The Application of Tracking or Fixed Solar Photovoltaic Panels

A Practical Comparison

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ABSTRACT

BACHELOR'S THESIS

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The aim of this thesis was to develop, assemble, document and compare output data for two different photovoltaic installations where one is a fixed panel system and the other a 2-axis solar tracking panel system.

In order to do so, a fully functioning solar tracking system was developed and programmed using a combination of both Modbus communication protocol and a LabVIEW interface for data acquisition and user control.

All the data were collected by a series of energy meters and transferred to Microsoft Excel for analysis and efficiency comparison.

The results indicate that a 2-axis solar tracker panel system can achieve greater values of efficiency than comparable fixed panel installations, with improvements that can reach up to 27%.

The outcome of this thesis resulted in the successful demonstration of a working photovoltaic comparison system, but some limitations were encountered due to time and material inconveniences.

Keywords: Modbus, LabVIEW, Photovoltaic, Solar tracker

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1 Introduction

Sunlight takes a little over 8 minutes (Cain, 2013) to travel from the sun to the surface of the Earth and some factors like the latitude affect the amount of solar flux that a country gets. In Finland, these values are generally no higher than 1500kWh/m^2 (Pihlakivi, 2015), but Spain, together with Portugal, are the countries with the greatest photovoltaic potential in Europe with values that can reach up to 2200 kWh/m^2 (Solargis, 2019).

It is very common in Spain, when travelling by car, to notice that there are solar photovoltaic installations on both sides of the road, in the countryside, outside the big cities that are operated by the big energy generation companies. Many of these installations are automated with solar tracking technology in order to get more efficiency and so on to obtain a much larger electrical output.

The scientific consensus indicates that global warming is caused in great part by the exploit of resources of the Earth, due to the extraction of fossil fuels, and the residual generation of GHG that pollute the atmosphere. Renewable sources of energy are the future that will take care of the planet and in this thesis, the idea is to concentrate on solar power.

Living in a one of a kind country like Finland helps to change the point of view and start comparing everything in different scenarios. That is why there is always the will of observing the differences between such different countries, in terms of solar power, like Spain and Finland.

Comparing the electrical use in Finland and Spain, the average consumption in Finland in detached houses is around 24.000 kWh (Heinonen, n.d.) and 27.000 kWh (Vertanen, 2018) every year. this means that to power the entire house off the grid you need more than 30 250-watt solar panels getting a daily average of eight hours of full sunlight. This in Finland is almost impossible as during winter sunlight lasts for between 1 to 5 hours (Santiago, 2015) depending on the exact location.

On the other hand, in Spain, the consumption of similar types of houses can vary depending on the location between 14.000 and 21.000 kWh (Luz, 2018) every year. There is not a big difference in consumption, so this means that a solar installation in Spain would have more or less the same conditions than in Finland. The difference is found in the amount of time that solar panels can be working throughout the day, as in Spain daylight in winter is much more significant than in the north. So, the same solar installation would always payback itself faster in Spain than in Finland.

However, the idea of these installations is not to cover everything but to help reduce consumption from the grid and to reduce the price of electricity. In order to do so, most modern solar units use net metering, a system that is hooked up to the power grid and measures the difference between the energy which is given back to the grid and the used from it. In order to control the deficits of energy, net metering makes it much cheaper and easier than when the electricity is stored in a set of batteries.

In this thesis, a practical comparison between different kinds of solar PV installations has been carried out. In particular solar trackers and steady panels have been compared in order to analyse the difference in terms of energy output and efficiency in both cases. The project has developed a solar tracker and a steady panel, both mounted in the same structure and with their respective data output combined in order to make the comparison easier. Before starting with the development of the project, the initial idea is that the solar tracker should get much better values of energy generation and efficiency, but it is not clear if it will be enough to compensate the higher initial investment.

1.1 Aims and objectives

The aim of this thesis is to develop and compare two different solar photovoltaic installations where one of them is fixed and the other one is tracking the sun.

To meet the aim, the following objectives have been developed:

- To assemble and install the fixed and sun-tracking solar panels system.
- To establish fully functioning real-time energy monitoring using Modbus and LabVIEW.

Once the systems are working properly and sending the desired data, the next objective is:

- To investigate the relative efficiencies and limitations of both installations.

And finally, the last objective is as follows:

- To determine the economic viability of fixed and sun-tracking solar panels for both Finnish and Spanish installation scenarios as the location of the solar panels is one of the factors to have in mind when creating an installation of these characteristics.

2 Theoretical foundation

The sun has always been present in the lives of humanity. Being one of the essential elements for the existence of life itself and helping in a lot of the fundamental chemical reactions that lead the diverse species to develop until the existing date.

For a lot of time, humans saw the sun as a blessing that gave light and heat to the known world. But in 1839 (Richardson, 2018), Alexandre Edmond Becquerel discovered the technique to take advantage of the sun and its power to benefit the human species, and the new technological developments that were about to come, in a way never seen before. Until then, the sun was used only to create fire, with magnifying lenses, or even to know the time of the day by the use of a sundial. However, Becquerel saw that it could be used to create electricity. He discovered something that later would receive the name of photovoltaic effect and how the sunlight, by hitting a conductor material with its rays, could create an electric current. Years after, all this energy would be used to feed the electronic devices of the age since DC current was already discovered and a lot of different inventions, such as motors were already in use. The creation of the first solar panels was made by Bell Laboratories in the year 1954 (Richardson, 2018).

2.1 Introduction to solar power

Having set the foundation for solar power and described the time it was discovered and first implemented, it is time to start with the physics that manage the functionality of solar panels.

Albert Einstein was one of the greatest minds of the 20th century and in 1921 (Prize, n.d.) he was awarded one of the most prestigious prizes, The Nobel Prize in Physics, for his services to Theoretical Physics, but most notably for the discovery of the law of the photoelectric effect. He determined that when hit by light, electrons are ejected from a conducting material.

Solar panels, which are the ones concerning this thesis, do not use this phenomenon to work, but it is useful to set a foundation to see how electrons behave under the effect of shining light. The photovoltaic effect is not actually about ejecting electrons and neither moving them, but it consists in the interaction of two groups of negative charges in two different semiconducting plates which, when connected by a conducting wire, will generate a current flowing in between. The type of current formed by the means of solar panels and sunlight is a direct current or DC in the range of voltage from zero to the maximum voltage given by the panel, which changes with every brand and design. This current can then be stored in a group of batteries, which will form what is called as an off-grid installation, it can be also set directly to the electrical grid if it is a grid-tied kind of installation or it can be a Hybrid installation when a part of the energy is stored in batteries and the other is sent to the grid.

Once knowing about how the photovoltaic effect works, it is essential to introduce the fact that solar panels have different responses to the variable spectrum of sunlight during the day as the changing of wavelengths affects some output parameters of solar cells such as the energy production. Light is made of photons, and each of them has different frequency of vibration, which determines its characteristic energy and so the amount of energy that will be given from the panel. Figure 1 shows the entire spectrum of sunlight as a function of wavelength and gives an idea of which is the value that affects more the production of solar photovoltaic panels.

