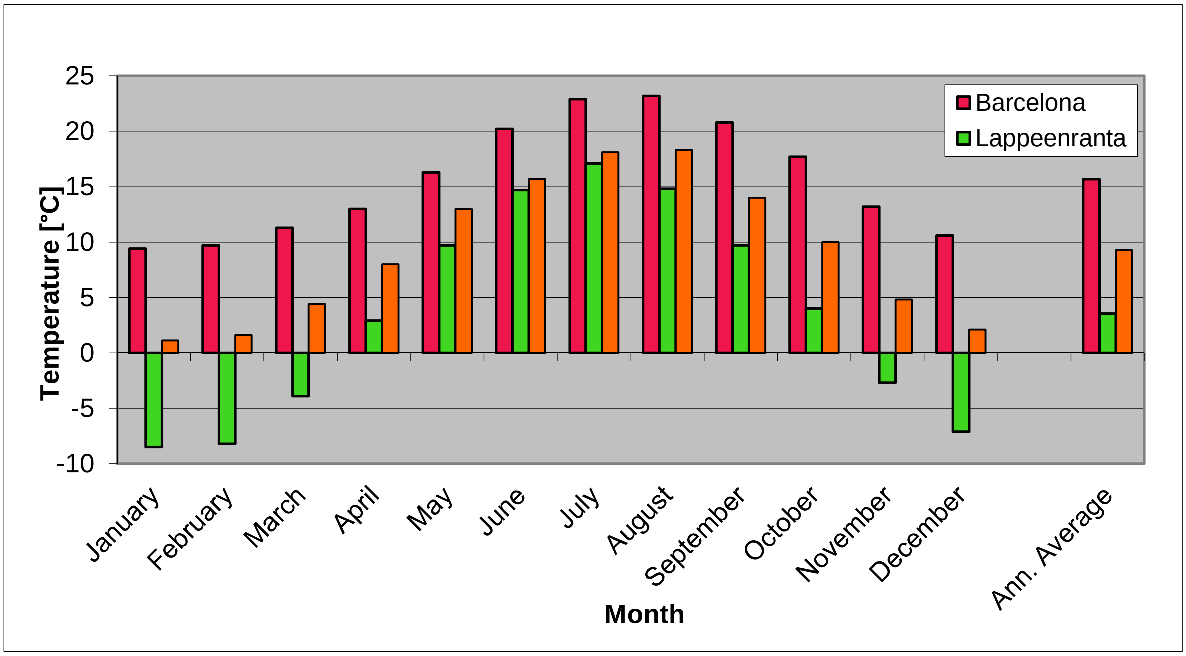

Figure 1.3, Monthly average temperature comparison between Barcelona, Lappeenranta, and Frankfurt (NASA, 2013).

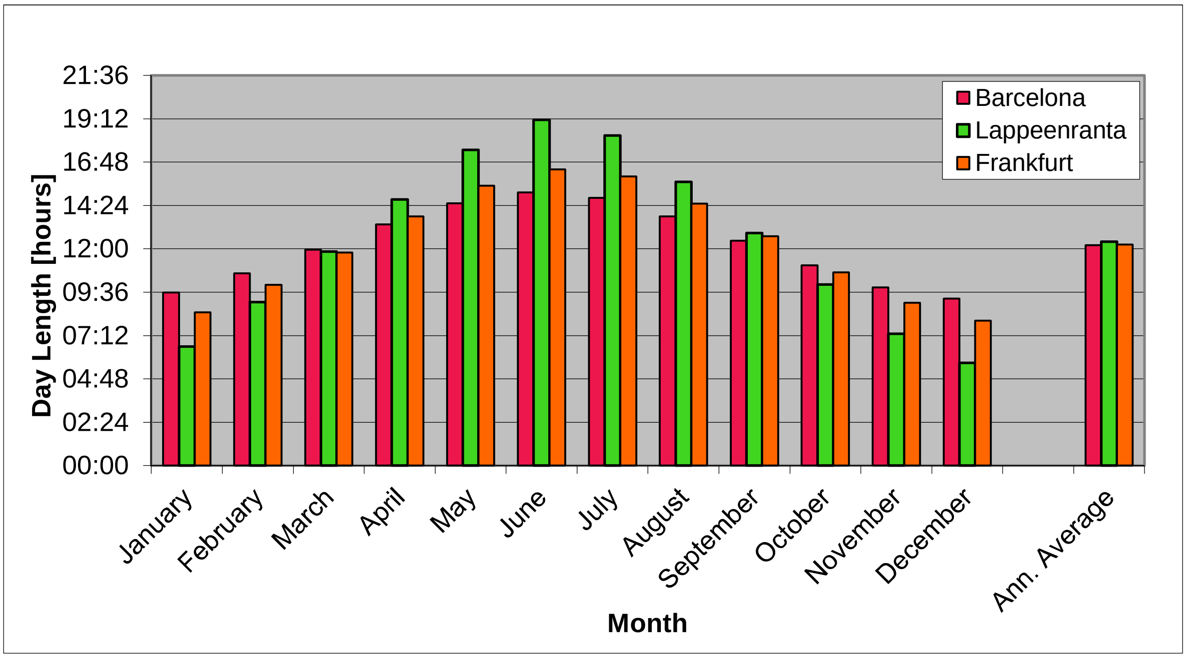

Figure 1.4, Monthly average day length at 2013 comparison between Barcelona, Lappeenranta, and Frankfurt (AS, 2010).

Since 2011, LUT is conducting the green campus (LUT, 2013): a project which goal is to save energy and natural resources, to promote the smart grid concept and renewable energy production as well as its research and technological improvement. The basic idea is that once those innovations are used in the campus, they are being set as a trend and as an example for the future urban planning.

The facilities of the green campus already contain a 20 kWp wind turbine and 5.5 kWp solar panels with a sun tracking system as green energy sources connected through a smart grid system (which handles power paths and data communication links between sources and loads) to the different charging stations for electric vehicles (bikes, cars). Car's batteries also can be used as an energy storage system since they are charged when the production exceeds consumption. That energy can be used in case that the energy requirements of the grid are higher than the production from the green sources. The information and communication technologies systems embedded with the smart grid are used to monitorize the production and consumption of the different devices connected in the smart grid for managing in the most efficient way the use of the available energy.

On 2013, LUT wanted to drive the green campus a step further with the construction of a huge (in Finland scale) solar power plant of 220 kWp at the college's facilities. Its main utilities will be to supply LUT's requirements of energy, research purposes about solar energy at the university and demonstrating the efficiency of the solar energy in Finland (Nordic conditions).

1.2 Objective

My objectives for this project are basically developing the software for the monitorization of the solar power plant using NI LabVIEW®. This software reads data from the solar inverters installed for the solar power plant and from the power measurement devices (Siemens® SENTRON PAC3200) in order to study the efficiency and functionality of the solar power plant. This data must be presented, stored in daily text files for posterior calculation purposes and used for updating the green campus' MySQL database. This last action will provide easy access to the data gotten from every single computer of the university network, which is interesting for enabling the possibility to upload information about the solar power plant on LUT's web site in real time.

A communication network between the measurement devices (which may be several meters away) and the monitoring computer is required. In this case, different protocols are used such as LAN (Local Area Network) (Ethernet), RS-485 and an optical fiber link. This communication system will be used also for the smart grid functionality (because it is necessary to know how much energy is available for optimizing the consumption).

An unexpected thing was the possibility of working on the construction of the solar power plant itself (i.e. helping to mount solar panels, setting the electrical connections, structure, etc.), so finally it became an other objective to learn how to do all that tasks and by the way trying to finish all the work outside as soon as possible before the arrival of winter, when the climatic conditions can make the work there an authentic challenge.

1.3 Report structure

This thesis is divided into two main parts. The first part talks about the structure of the solar power plant, describing all the panels that are handled by inverters, structure of strings and configuration (serial, parallel connections), communication system, etc. The second part talks about how the measurements carried out using each device and how the data is managed (for the database, for the presentation, etc.). Finally conclusions of the work done are given and some pictures of the project are attached.

2 Structure of the solar power plant

The first stage of the solar power plant consisted of the installation of 638 solar panels (both mono-crystalline and poly-crystalline types) with a rated power of 250 W each. The Chinese company Tianwei New Energy (Yangzhou) Co., Ltd and Cencorp Oyj –a local company from Finland– are the manufacturers of the photovoltaic modules. Those panels are installed on two different zones of the campus: the flat roof of building number 3 and two carports next to building 7. At the end of that stage, the solar power plant is able to generate a peak power of about 160 kWp. Table 2.1 describes the main characteristics of the different panels used for the solar power plant.

Table 2.1, Main characteristics of the solar panels used.

Characteristics	**Tianwei**		**Cencorp**
	TWY250M660 (Mono-crystalline)	**TW250P60-FA (Poly-crystalline)**	**Poly-crystalline**
Pmax [Wp]	250	250	250
Efficiency [%]	15.3	15.37	17
Voc [V]	38.1	37.8	38.6
Isc [A]	8.8	8.65	8.8
Area [m^2]	1.63	1.63	1.59

The solar panels are grouped in strings of 17 or 18 panels (serial connection) and there are two strings parallel connected per inverter[2]. Inverters used for this project are ABB PVS300-TL-8000W-2, which can handle up to 8.9 kW of input DC power and a maximum of 4 strings in parallel, so the configuration chosen fulfils their requirements.