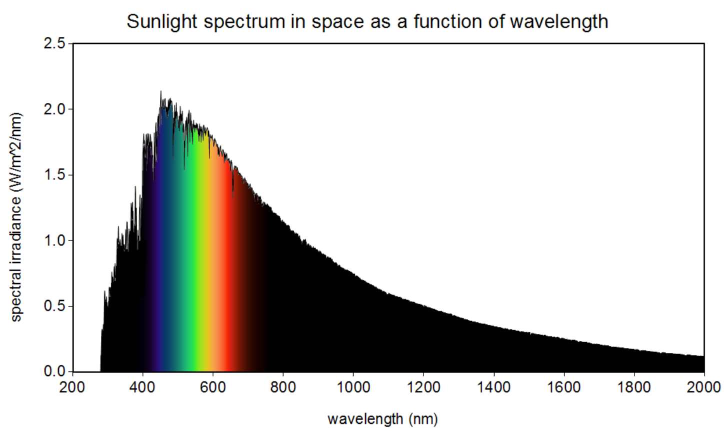

Figure 1: Spectrum of sunlight relating to wavelength (Braid, 2013)

Sunlight has all the spectrum in it but there are only determined wavelength values that are short enough to affect solar panels and create the photoelectric and photovoltaic effects, meaning that other characteristics of light such as brightness or dim are not significant for the functioning of the solar panel as wavelength is the only factor that directly affects the production. This does not mean that the previous is not important as brightness affects the temperature of the panel and so the production of electricity, but this point is not considered in this thesis. In the previous diagram (Figure 1) the different types of light are marked with its colours and as clearly seen, the ultraviolet radiation has a short wavelength, which means that it also affects the production of the panel. Directly referring to this fact is that ultraviolet rays can penetrate the clouds, this means that even in cloudy days, solar panels can continue generating some electricity. It is clear that the value of generation will be very much reduced, but it still is something positive to have in mind when considering the necessity of increasing the installation of solar power.

One of the most important aspects to know when discussing about solar panels is the efficiency of them and which are the differences between different brands in the market. There is a wide range of brands that are, nowadays, producing solar panels, mainly made out of silicon, with average efficiencies that can vary from 15% to 17% (Aggarwal, 2019) as much. However, the biggest brands such as LG and SunPower, who are always battling for the efficiency records in solar panels, are actually producing solar cells that have a very high quality compared to the others and reach the highest value of efficiency in the whole market which is 22,2% (Aggarwal, 2019). Despite this fact, it is very important to set a difference between maximum efficiency and average energy efficiency ratings. In fact, it is as much important to reach a high-efficiency peak, as to be able to record and maintain consistent average energy efficiency, which means that the panel is generating efficient electricity during a lot of time and not only having peaks of good efficiency in special moments of the day.

This is precisely why is it so important to mount the panels in the perfect orientation so they can get the maximum input of light throughout the day. This part is directly related to the main theme of this thesis as it is facing the issue of panel orientation and inclination. It is well known that the sun rises from the East and sets through the West, but what most people is not aware of is that it describes a trajectory which favours the South, and that is why if the installation in question is fix, the solar panels should always be facing this cardinal direction. After this, the optimal inclination of the panel in order to get the maximum output needs to be calculated and it will differ depending on the location of the installation. In this case, there are three possibilities, if panels are located in a latitude below 25 degrees, which comprises countries under the line of Mexico, Egypt or India for example, the calculus is the value of the latitude times 0,87 (Landau, 2017). When the location is between 25 and 50 degrees, so under the line of northern France, Belgium and Poland, the formula is slightly different, and it goes by latitude times 0,76 plus 3,1 degrees (Landau, 2017). The last option is the most special one as it is the one containing northern countries such as Finland, Norway, Iceland and all these places where the sun is always shining in the summer and never seen in winter. These countries need a specific study of every exact location because there is not any generic formula which can give an approximation of the perfect inclination.

After having seen what is best for fix solar panel installations, it is time to develop some information about solar tracking fittings and how the differences between them can hugely affect the output of the solar panels. Solar trackers are, in essence, the panels that are capable of following the sun like a sunflower does so they can always have a direct impact of sunlight and so, have the maximum output of the panel. The position of the sun is determined by the use of two different magnitudes named Altitude and Azimuth. As the name indicates, altitude is the angle formed by the line of the ground and the line that connects the point where the panel is located and the position of the sun. In the other hand, azimuth is, watching the panel from the top, the angle formed by the position of the sun and the cardinal point North. So, the conclusion after this is that there are two types of solar tracker depending on the axes of mobility possessed. One axis solar panels are the ones that have a fix inclination and rotate during the day to follow the sun, so the only value used is the azimuth. Two-axis solar panels are the ones that use two different motors to vary both the inclination and orientation of the panel in order to get a complete following of the position of the sun. In this thesis, a dual axis solar tracker has been developed.

2.2 Modbus

Modbus is a communication protocol which was developed by Modicon in 1979 (BrainB, n.d.) to use it with Programmable Logic Controllers or PLC's. It is defined also as a way of transmitting information using serial lines between electronic devices. Modbus can be seen as a language of the electronic devices when two devices speak the same language they can easily communicate. The fact that it is an easy to use the system, and it is royalty-free, made this method of communication as one of the most popular in the industry sector. In fact, it is the default language used in almost all the different industries, textile, machinery, agricultural, all kinds of industry use different devices that need to be in constant communication and Modbus is certainly one of the best ways to do it.

We can differentiate the Modbus Master which is the device requesting information and the Modbus Slaves which are all the devices such as sensors which supply the information for the principal controller. One standard Modbus network always has one Master and can have all the way up to 247 Slaves (ScheiderE, n.d.), all of them with a different Slave address which permits the communication between the two devices. The curious part of this is that the Master can also write information to the Slaves.
The official Modbus specification can be found at the official webpage (Modbus, n.d.).

As previously stated, Modbus is the most commonly used language to set communication between two different electronic devices, this provides a lot of applications for it. It is normally used to transmit signals from instrumentation and control devices such as sensors to the database centre or the computer in control (ScheiderE, n.d.).

The most common use of Modbus is in Supervisory Control and Data Acquisition or SCADA systems. SCADA consists in a system of software and hardware which permits the control of industrial processes locally or at remote locations, gathering and processing of real-time collected data or the direct interaction with devices like sensors, pumps, motors and other devices as well as other applications. These systems help to improve the efficiency of the industrial process and to gather a lot of different and helpful information for the development and decisions of the company.

Modbus here is responsible for connecting and transmitting the information collected by the sensors and other devices to the main control system, for example, a SCADA system.

This kind of systems are used in a wide range of sectors due to the fact that all sectors have some kind of industrial processes which need to be controlled and Modbus is very useful in all of them. Some examples would be the energy and power sector, oil and gas, transportation, water and wastewater. All of them are industries which need to collect a lot of data and store it and study it to improve all the systems in them and make them better.

Figure 2 is a representation of the connection between the main control and the sensors in a SCADA system. As seen the main connector which can be used is Modbus RTU or also PLC.