2.1 Flat roof

On the flat roof, 206 solar panels have been installed (136 poly-crystalline and 70 mono-crystalline). The type of the solar panel has been chosen regarding on the situation on the roof, since poly-crystalline technology behaves better in working conditions affected by shadows than mono-crystalline technology.

[2] Solar inverter: device used in order to transform the DC power supply from the solar panels into a suitable format for domestic/industrial consumption (230/400V AC power signal).

Six solar inverters are mounted on the wall in the roof. Each one with the following configuration described on Table 2.2:

Table 2.2, Configuration for the inverters of the flat roof.

Inverter	Strings x Panels	Type	Rated Power [kWp]
1	2x17	Poly-crystalline	8.5
2			
3			
4		Mono-crystalline	
5	2x18		9
6	2x17	Poly-crystalline	8.5
Total	12 Strings, 206 panels	-	51.5

It is unavoidable noticing that inverter number 5 exceeds by 100 W its rated power; however it is not critic since it is very difficult in Finland to receive enough solar radiation to produce the peak power. Moreover, the solar inverters are protected against over voltages and over currents scenarios. Finally, summing the rated power of every inverter, we obtain the rated power of the whole flat roof: 51.5 kWp.

Figure 2.1 to Figure **2.3** show how all the panels are distributed on the flat roof and the inverters that handle them.

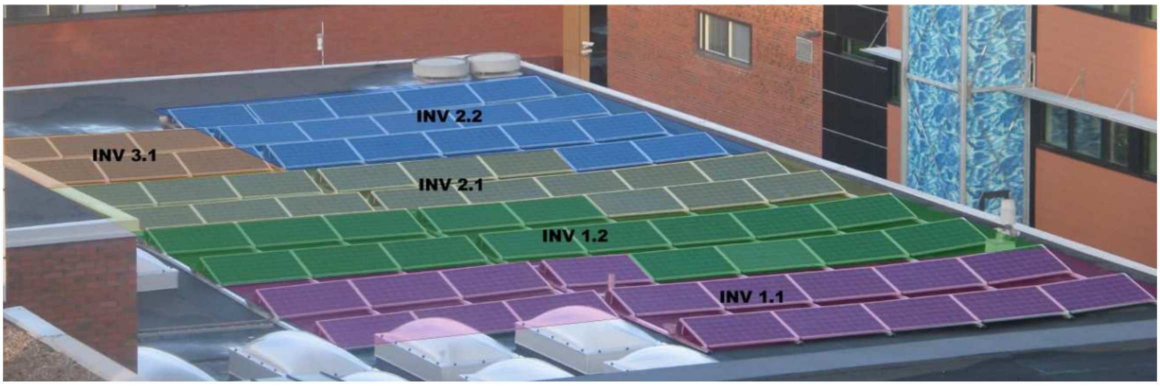

Figure 2.1, Distribution of the solar panels for the flat roof (I).

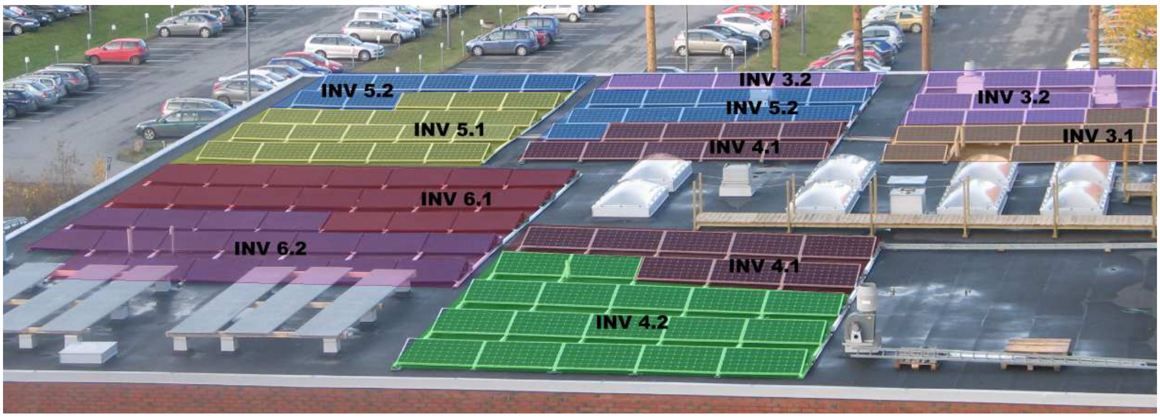

Figure 2.2, Distribution of the solar panels for the flat roof (II).

Figure 2.3, Inverters mounted on the flat roof zone.

2.2 Carports

On the carports, a total amount of 432 solar panels have been installed (396 poly-crystalline and 36 mono-crystalline from Tianwei), these last ones were used due to the lack of poly-crystalline solar panels at the moment they were needed (otherwise carport’s construction would have been delayed).

Both carports are holding 216 solar panels organized in 12 strings series connected of 18 panels each. Every solar inverter manages 2 strings of solar panels, so every carport has 6 inverters. The 12 inverters installed among both carports use the configuration detailed at Table 2.3.

Table 2.3, Configuration for the inverters of the carport 1 (CP1) and carport 2 (CP2).

<table>
<tr><th>Inverter</th><th colspan="2">Strings x Panels</th><th colspan="2">Type</th><th colspan="2">Rated Power [kWp]</th></tr>
<tr><th>-</th><th>CP1</th><th>CP2</th><th>CP1</th><th>CP2</th><th>CP1</th><th>CP2</th></tr>
<tr><td>1</td><td colspan="2" rowspan="6">2x18</td><td rowspan="6">Poly-crystalline</td><td rowspan="4">Poly-crystalline</td><td colspan="2" rowspan="6">9</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td></tr>
<tr><td>5</td><td>Mono-crystalline</td></tr>
<tr><td>6</td><td>Poly-crystalline</td></tr>
<tr><td>Total</td><td colspan="2">12 Strings, 216 panels</td><td colspan="2">-</td><td colspan="2">54</td></tr>
</table>

Figure 2.4 shows how all the panels are distributed on the carport and the inverters that handle them.

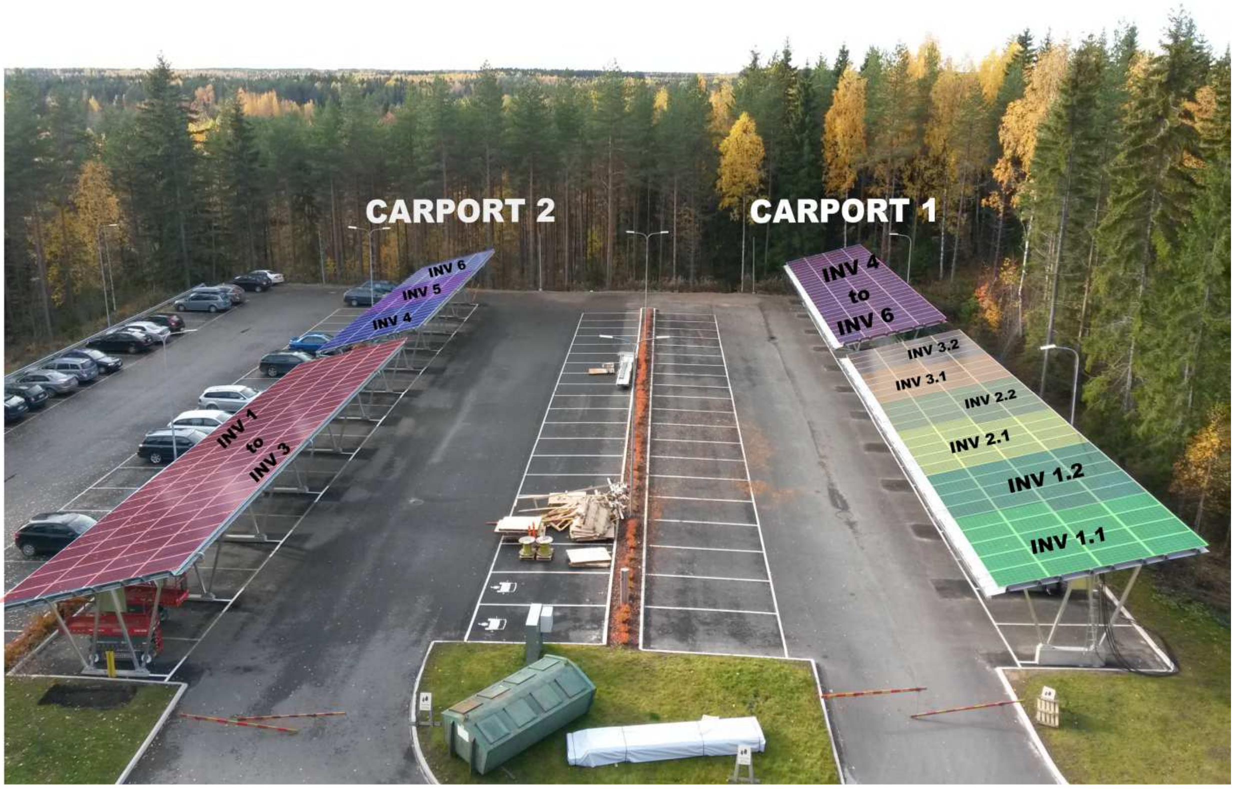

Figure 2.4, Distribution of the solar panels for the carport.

2.3 General structure

Figure 2.6 shows all the power lines that connect the solar power plant and the references for the wires. The red lines are the connections from the solar panels to the inverters and they drive DC current. As explained before, there are four cables going to each inverter corresponding to the plus and minus terminal of the two series connected strings that every inverter handles. The purple connections represent the I2I (Inverter to Inverter) links used for communication purposes between them; they allow to group three inverters for creating a three-phase power line. All the outputs from the inverters (MCMK 2x16 mm^2 + 16 mm^2) are painted in green and drive AC current and their three wires correspond to the phase, the neutral and a protective earth, respectively.

To describe the connections after the inverters, a name to each output is set: the outputs of the six inverters of the flat roof are named F1A, F1B, F1C, F2A, F2B and F2C, and the outputs of the 12 inverters of the carport are named C1A, C1B, C1C, C2A, C2B, C2C, C3A, C3B, C3C, C4A, C4B and C4C. The first letter corresponds to the zone of the inverter (F = Flat roof, C = Carport), the outputs with the same number correspond to the same three-phase line. Finally, the last letter is the phase reference (A, B or C). Figure 2.5 gives an example of the delay created between a string of three inverters connected by the I2I link for the lines C1A, C1B and C1C.

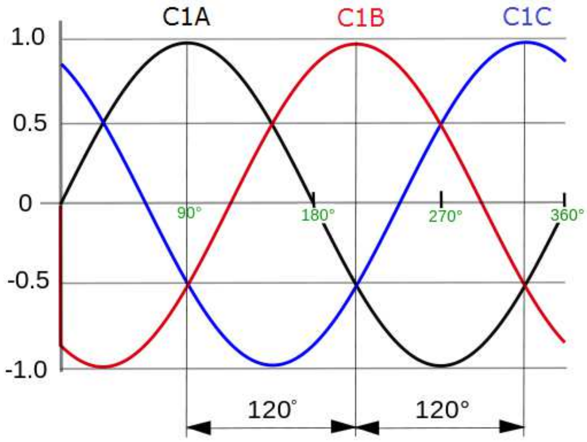

Figure 2.5, Example of the wave for the output C1.

The electric centrum's aim is to connect physically the phases for creating a unique output line for each zone. It also contains protection and measurement devices. For the flat roof, the neutral cables are connected all together and the phases are separated by their letter reference (i.e. F1A and F2A are connected together, also F1B and F2B and so on) as well as in the carport (see Table 2.4). The solar power plant is connected through aluminium cables (in blue, AMCMK 4x120 mm^2 + 41 mm^2) to LUT's electrical grid. The 120 mm^2 wires correspond to the three phases and the neutral cable and the 41 mm^2 wire is the protective earth.

Table 2.4, Connections in the electric centrums of the solar power plant. Every cell of "input lines connected" column contains all the lines that are physically connected at the same electrical point.

Electric centrum	**Input lines connected**
Flat roof	F1A, F2A
	F1B, F2B
	F1C, F2C
Carport	C1A, C2A, C3A, C4A
	C1B, C2B, C3B, C4B
	C1C, C2C, C3C, C4C

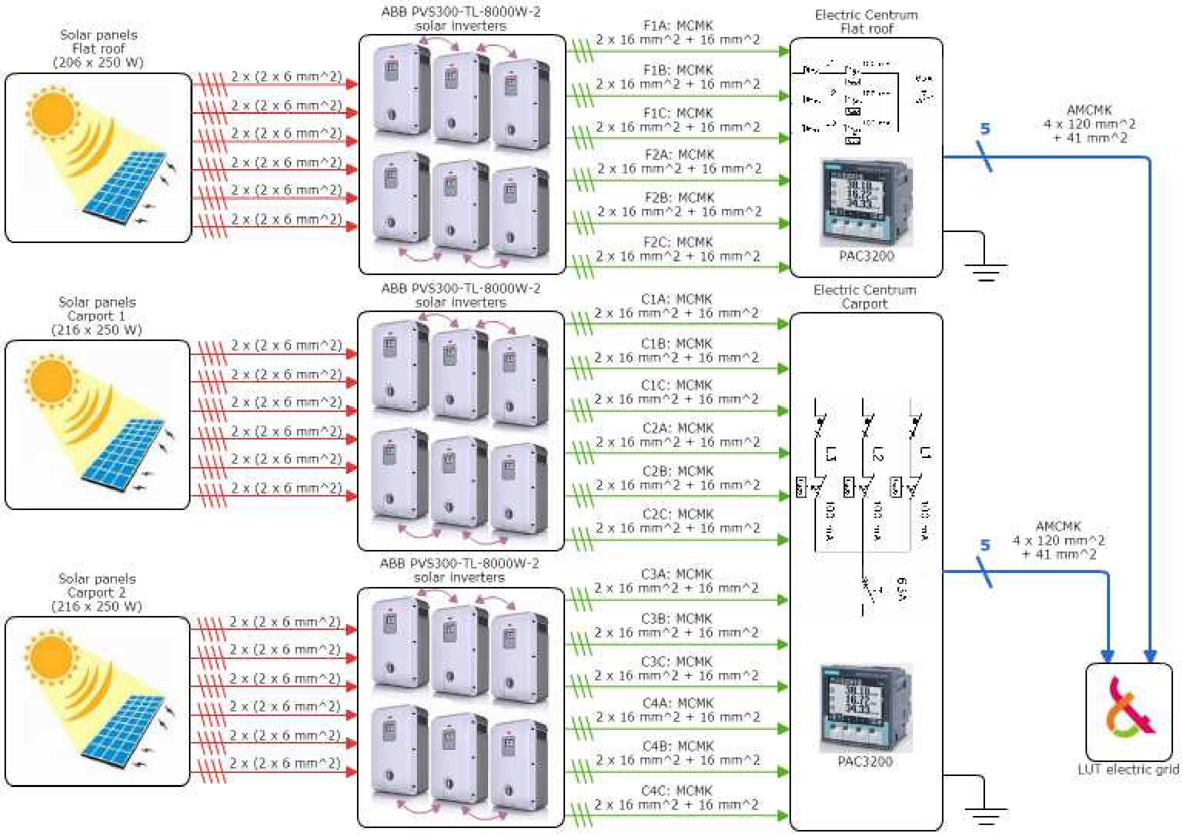

Figure 2.6, Power lines for the solar power plant.

Figure 2.7 shows the structure of the communication system for monitoring the solar power plant. This configuration uses LUT's metering Virtual Local Area Network (VLAN) to interconnect all the used resources with the monitoring computer.

The inverters send their measurements of power and energy through a communication accessory via series connection working on protocol RS-485 (black arrows). The yellow lines are referred to all the links set using Ethernet. Power measuring sensors and communication accessories use this interface to communicate with LUT's VLAN. The hosting machine of the green campus' database is also found on this VLAN as well as the monitoring computer. This makes possible to get all the required data from a single station to accomplish all the related objectives exposed in chapter 1.2. Finally, from the monitoring computer, the data is shared to be published on the Internet.

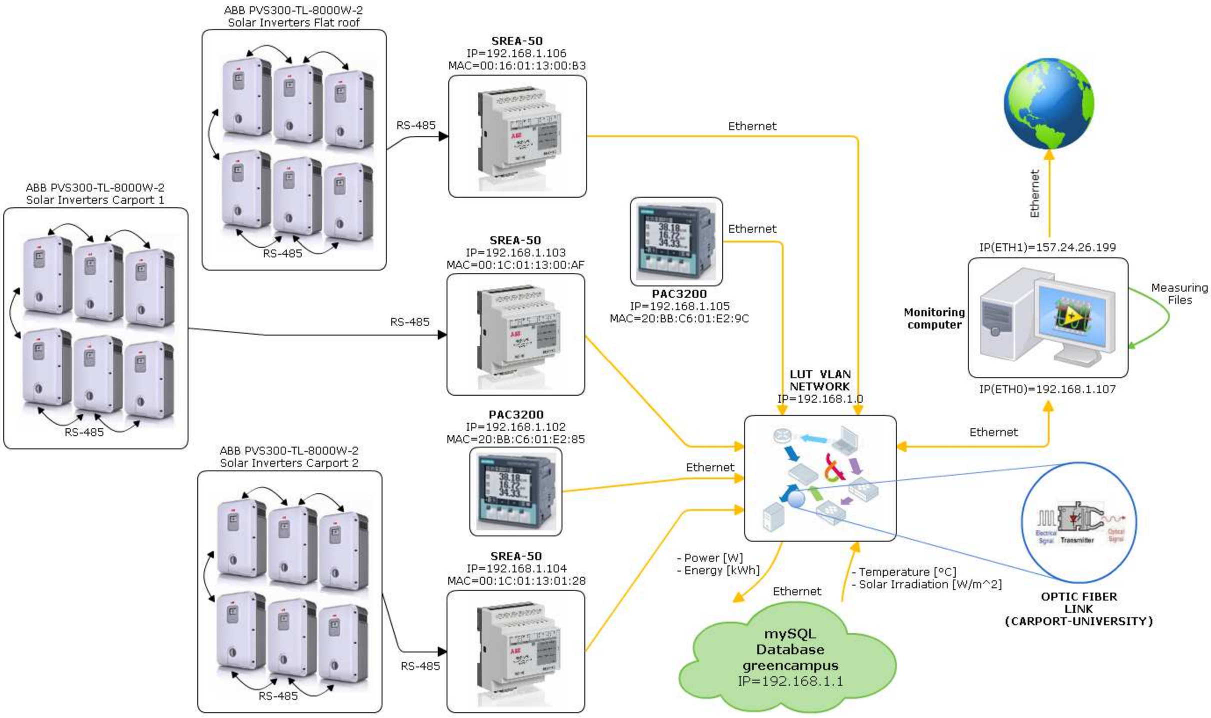

Figure 2.7, Communication system for the solar power plant.