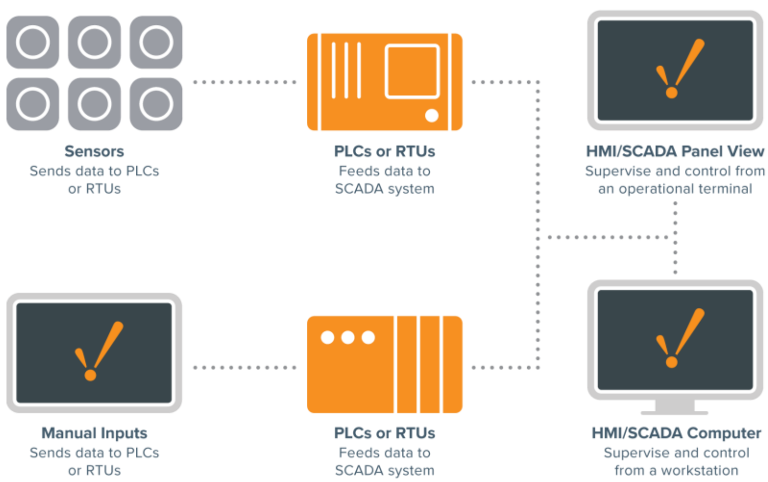

Figure 2: Control connections when using Modbus (Anon., 2018)

In these systems, SCADA uses Modbus to request the needed information from the sensors, and they can just answer with that information, this is a master-slave example.

2.3 Applications and connections of Modbus

Modbus main application will be found in the engineering industry. It will be mostly used in communications between terminals, which refer to electronic equipment consisting of a device providing access to a computer, and electronic devices such as sensors, detectors, etc. Modbus uses a register and address-based communication protocol to connect between master and slave units. The following simple example will demonstrate this:

A temperature sensor is used in a hypothetical system. It is wanted to be connected to the terminal (master unit) so that the temperature can be read. In order to do that, Modbus RS485 devices are needed. These ones are going to be used to convert the signal provided by the sensor into a Modbus type of one so that the terminal can read them. The devices work with RS485 type of protocol (it is also the one all the devices work with in this thesis project). (See Figure 3, Figure 4 and Figure 5).

Figure 3: Modbus RS 485 DSUBB9 device (Linden, 2019)

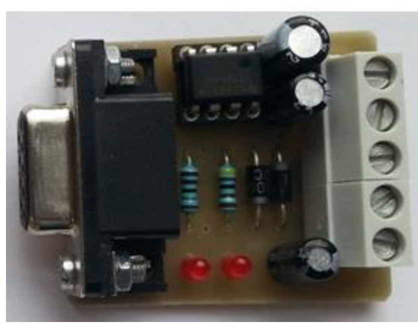

Figure 4: Modbus RS 485 DSUBB9 to wires adapter (Linden, 2019)

Figure 5: Papouch TQS3 temperature sensor (Linden, 2019)

When everything connected, the master will need to know some data in order to synchronize with the slave(s) and send/receive information properly. Data bits, parity, stop bits, function code number and data address are needed. The terminal will send the message and get a response for that one. It can be a message showing the desired value (in this case the temperature) or either an error message, which means that the message was not built properly.

2.4 Other networking protocols and variances with Modbus

Modbus is not the only communication protocol existing, there are more ones and there is another similar protocol which is being used the same or even more than Modbus. Its name is Profibus. It is lean and fast. It was designed in the 1990s (Jayesh, 2017) in order to meet industrial and communication needs. It is also a master-slave as Profibus, but there are several differences between them. First is that all devices go through a start-up sequence in which they join the network. Modbus does not do that. Profibus can operate in multiple master mode while Modbus cannot. Modbus can only be one single master. Profibus cannot operate on Ethernet. Modbus can.

Profibus was designed to automate entire plants. For situations with simple connections (connections of a controller to one smart device), Modbus is the easiest solution, but for more complex situations with for example more points of connection, Profibus is the best solution.

There is one way to combine the two systems in order to make more profit. It consists of using Modbus in the data transport and then the application has a remote station, which refers to a terminal connected to a computer by a data link, that uses Profibus. However, this project will only require of Modbus type-of communications.

2.5 Labview

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a software platform which operates as a test, control and design graphic tool. It offers the user the possibility of creating control, test and design programs through visual programming. It was created by National Instruments in 1976 (Travis & Jim, 2007), but it wouldn't be available for purchase until 1986 (Travis & Jim, 2007). By then, it was only compatible with Apple Macintosh computers. Nowadays LabVIEW can be used with Windows, Linux, MAC and UNIX.

LabVIEW's designed programs are named Virtual Instruments (VIs). Its origin comes from control of instruments, although nowadays it has expanded to all types of electronic instrumentation control, but also to its corresponding programming, mathematics, etc. One of LabVIEW's main objectives is to reduce applications designing time and facilitate the entrance of all type of professionals to the IT field.

As mentioned before, LabVIEW is a graphical programming tool, which means that the programs are not written but drawn. When opening LabVIEW, 2 screens will show up. The Front Panel and the Block Diagram Panel. The Front Panel is the user interface. The user will be able to interact with it while the program is running. The data will appear (graphs, number indicators, etc.), but also interactive elements (knobs, slides, etc.).

The Block Diagram Panel is where the main program is drawn. Here the icons will be placed and connected in some way that the functionality of the program achieves the desired one. When inserting an icon into the Block Diagram Panel, the corresponding element to this one will automatically appear at the Front Panel and vice versa.

LabVIEW is commonly used for data acquisition/generation, laboratory instruments control, industrial automation, control design, supervision and control of microchips, robotics, artificial vision and movement control.

In order to understand how LabVIEW looks like and how it works, the next section will show the code for one kind of program and how does it look like in two different languages (LabVIEW and C).

The codes show a 'while loop' structure. A 'while loop' is a programming structure which requires a condition. When going through it, the program will be running into the loop continuously while the condition is true. Once the condition is false, the program will leave the loop and it will continue with the execution after it (See Figure 6, Figure 7 and Figure 8).

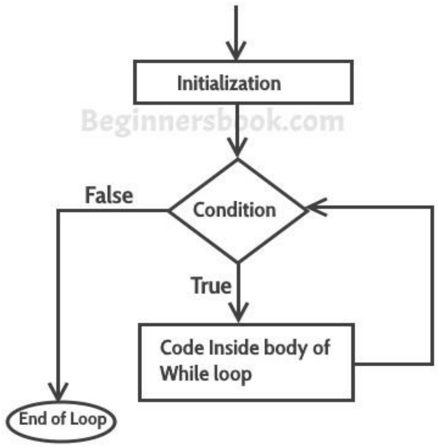

Figure 6: While loop Structure in Block Diagram Scheme (W3Resource, n.d.)

```
int main(){

    int cnt = 0;
    int i;
    int j;
    while (cnt <= 20) {
        i = random(5);
        j = random(10);
        printf("%d\n",i);
        printf("%d\n",j);
        printf("\n");
        cnt += 1;
    }
    return 0;
```

Figure 7: While Loop Structure in C programming (Hayes, n.d.)

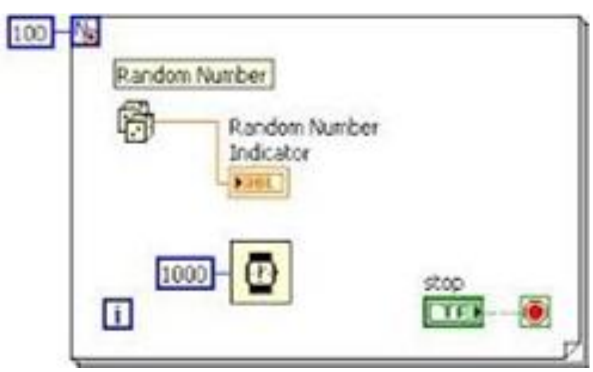

Figure 8: While Loop Structure in LabVIEW (NI, n.d.)

2.6 Comparison using existing data

It is important to know about what has been already made, before getting into the building of the solar tracker and the comparison of all results. In this section of the thesis, three different studies have been used in order to get an idea of which are the results that should be obtained after the realization of this experiment.

The first study was carried out in the country of Malaysia and it was made as an experiment to see what was best for the country to increase the generation of electricity to meet the demand. The comparison was made between a fix solar panel and a single axis solar tracker and the results were not surprising. Figure 9 demonstrates that the power output of panels following the sun is much more consistent than fix installations, both reach a similar peak in the middle of the day, but there is a big difference in both starting and ending of it.

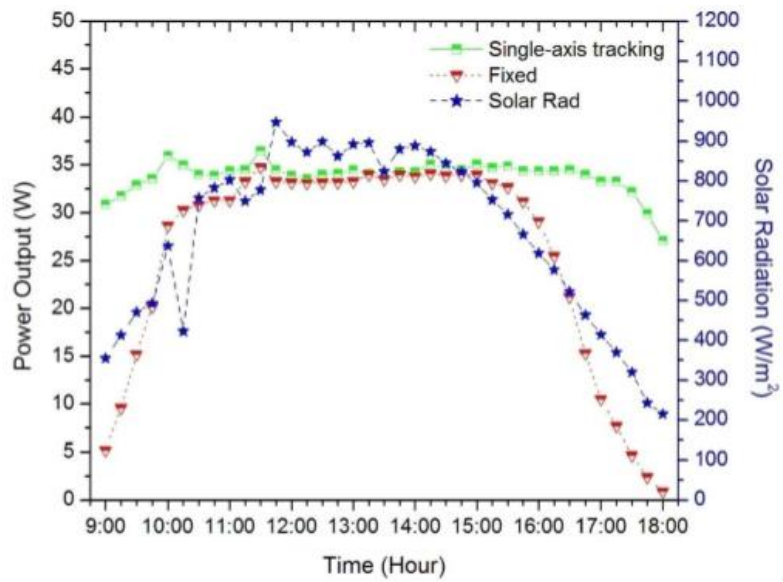

Figure 9: Power output comparison (Mahendran, et al., n.d.)

First conclusion is that the maximum power output difference in one day between the two structures is up to 28W as Figure 9 proves at the end of the day, when the output of fix installation is close to zero, while tracking panel is still getting more than 25W (Mahendran, et al., n.d.) of electricity. Other comments claim that the percentage of power output increment reached using the tracking solar panel was 66,9% (Mahendran, et al., n.d.) higher than the results given by the fix installation. The study concludes by stating that tracking installations are much more efficient than steady ones and that this fact would reduce the payback time of the installation, which would make it a better option to invest the money in.

The second study was carried out in Bangladesh by BRAC University and obtained similar results of power output. However, the difference is that this study made also a comparison between dual and single axis solar trackers with respect to the fix installation. It concluded that the dual axis solar tracker was the one giving more efficiency, by incrementing the value of the steady panel by more than 27% (Chowdhury, et al., 2017) and the tracking system with a single axis increased also the efficiency but only by 23% (Chowdhury, et al., 2017), so the conclusion there was that a lot of times is not only worth it to install a solar tracking installation but to do it by fully following the sun in the two directions.

The last study was made in a region of Jordan and it consisted of the comparison in the performance of a dual axis solar panel and a steady panel tilted at 32 degrees facing the South. The results obtained here lead us to the final conclusion that the solar trackers are capable of getting much more electricity from the sun than the fix installations as the results here gave an increment of 41,3% (Abdallah & Nijmeh, 2003) in efficiency for the solar tracker.

After having seen all these results, there is a clear tendency of improvement when the panels are tracking the sun. Exact values will fluctuate depending on the location of the panel but using solar trackers will always improve both power output and efficiency of the installation.

3 Methodology

In the next section of the thesis, the practical part of it will be developed as it goes through the planning and development of the installations, as well as all the important schemes and data that the reader needs to understand the working process of the system itself. The section will result in the obtention of the results, which will lead to the discussion process and the actual comparison between the data from both the fix and the sun tracking solar panel.

3.1 Materials used

The best way to start planning all the installations is to have in mind all the material and different devices that will be used, what they are and how they are actually implemented in the system. In order to do a table has been created containing all the relevant information about materials used in both fix and sun tracking installations. Find attached this table in Appendix 1.

Both installations have some common material as the idea of the comparison was to have the minimum differences between the installations, so the results showed us only the difference made by the solar tracking system and the losses in efficiencies of inverters, solar panels and energy meters were the same for both cases.

The microinverters have been chosen for its high efficiency which reaches up to 95,6% (Envertech, n.d.), this means that almost all the electricity generated for the panels will be transmitted to the energy meters and so the electrical grid.

Energy meters will collect a lot of information including power and energy output and the program will store it in Excel documents in order to have a complete overview of all the important data at the end of every day of operation.

3.2 Modbus devices and specifications

In the beginning, the intention was to use one single Modbus device for the whole system. All slaves were going to be connected to this one. In order to make it work, all Modbus parameters except slave address were set the same for all the devices. The configuration selected was the next one:

- Baud rate: 9600
- Parity: none
- Stop bits: 1

Analog input module and energy meter already had this configuration. Digital I/O module and Pyranometer had different configurations, so they had to be changed. However, in the end, one single Modbus device was causing lag troubles in the communication between LabVIEW and the system, and the solution for this was to use one Modbus device for each slave (4 in total). Still, baud rate, parity and stop bits will remain 9600, none and 1 for all the devices, as Table 1 shows.

Table 1: Specifications of devices using Modbus

MODBUS DEVICE SPECIFICATIONS								
DEVICE	DEFAULT				SELECTED			
	MODBUS ADDRESS	BAUD RATE	PARITY	STOP BITS	MODBUS ADDRESS	BAUD RATE	PARITY	STOP BITS
AMPERO SDM 8I8O	1	19200	None	1	2	9600	None	1
MAX-MR-AI-1	90	9600	None	1	90	9600	None	1
HUKSEFLUX SR05-D1A3	1	19200	Even	1	1	9600	None	1
CARLO GAVAZZI EM 111	41	9600	None	1	41	9600	None	1

3.3 Electrical connections of the devices

The solar panel will be connected to 5 different devices (pyrometer, vertical & horizontal rotation motors, limit switches and Victron Blue Solar MPPT device). This last one's function is to store the energy, so it is directly connected to the batteries. The pyrometer is directly connected to the computer through Modbus. The rest of the devices are connected to Modbus through the digital and analogue I/O modules. The LabVIEW program will be receiving information from the pyrometer, the switches and the angle sensors continuously. It will also be calculating the position of the sun every time, processing the information received and providing the necessary output voltage to the motors, in order to adjust them to follow the sun correctly.