3 Measurements and calculations

In this chapter, all the devices and tools for the monitoring system are introduced (i.e. the power sensors from Siemens, the sensors embedded in the solar inverters and the green campus' database). It is also detailed how the data is managed and all the information calculated with it. For this project, four different applications have been developed by LabVIEW®: first and second ones (PAC3200_FR_reader and PAC3200_CP_reader) are identical, they read and process data from both power sensors SENTRON PAC3200, the third application (SREA-50_reader) reads and processes data from all ABB PVS300-TL-8000W-2 inverters installed and the last one (DataBase_RW) is used for the management of the green campus' database.

3.1 Siemens SENTRON PAC3200

3.1.1 Description

SENTRON PAC3200 is a power monitoring device for displaying and storing all relevant system parameters in low-voltage power distribution. It is capable of single-phase, two-phase, or three-phase measurement and can be used in two-wire, three-wire, four-wire, TN, TT, and IT systems. Among those parameters, there is power, voltages, currents, energy, etc. The measurements are taken continuously and stored every tenth of second in different registers, which can be read by using Modbus TCP protocol through the 10 / 100 Mbit Ethernet interface incorporated. This device is used for many reasons: apart from its good measurement accuracy, the ease of accessing the registers is a key feature for the project development. For the first stage of the solar power plant, two PAC3200 are used: one for the flat roof and another for both rows of the carport.

3.1.2 Data collection

Figure 3.1 shows the steps done by PAC3200_FR_reader and PAC_3200_CP_reader while they are running: First of all, it is necessary to open a Modbus TCP connection between the monitoring computer and the monitoring device. The IP address to connect with is specified in Figure 2.7 on page 23 depending on the device we want to get data from. The next step is to read the holding registers containing the information and transforming the data format according to LabVIEW® requirements for enabling the possibility to use that data for our purposes. Once it is possible working with that data, we proceed to realize the different calculations for getting the most interesting information. Finally, the result of the calculations and all the values are stored and sent to the application for managing the database using shared variables.

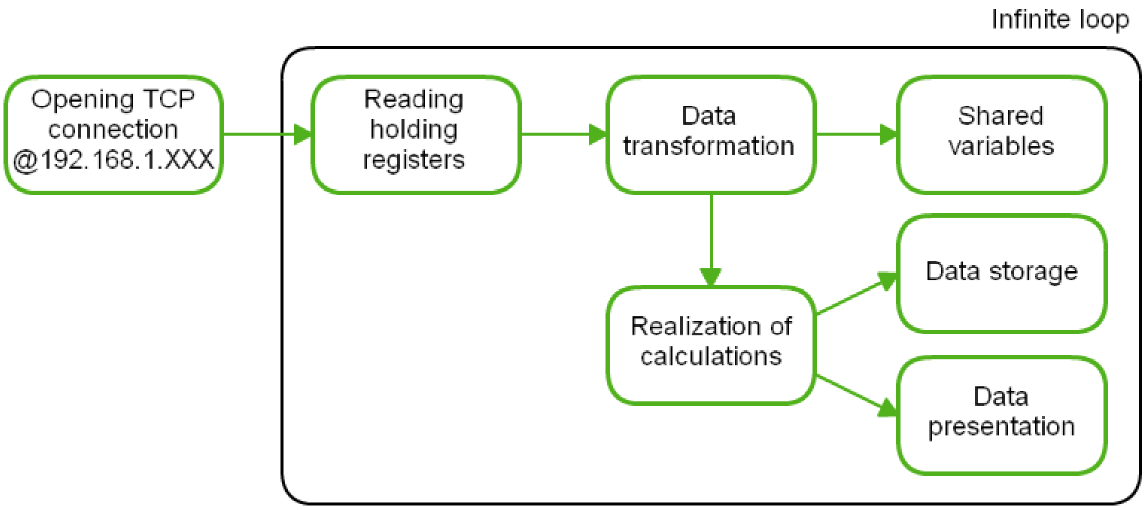

Figure 3.1, Block diagram of the PAC3200_XX_reader operation.

3.1.3 Values and calculations

All the parameters read directly from the holding registers by PAC3200_XX_reader are detailed on Table 3.1 (SIEMENS, 2008). They are read every second and used to realize all the calculations:

Table 3.1, List of the registers read from Siemens Sentron PAC3200.

Name	**Unit**	**Holding registers**
Voltage a-n	V	1, 2
Voltage b-n	V	3, 4
Voltage c-n	V	5, 6
Voltage a-b	V	7, 8
Voltage b-c	V	9, 10
Voltage c-a	V	11, 12
Current a	A	13, 14
Current b	A	15, 16
Current c	A	17, 18
Total Apparent Power	VA	63, 64
Total Active Power	W	65, 66
Total Reactive Power	VAR	67, 68

Energy Imported[3]	Wh	801, 802, 803, 804
Energy Exported[4]	Wh	809, 810, 811, 812

The first and maybe the most important parameter calculated is the absolute energy difference (E_{D}) (i.e. all the energy that the plant supplied to the electric grid). Subtracting the total energy imported (E_{I}) to the total energy exported (E_{E}) as described in

$$E_{\mathrm{D}} = E_{\mathrm{E}} - E_{\mathrm{I}} \tag{3.1}$$

Also relative values (to the day) are calculated by storing a sample both absolute energy imported and exported values at 00:00 every day ($E_{\mathrm{I}}(0)$ and $E_{\mathrm{E}}(0)$ respectively). Subtracting that value to the current values of the energy the result is the relative energy imported (E_{rI}) and exported (E_{rE}) values of that day as follows

$$E_{rI} = E_I - E_I(0) \tag{3.2}$$

$$E_{rE} = E_E - E_E(0) \tag{3.3}$$

The relative difference (E_{rD}) is the value of the energy produced in that day (i.e. an energy counter restarted daily), and it is calculated by subtracting the relative energy imported to the relative energy exported as shown in

$$E_{rD} = E_{rE} - E_{rI} = E_D - E_D(0) \tag{3.4}$$

The average power of last minute is calculated by the typical arithmetic averaging algorithm. In this case, the 60 last samples (because the software reads one value per second) of power values read are summed and the result of that is divided by 60 as in (3.5). In the same way, averages for currents and voltages are calculated.

$$P_{\mathrm{avg,1min}} = \frac{\sum_{i=1}^{60} p(i)}{60} \tag{3.5}$$

The average power over one hour ($P_{\mathrm{avg,1h}}$) is calculated by means of subtracting the absolute difference given one hour ago to the current absolute difference like in (3.6). Without the division by 1h, the result is the energy produced during last hour (which is also stored and presented every hour).

[3] Energy Imported: all the amount of energy taken from the electric grid used by the solar power plant (usually when it is not producing energy and there is need to keep some electronic devices on).
[4] Energy Exported: all the amount of energy produced by the solar power plant.

$$P_{\mathrm{avg,1h}}(t)[\mathrm{W}] = \frac{(E_D(t)[\mathrm{kWh}] - E_D(t-1\mathrm{h})[\mathrm{kWh}]) \cdot \frac{1000\ \mathrm{Wh}}{1\ \mathrm{kWh}}}{1\mathrm{h}} \qquad (3.6)$$

The average power of the whole day is calculated using the relative difference E_{rD} in Watt-hour and the time in hours since 00:00 of each day. With the division E_{rD} [Wh]/t [h] the average power of the day in Watt is calculated.

Using the instantaneous power (P) and the rated power of every zone ($\mathrm{P_{rtd}}$), the percentage's calculation of the working performance of the power plant is carried out following (3.7). This value is used to drive a dial, which gives a fast idea of the working intensity of the whole plant.

$$P_{\%}[\%] = \frac{P[\mathrm{W}]}{\mathrm{P_{rtd}}\,[\mathrm{W}]} \cdot 100 \qquad (3.7)$$

Knowing all the amount of energy produced during the lifetime of the solar power plant and the ratio "kg_{CO2}/kWh" (which on 2011 was 0.24 for Finland (OSF, 2013)), just by implementing a product between those two values, the amount of kg_{CO2} saved by the solar power plant is obtained. Also, in the same way all the money saved in terms of energy thanks to the production is calculated knowing how much the university is paying to the energy provider per kWh consumed (currently 0.11 €/kWh).

Using the daily relative values of the energy (E_{rD}) and using the same ratios of kg_{CO2}/kWh and €/kWh, daily money saved and CO_2 saved is calculated too. Other economical parameters are calculated such as the difference (money left to pay back the solar power plant M_{D}) between the total investment ($\mathrm{M_I}$) and all the money saved (M_s) as done in (3.8), the percentage amortized of the solar power plant's investment ($M_{\mathrm{AM\%}}$) following (3.9) and the time left to amortize the investment (T_{AM}) (in days) as shown in (3.10). This last parameter is calculated taking the future production of the average power value of the last day ($P_{\mathrm{avg,24h}}$) and knowing the energy cost per kWh (M_{E}) that LUT is paying to the provider.

$$M_{\mathrm{D}}\,[€] = \mathrm{M_I}\,[€] - M_s\,[€] \qquad (3.8)$$

$$M_{\mathrm{AM\%}}\,[\%] = \frac{M_s\,[€]}{\mathrm{M_I}\,[€]} \cdot 100 \qquad (3.9)$$

$$T_{\mathrm{AM}}\,[\mathrm{days}] = \frac{M_{\mathrm{D}}\,[€]}{P_{\mathrm{avg,24h}}[\mathrm{kW}] \cdot M_{\mathrm{E}}\left[\frac{€}{\mathrm{kWh}}\right]} \cdot \frac{1\ \mathrm{day}}{24\ \mathrm{h}} \qquad (3.10)$$

Finally, the application stores the weather conditions that favoured the maximum power value of the day. All the power values are given in Watt (W) and all the energy values are given in Kilo Watt hour (kWh).

3.1.4 Files and presentation

The application developed displays and plots all the measured and calculated values; it creates also daily texts files containing all the interesting data, which may be useful for researching purposes and for studying the production in a detailed way:

FILE 1

Table 3.2, Description of File 1; Name: Currents_Voltages_DAY_dd.mm.aaaa.lvm, updating period: 1 minute.

Headers
Time
Current a [A]
Current b [A]
Current c [A]
Voltage a-n [V]
Voltage b-n [V]
Voltage c-n [V]
Voltage a-b [V]
Voltage b-c [V]
Voltage c-a [V]

FILE 2

Table 3.3, Description of File 2; Name: Power_Energy_DAY_dd.mm.aaaa.lvm, uptading period: 1 minute.

Headers
Time
1 min Average Active Power [W]
Absolute Difference [kWh]
Total Absolute Energy Imported [kWh]
Total Absolute Energy Exported [kWh]
Daily Relative Difference [kWh]

FILE 3

Table 3.4, Description of File 3; Name: Budget_DAY_dd.mm.aaaa.lvm, updating period: 1 minute.

Headers
Time
Total Money Produced [€]
Money left for amortize the investment [€]
% Amortized
Total CO2 Avoided [kg]
Money Produced/day [€]

FILE 4

Table 3.5, Description of File 4; Name: Weather_&_Maximum_Power_Values_DAY_dd.mm.aaaa.lvm, updating period: 1 minute.

Headers
Time
Solar Irradiation [W/m^2]
Temperature [ºC]
Maximum Power [W]
Solar Irradiation (Pmax)
Temperature (Pmax)

FILE 5

Table 3.6, Description of File 5; Name: 1h_Energy_Produced_DAY_dd.mm.aaaa.lvm, updating period: 60 minutes.

Headers
Time
Last Hour Energy Produced [kWh]

Figure 3.2 to Figure **3.7** correspond to the images created by the application on 13/11/2013 and 14/12/2013 containing daily plots of different parameters.

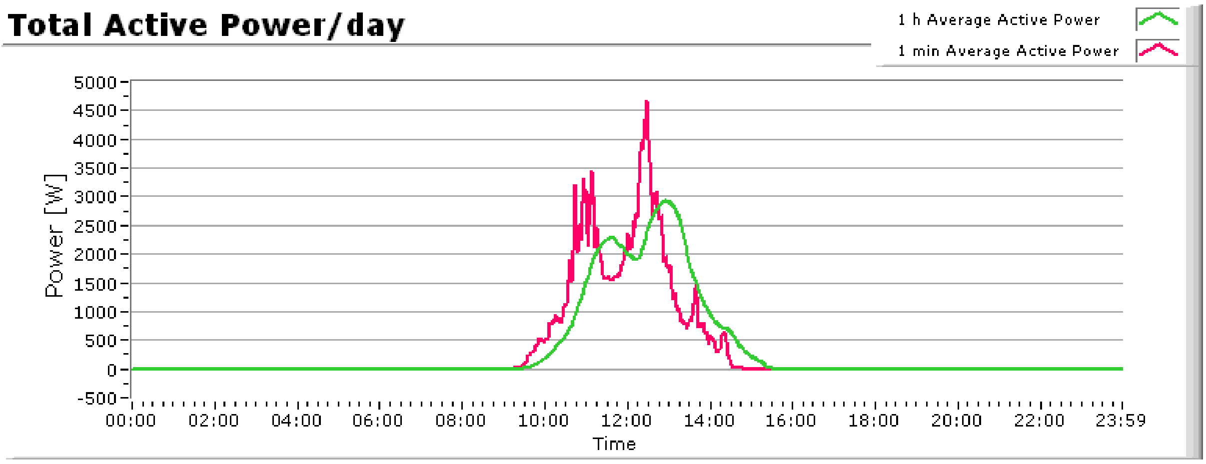

Figure 3.2, Evolution of the power production (14/12/2013).

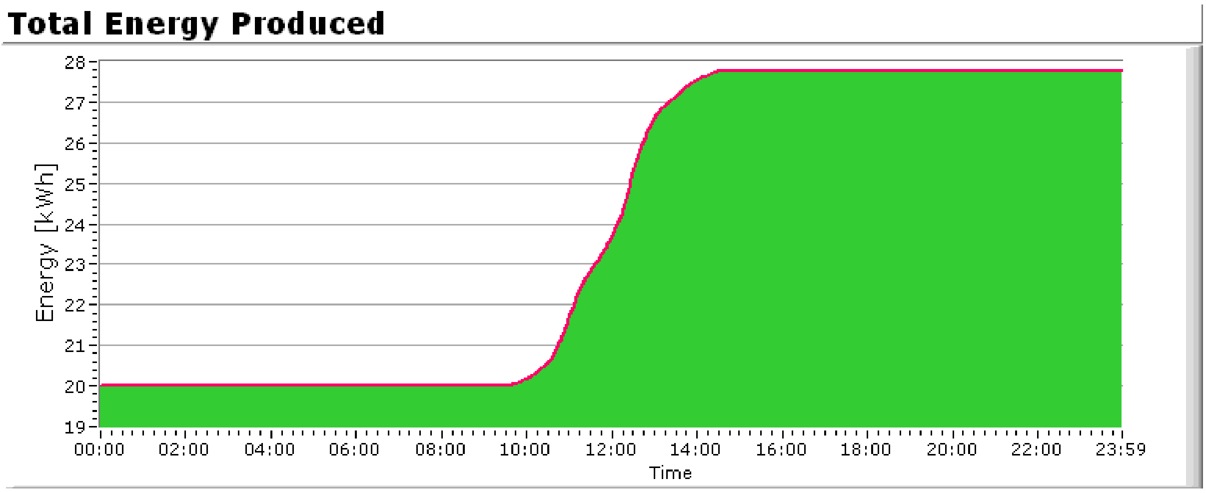

Figure 3.3, Evolution of the absolute difference (14/12/2013).

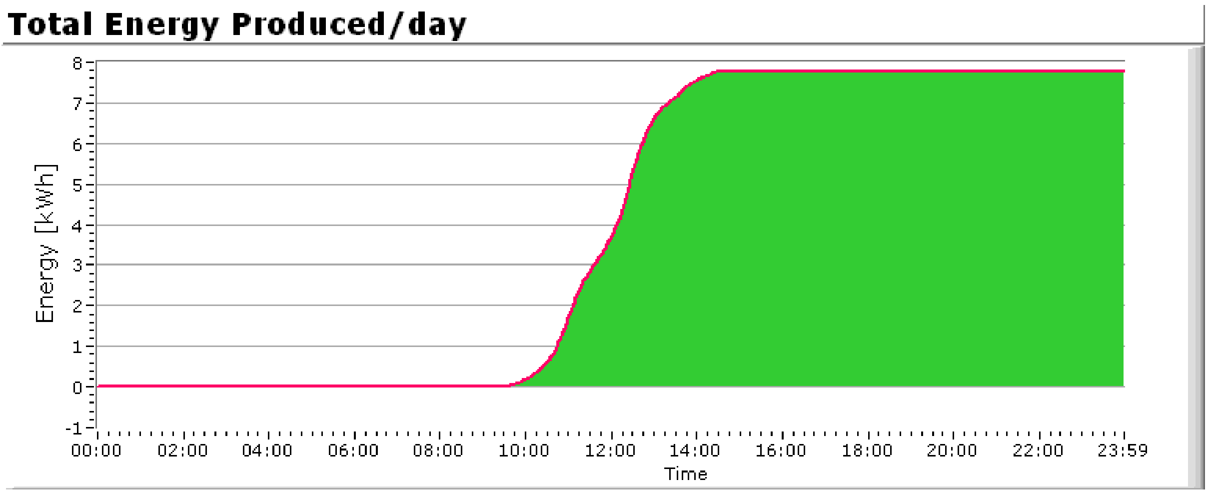

Figure 3.4, Evolution of the relative difference (14/12/2013).