Figure 10 shows a basic diagram of the connections between the solar panel, the devices and the computer. Find it bigger in Appendix 2.

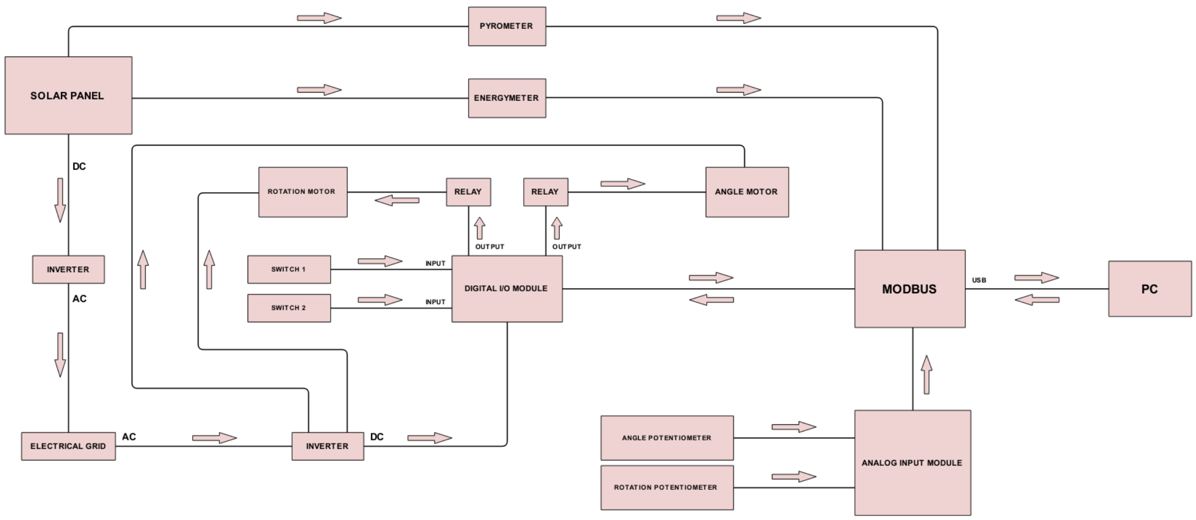

Figure 10: System connections diagram

Once the idea is clear it is time to give a more realistic view of the electrical connections of the system so Figure 11 is a graphical representation of how the electrical box should look when all the connections are made.

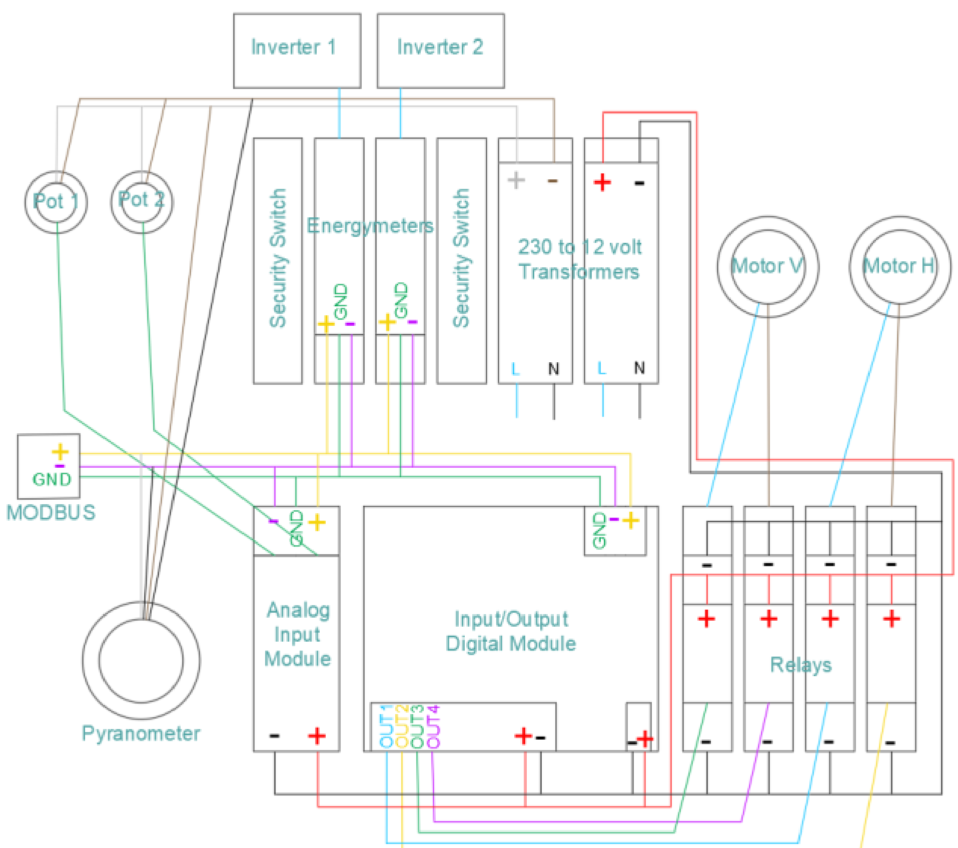

Figure 11: Electrical Scheme

Security switches are installed to avoid major overcharging issues due to the necessity of working with a maximum voltage of 230 volts. One is for the grid line that feeds the power for the electronic devices and the other one will disable the power output from the inverters if there is any problem in order to avoid major damage to the solar panels. In Figure 11 both L and N are referred to the line and neutral cable of the 230-volt grid.

3.4 QModmaster and Labview Tests

The first step when starting to build and program the system was to test the first devices. Testing a digital input/output module was the starting point. It was an "F&F" device, concretely the Max-MR-DIO-1. First, QmodMaster tests were done in order to check how the device was working and how the programming had to be done. This first device was found to not be operating as desired. It was not giving enough current to run the motors, so it had to be changed. After that, another digital input/output module was tested. This one was working well, but it had not enough outputs. In the end, Ampero SDM 8I8O was the one communicating as looked-for.

The digital input/output module was the first device tested and ready to program. When that was done, more devices were added to this initial one in order to start building the complete system. Relays were connected to the Ampero module in order to make the motors run two ways. Also, the first version of the final LabVIEW program was built at this point.