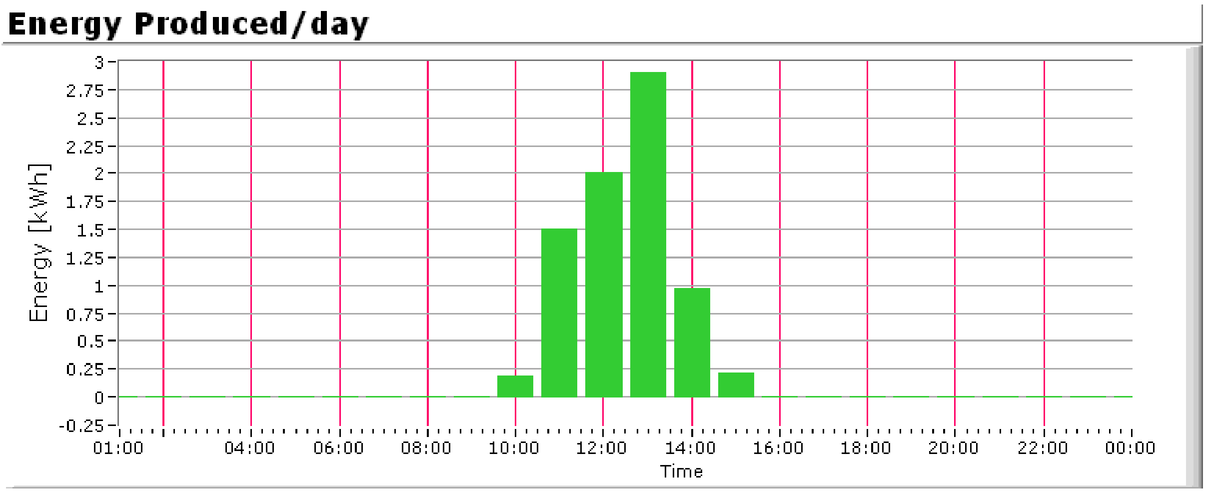

Figure 3.5, Evolution of the energy produced every hour (14/12/2013).

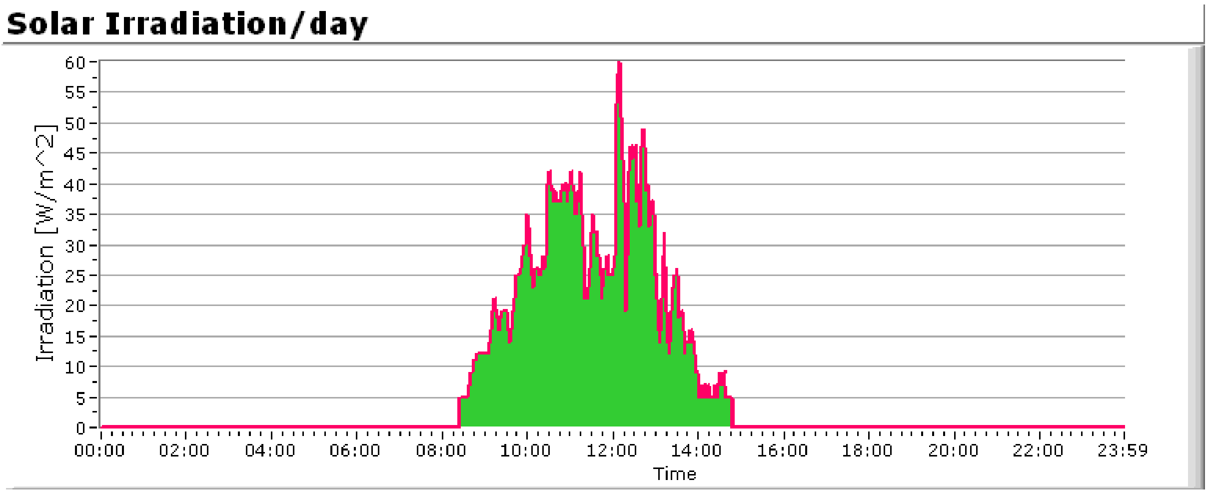

Figure 3.6, Evolution of the solar irradiation (13/11/2013).

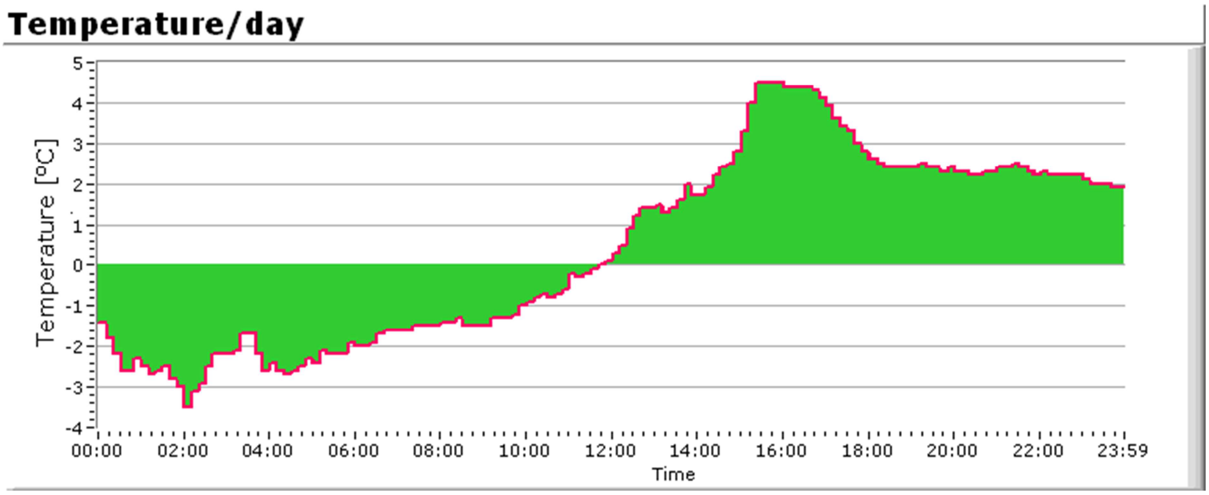

Figure 3.7, Evolution of the temperature (13/11/2013).

3.2 ABB SREA-50

3.2.1 Description

The solar inverters used for the solar power plant monitor all the electrical variables needed for this project. All these values are stored and are available for reading using a communication accessory. The most interesting examples are:

- Output power [kW]
- Energy counter [kWh]
- Output current [A]

The communication accessory for the solar inverters mentioned before is ABB SREA-50, a device used in order to set a link between the solar inverters and the monitoring computer. It can handle the communication between 10 inverters and a single monitoring computer thanks to the 10 / 100 Mbit Ethernet interface and the possibility for setting a serial connected link between inverters (ABB, 2012). This device is widely used because it runs a GUI (graphical user interface) for data presentation – and also for configuration purposes – which is very simple to use and complete.

In this project, SREA-50 is used as a tool for accessing to the inverters data using LabVIEW® for establishing a connection under the protocol Modbus/TCP, so the GUI is only helpful for configuring some device's parameters:

AT THE START-UP

- Setting user and password.
- Setting date and time.
- Connecting devices (i.e. search for inverters connected).

COMMUNICATION PARAMETERS

- Changing the default IP address.
- Modbus access enabling (disabled by default).

Since the maximum number of inverters that they can drive is 10, the total number of SREA-50 used is 3: One for the flat roof and two for the carports (each one handles then six inverters). Having the same numbers of inverters per SREA-50 is adequate because in this way it is possible to compare, which are the fields producing more energy and so knowing which is the most efficient.

3.2.2 Data collection

The process for reading the available data from ABB SREA-50 is exactly the same described on chapter 3.1.2. The only difference is that in this case shared variables are not used because there's no need to upload information gotten from this device to the data base, the use of that information will be only for posterior calculations and research purposes.

3.2.3 Values and calculations

All the parameters read by SREA-50_reader application directly from the holding registers are just power and energy values from every single inverter, as well as the total values per string of 6 inverters. These are read every second. With those values the application calculates similar parameters as PAC3200_XX_reader and using the same equations/methods:

First of all, all the power values are averaged in one minute, one hour and one day as described on page 27 in (3.5) and (3.6). Also the percentage of the working performance of every zone (carport 1, 2 and flat roof) is calculated following (3.7). Moreover there are two energy counters for every inverter and for the total values of each zone; one restarted every day and one restarted every hour, they operate as described in (3.4)[5] and (3.11), respectively. Finally, this application also receives information of temperature and solar irradiation from the weather station. Thus, maximum power values for every zone are saved as well as the weather conditions at the moment of maximum production.

$$E_{1\mathrm{h}}(t)[\mathrm{kWh}] = E(t)[\mathrm{kWh}] - E(t - 1\mathrm{h})[\mathrm{kWh}] \qquad (3.11)$$

3.2.4 Files

In the same way as the application PAC3200_XX_reader, this one creates blank text files daily with the adequate headers, which will be

[5] For this equation, the used parameter is directly the energy value read from SREA-50 instead of the absolute difference E_{D} defined for PAC3200_XX_reader.

overwritten periodically with the actual values to save. Their names are set regarding the date and the zone of where those values were taken. In this case, the files created will contain the following information:

FILE 1

Table 3.7, Description of File 1; Name: Power_Energy_Weather_DAY_dd.mm.aaaa.lvm, updating period: 1 minute.

Headers
Time
Total Active Power FR [W]
Total Active Power CP1 [W]
Total Active Power CP2 [W]
Total Energy Produced FR [kWh]
Total Energy Produced CP1 [kWh]
Total Energy Produced CP2 [kWh]
Temperature [ºC]
Solar Irradiation [W/m^2]

FILES 2 to 4

Table 3.8, Description of Files 2 to 4; Updating period: 1 minute.