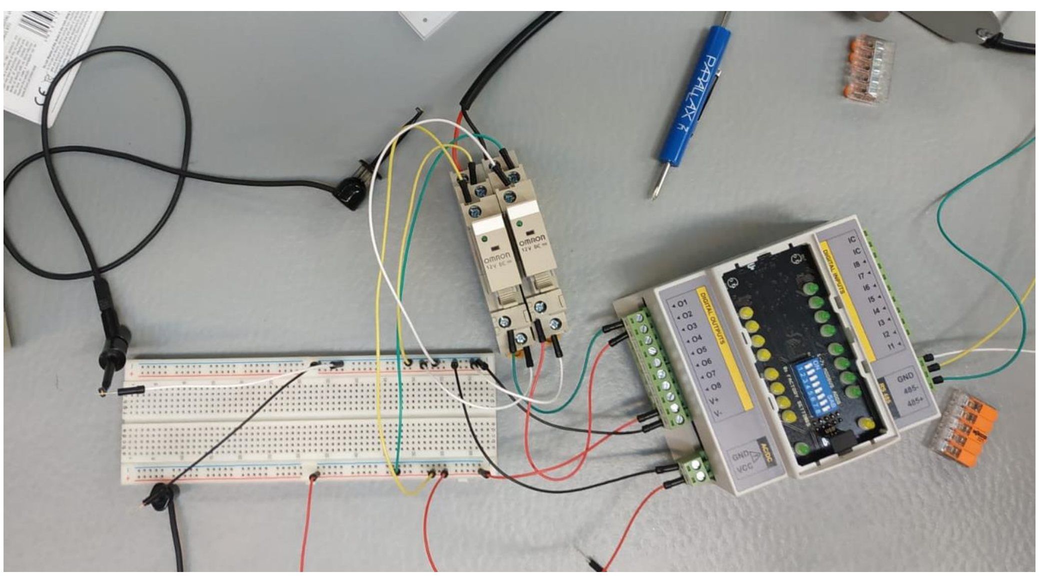

Figure 12: Firsts tests done with Ampero SDM device, the motors, the relays and Modbus

LabVIEW initial tests with Modbus and first devices looked like this:

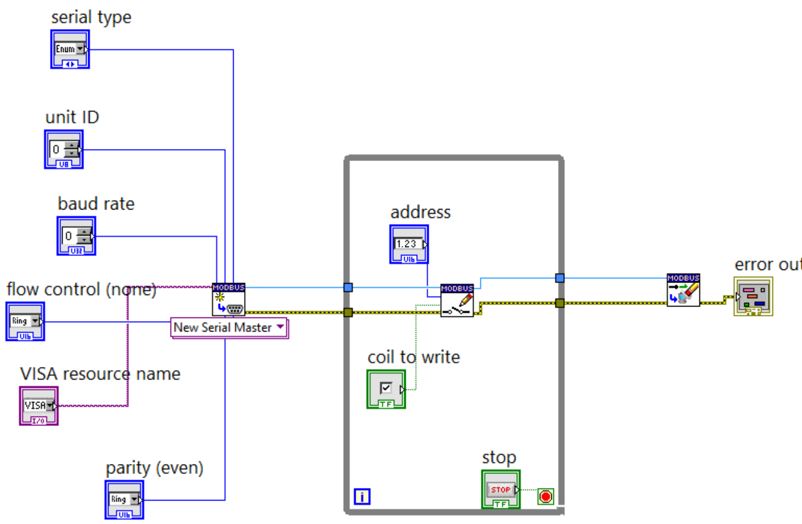

Figure 13: LabVIEW program designed for testing the Ampero SDM device

Figure 14 shows the first draft done in LabVIEW. This was used before testing any device in order to give an initial idea of how the system would work. It was simulating the sun vertical and horizontal position and also the panel position, and the digital signals received by the motors. The final program looks very different compared to this initial draft, but the main initial can still be seen there, in some particular parts of the program.

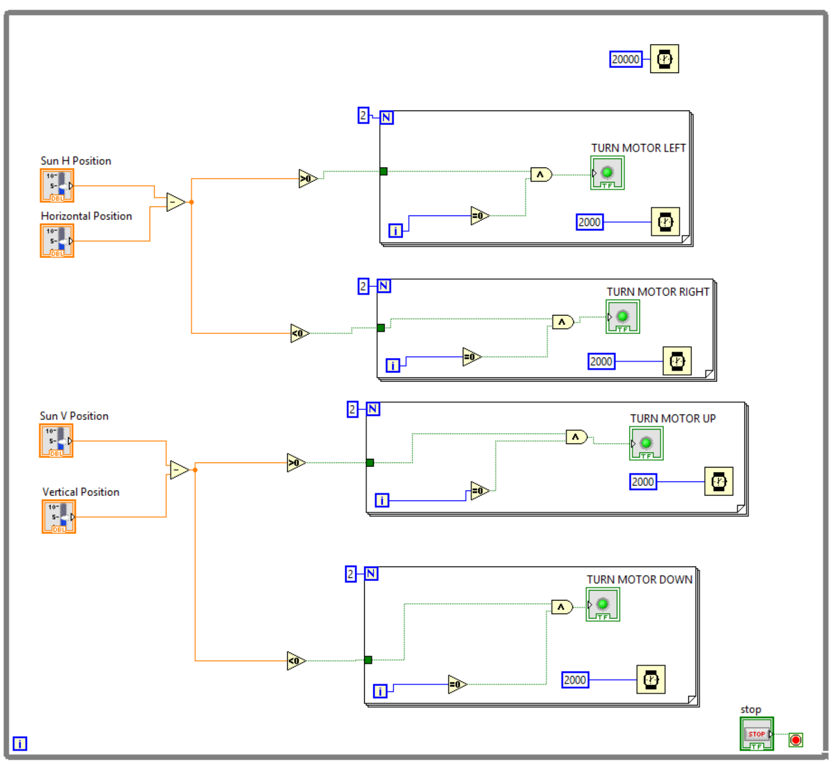

Figure 14: First LabVIEW draft

3.5 Excel data storage

The initial idea was to use MySQL data transmitting systems to create a series of tables that would automatically communicate with the database in NOVIA. However, the lack of time forced the project to reduce its ambition and acquiesce to the easiest way of storing a big amount of data and that was using Excel. The LabVIEW program would create the series of necessary programming in order to analyse all the data given by the energy meters and store it in two different tables in two different Excel files, one file for each installation. Tables in Excel will contain the data for the date and time of the measurement and all the technical data such as power and energy output, voltage and current generated by the solar panels and it will also combine with the information given by the pyranometer to calculate the theoretical amount of power that the panel should be obtaining and so the calculation of the efficiency. The idea of the program is to read the information and get feedback once every 10 minutes which it was decided to be enough time for the sun to move and still get a decent amount of data. The program will stop at the end of the day and then all the data will be reflected in excel files, which the user then can save and have a daily database of all parameters that are interesting for the development of the installation.

3.6 Labview program

In order to be able to communicate LabVIEW and Modbus devices, some special program is required in LabVIEW. This one is a program that sets the information required for each Modbus device (unit ID, parity, baud rate, etc.), writes/reads the information to the device and returns the error if there is any. Figure 15 shows an example of Modbus communication program with one device in LabVIEW.

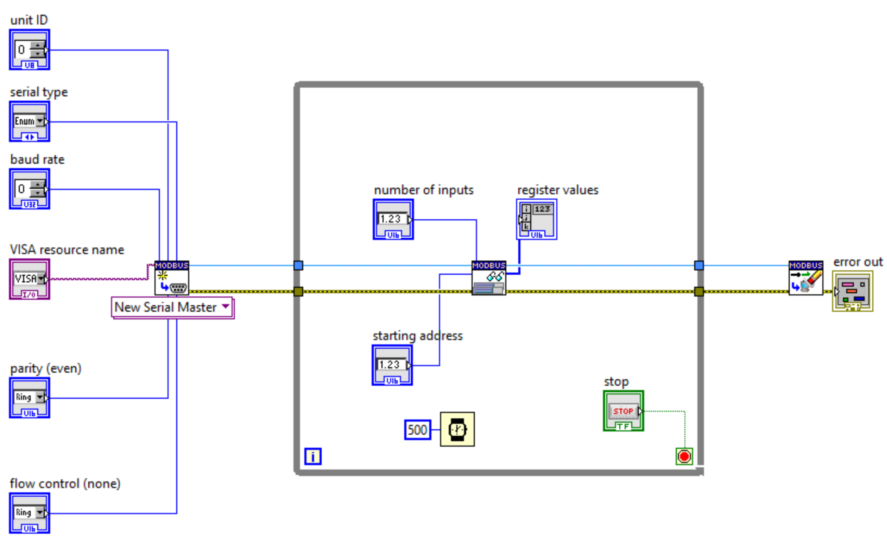

Figure 15: Example showing how a LabVIEW – Modbus communication is done

In the program illustrated in Figure 15, 3 parts can be distinct. First part is the one in the left of the figure. This is the one opening the communication and it is where the main Modbus settings are set in order to recognize the device being used. In the central part, there is a loop, that in this case, is reading the information of the device continuously. There, the number of inputs, register values and starting address can be adjusted, so that Modbus can read different inputs and different numbers of them starting at different addresses. Finally, the section closing the communication, which is the one at the right of the photo. This one is also giving the error out.

As already mentioned before, the figure is not showing the program being used for the solar panels, it is just an example. However, in the final version, this exact system is integrated into the whole main program.

The final LabVIEW program is formed by two sections:

- Calculation of the position of the sun.
- Data processing and panel programming part with Modbus communication.

Figure 16 shows a scheme of how the LabVIEW program is built.

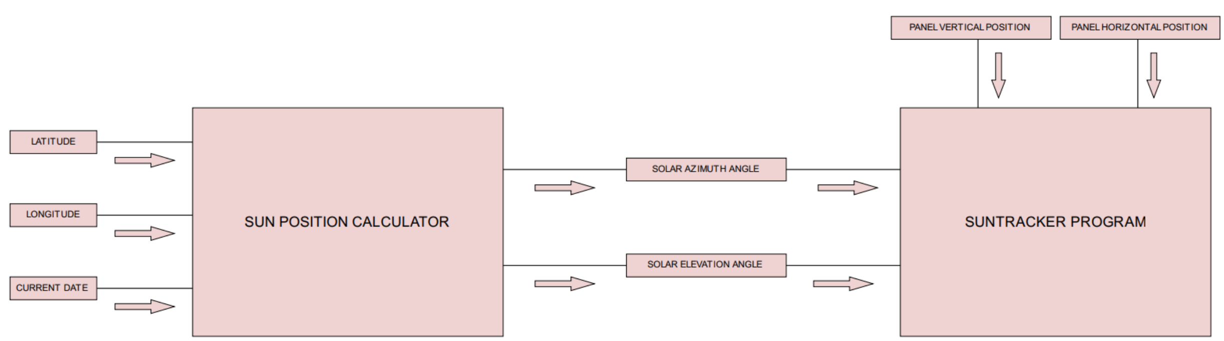

Figure 16: LabVIEW program scheme

The first part is based on some operations that are done in order to calculate the Solar Azimuth and Elevation angles, which are going to be used in order to adjust the position of the panels. Apart from these ones, the program calculates other outputs (for instance sunrise and sunset time, sun declination, solar noon, etc.) which are not used at all in the panel processing section of the program but are needed in order to calculate both Solar Elevation and Azimuth angles. As the last photo reflects, the program receives the latitude and longitude position and the current date as inputs. Latitude and longitude position are filled in manually and the date is acquired automatically by the program itself. Algorithm to calculate the position of the sun can be found in Appendix 3.

The second part of the program will receive information of both Elevation and Azimuth angle, but also from the current position of the panel. The main idea is that the program will be constantly comparing these in order to adjust the panel. The vertical angle will be compared with Solar Elevation angle and Azimuth Angle with horizontal Angle. The principle is that the panel will have the right position when Azimuth Angle is equal to the horizontal angle, and the same for Elevation and Vertical angle. Figure 17shows how the main LabVIEW program looks like. Find it bigger in Appendix 4.

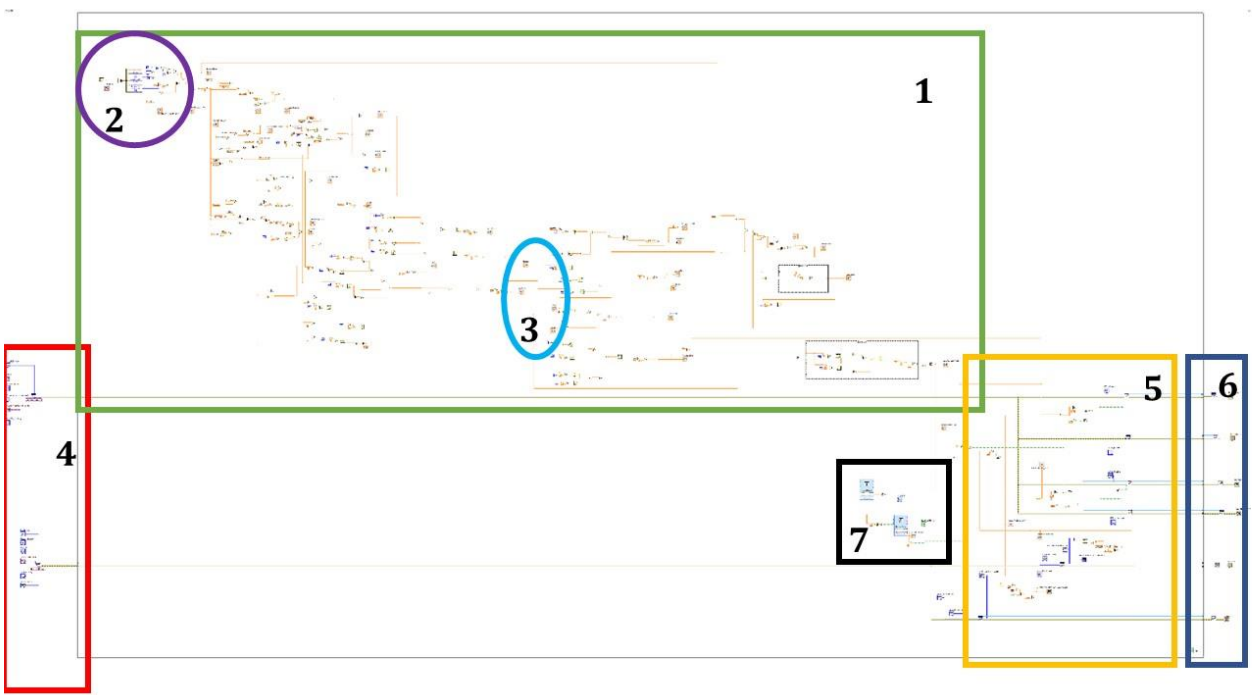

Figure 17: Main LabVIEW Program

The numbers in Figure 17 represent different sections of the program. These are explained next:

1) Whole sun position calculation program.
2) Current date input
3) Latitude and longitude input.
4) MODBUS opening connection.
5) Sun tracker program with MODBUS communication.
6) MODBUS closing connection.
7) Timer activating the panel motors when needed.