Headers
Time
Power_INV1 [W]
Power_INV2 [W]
Power_INV3 [W]
Power_INV4 [W]
Power_INV5 [W]
Power_INV6 [W]

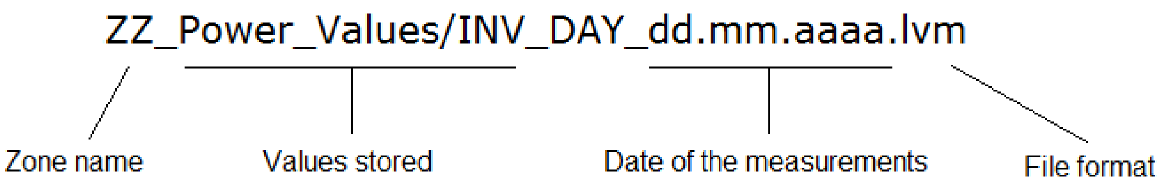

Figure 3.8, Name of the files 2 to 4. ZZ = CP1, CP2 or FR for Carport 1, Carport 2 and Flat roof respectively.

FILE 5

Table 3.9, Description of File 5; Name: 1h_Energy_Produced_DAY_dd.mm.aaaa.lvm, updating period: 60 minutes.

Headers
Time
Last Hour Energy Produced FR [kWh]
Last Hour Energy Produced CP1 [kWh]
Last Hour Energy Produced CP2 [kWh]

FILE 6 to 8

Table 3.10, Description of File 6 to 8; Updating period: 60 minutes

Headers
Time
Last Hour Energy Produced INV1 [kWh]
Last Hour Energy Produced INV2 [kWh]
Last Hour Energy Produced INV3 [kWh]
Last Hour Energy Produced INV4 [kWh]
Last Hour Energy Produced INV5 [kWh]
Last Hour Energy Produced INV6 [kWh]

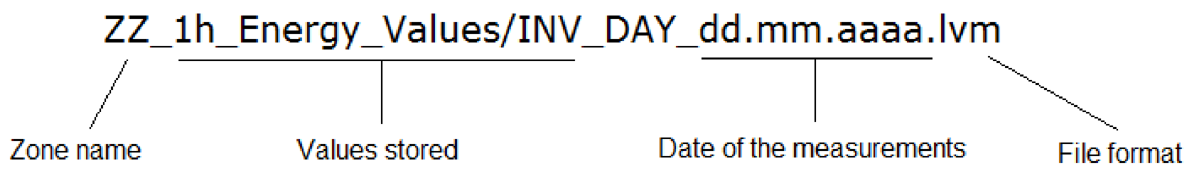

Figure 3.9, Name of the files 6 to 8. ZZ = CP1, CP2 or FR for Carport 1, Carport 2 and Flat roof respectively.

3.3 Data base operations

As mentioned before, the aim of the DataBase_RW application is to manage the green campus' database in order to perform reading and writing operations regarding the specifications of the data base manager from LUT. This database contains several tables storing different kinds of information. For this project the tables used are "gcweather", "gcems", "gcu93301", "gcu93601", "gcudata93301" and "gcudata93601".

Figure 3.10 describes the operation conducted by the designed application for managing the data base: The first step is to open the connection between the monitoring computer and the database. Once this connection is opened it is possible to perform reading and writing operations; in this case the application follows two main paths in parallel:

On one side the application reads the weather information and transforms the data gotten in a suitable format for LabVIEW® functions before copying it to the corresponding shared variables or plotting the values in different graphs. On the other side, the application reads the data gotten from PAC3200_reader via shared variables, then it is transformed on the different formats used in the database before writing them on the corresponding table.

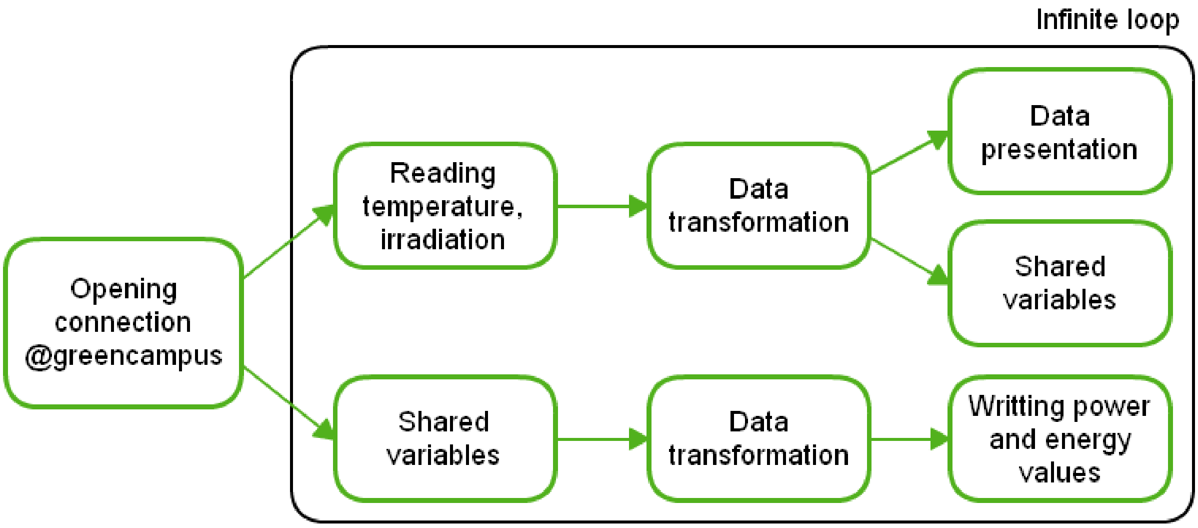

Figure 3.10, Description of the DataBase_RW operation.

The next paragraphs describe the use and operations done for each table:

3.3.1 Table gcweather

Figure 3.11, Weather station of the university.

Table gcweather is a one-row table that is updated every minute with weather information measured by the weather station of the university; it contains the value of the temperature [ºC], solar irradiation [W/m^2], a time stamp of the last update and some other parameters unused in this project such as the cloud altitude. The application reads temperature and solar irradiation values also every minute and sends them using shared variables to PAC3200_reader application. It also displays the current values and plots their daily evolution.

For the solar irradiation it was possible to get some zero values distributed randomly during the day for unknown reasons, so an algorithm for avoiding that results was developed; basically the application checks for zeroes and if the last value gotten was greater than 9 W/m^2 then the value assigned for the solar irradiation at that moment is the previous one until getting another value different than 0. Figure 3.12 and Figure 3.13 show the difference achieved with the 0-detection algorithm.

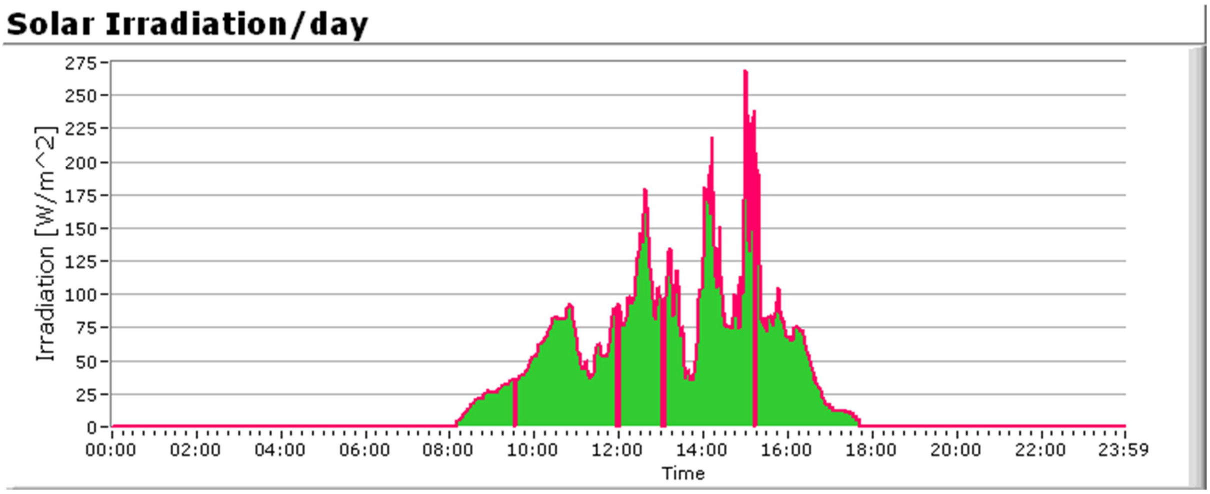

Figure 3.12, Solar irradiation results without the 0-detection algorithm.

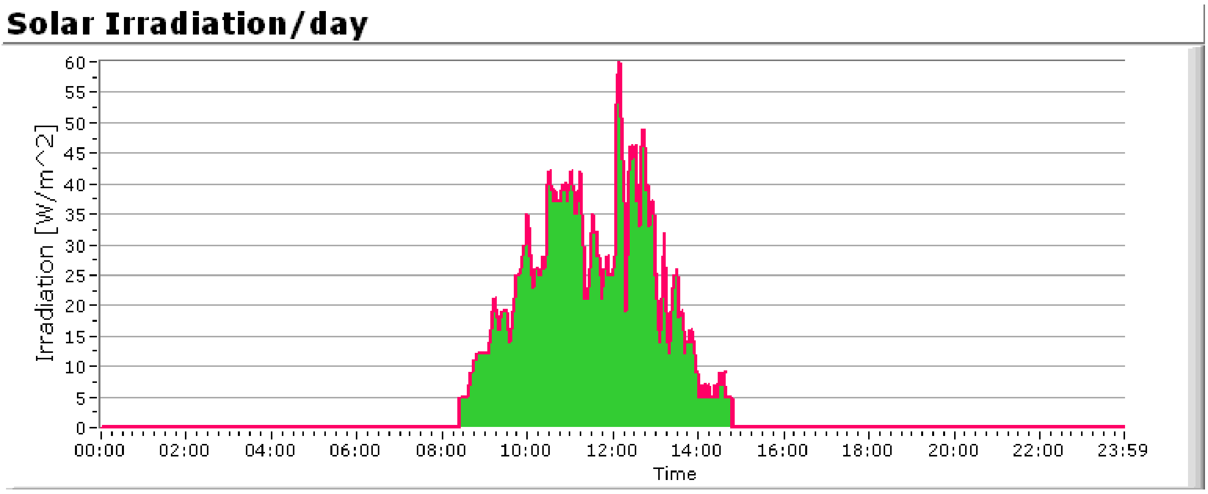

Figure 3.13, Solar irradiation results with the 0-detection algorithm.

3.3.2 Table gcems

Table gcems has one row per device updating information in the green campus database. For the solar power plant two rows are managed, one for the carport and another for the flat roof:

This table includes constant parameters like a numeric id (93301 and 93601 for the flat roof and carport, respectively), a call sign (a little text description for every row like "Solar Power Plant Flat roof" and "Solar Power Plant Carport") and the rated power production [W] for each zone (51500 for the flat roof and 108000 for the carport). Also non constant parameters like the current power production [W] and a control flag (1 if active, 0 if inactive) are updated every second by the application.

3.3.3 Tables gcu93301 and gcu93601

Tables gcu93301 and gcu93601 include specific and instantaneous information about the two zones of the solar power plant (one table per zone) and are updated every minute. The information updated into them are: a control flag, 1 minute average active power [W], total energy [kWh], grid frequency [Hz], mono-phase voltages [V] of each line, 1 minute average current [A] of each line too and a time stamp added automatically by the data base server.

3.3.4 Tables gcudata93301 and gcudata93601

Tables gcudata93301 and gcudata93601 contain exactly the same information as gcu93301 and gcu93601 but the difference is that instead of updating the information, every minute a new row is added with the current information, creating so, a register of the described values that can be accessed anytime using any computer connected to the university network with grants for doing it.

4 Discussions and conclusions

The fact that the developed software was going to be used in a real environment was really motivating and also challenging. This tool had to be reliable and functional because the university will use the data read for serious purposes such as updating LUT's public web page accordingly and so, showing to the world the production of its solar power plant. The software is also a useful tool for the research in solar energy because with the stored results it is possible to analyse, which are the conditions (technologies of the solar panels, physical location or weather) that favour the most the production of solar energy in the campus.

About the developed applications, the results obtained were like the ones expected for PAC3200_reader but the rest of the applications are not that efficient: For the application SREA-50_reader, tests were carried out late (because solar inverters couldn't be started before). It was possible to read information about date and time from the communication accessory of the inverters (ABB SREA-50) but it was not possible to read power or energy values from the inverters because the device could not recognize them all and the registers to read are still unknown. The application DataBase_RW works quite well for tables "gcems", "gcu93301" and "gcu93601" but crashes for a connection problem with the data base server after several hours (it has been running more than two days in a row at the best case). For the tables "gcudata93301" and "gcudata93601" any achievement was gotten; every time that the program was trying to write something in them, the connection was refused by the server of the data base and it made the application crash as well. About the application PAC3200_reader, really successful results were gotten at the laboratory tests using the device monitoring the windmill. The application is very reliable and it never crashed during tests. On the real environment a successful connection could be set and it was possible to collect data of solar production from both power measurement devices installed at the flat roof and at the carport. The first day that the values were gotten was the 14/12/2013; solar panels were not covered by snow (fact that is not usual by that dates) but anyway the production was really low (<5% of the maximum power). That's why at winter time the solar power plant will be just turned off.

5 References

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Appendices

A. Software captures of PAC3200_XX_reader

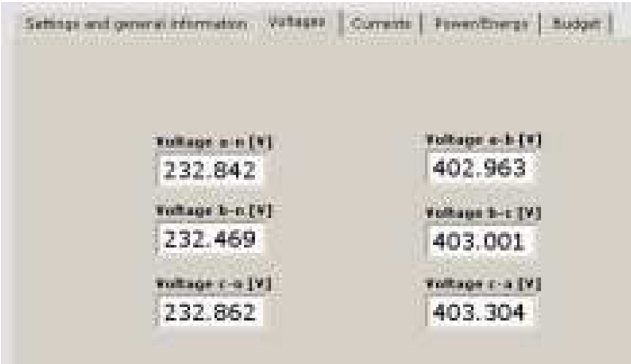

Figure A.1, Voltages tab. In it, it is possible to observe the instantaneous value of the mono-phase or three-phase voltages.

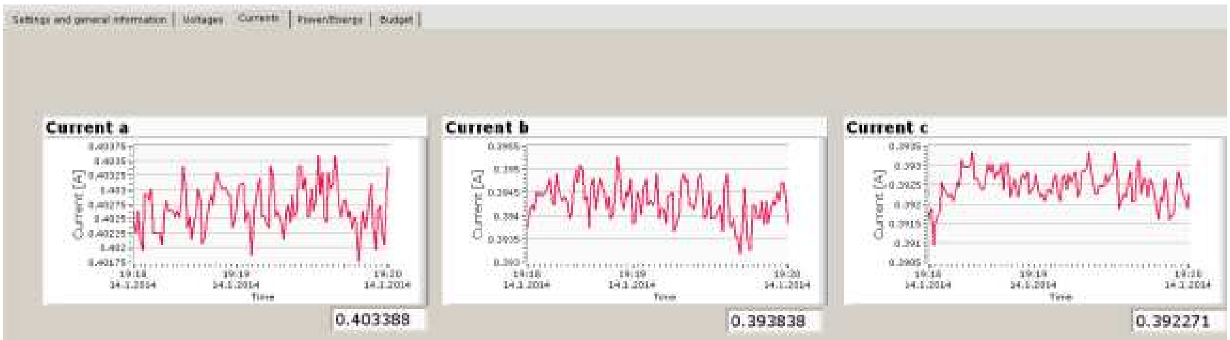

Figure A.2, Currents tab. Plots the evolution of the current of last minute.

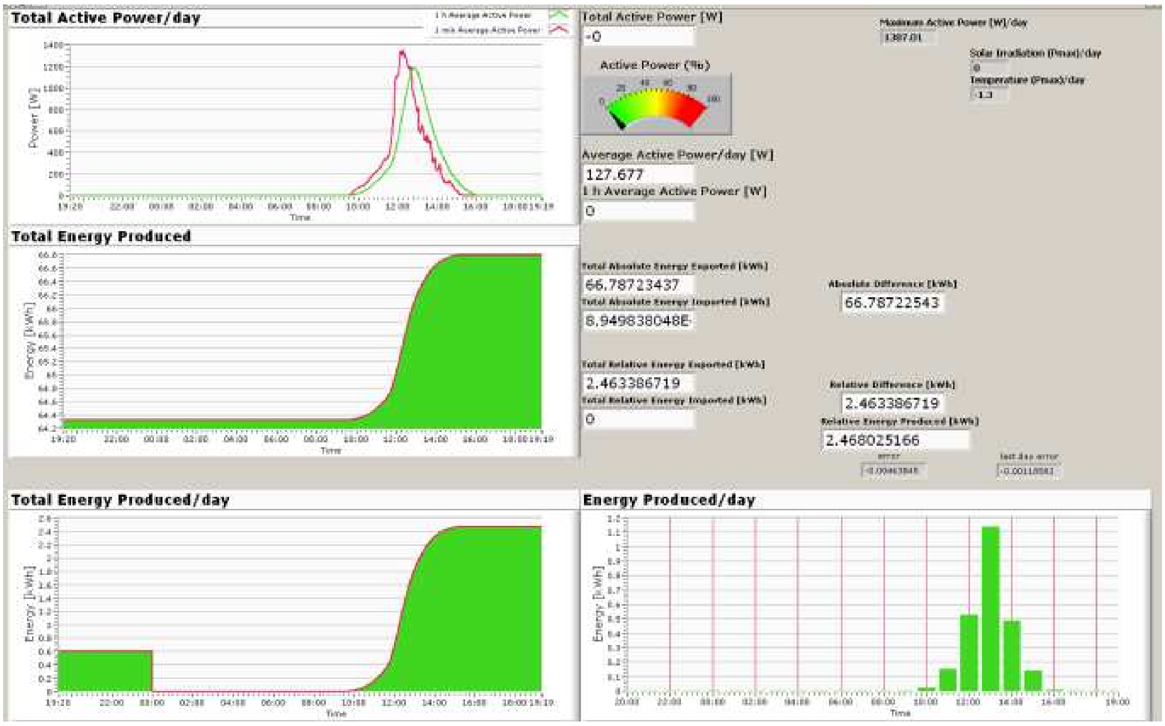

Figure A.3, Power/energy tab. Displays the instantaneous power and energy (relative and absolute) values, as well as their evolution during the whole day. Also the maximum power and the weather conditions (solar irradiation and temperature) at that time.

Figure A.4, Budget tab. All the economic parameters calculated are displayed here.

B. Physical pictures

Figure B.1, Monitoring computer.

Figure B.2, Carport before construction.

Figure B.2, Carport during construction.

Figure B.4, Carport after construction.

Figure B.5, Flat roof before construction.

Figure B.6, Flat roof during construction.

Figure B.7, Flat roof after construction (I).

Figure B.8, Flat roof after construction (II).