Figure 18 and Figure 19 show the inputs of the sun position calculation part of the program. The first one is showing the date input and second one Latitude and Longitude input.

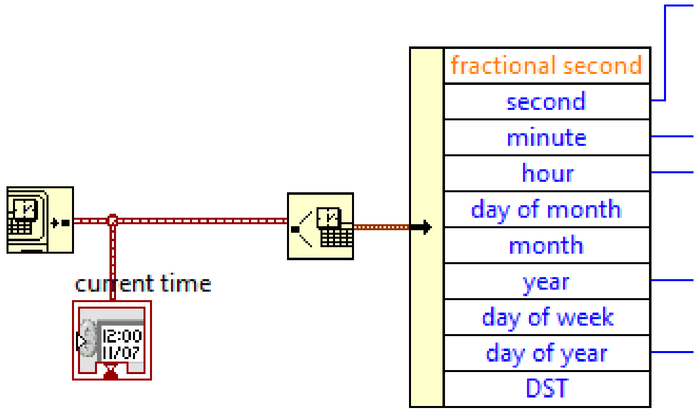

Figure 18: Current time acquisition

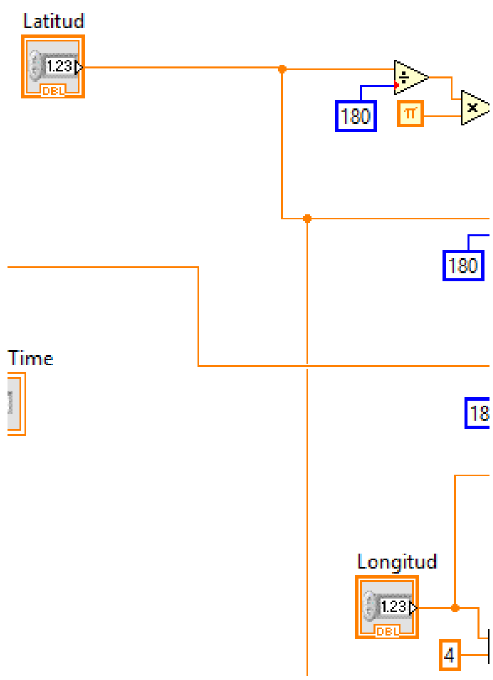

Figure 19: Latitude and Longitude input

2 Modbus devices are used in the tracking programming part and that is why two connection openers are created in the main program (one is used for the Analog Input device and the other one for the Digital I/O one).

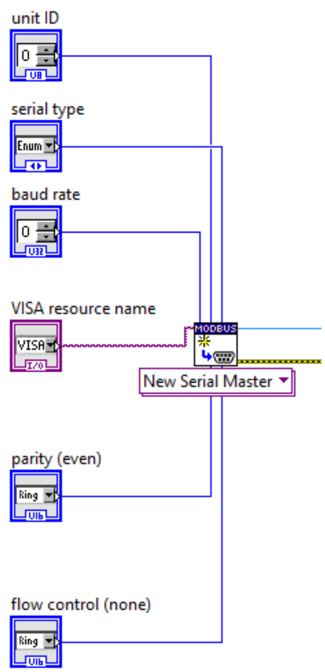

Figure 20: Modbus opening connection

The following figures are the ones belonging to the sun tracker part of the program. Current panel position is acquired through two potentiometers connected to Modbus via the analogic input module. Two Modbus addresses are used; one for the horizontal position value and another one for the vertical position value. Modbus reads through the analogic input module both signals. They are voltage signals, so they have to be converted to degrees, in order to be able to compare them with the solar angles. These conversions are the ones highlighted in yellow colour in the picture.

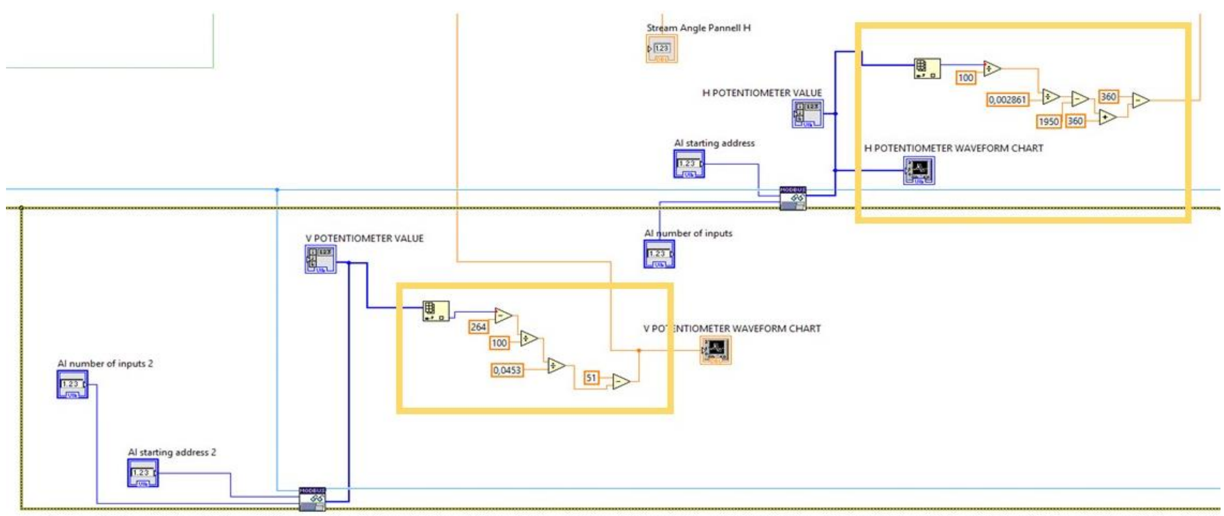

Figure 21: Sun tracking program (Part 1)

The data acquired is compared with the position of the sun in order to know if the panel has to move up, down, left or right in order to reach the desired position. It is not an exact adjustment. There is an offset of 2.5 degrees for the horizontal position and 1.5 degrees for the vertical one. (Vertical potentiometer is more accurate). It is done this way because there is no need to obtain high accuracy. Also, the panels will work more fluently by doing it this way.

When the day is over and the panel has reached the limit position, it will return to its initial position waiting for the sun to rise again and repeat the process. The program knows the limit position of the sun by measuring the vertical angle of the panel. When this one reaches 0 degrees, the program itself makes the panel return to the initial position.

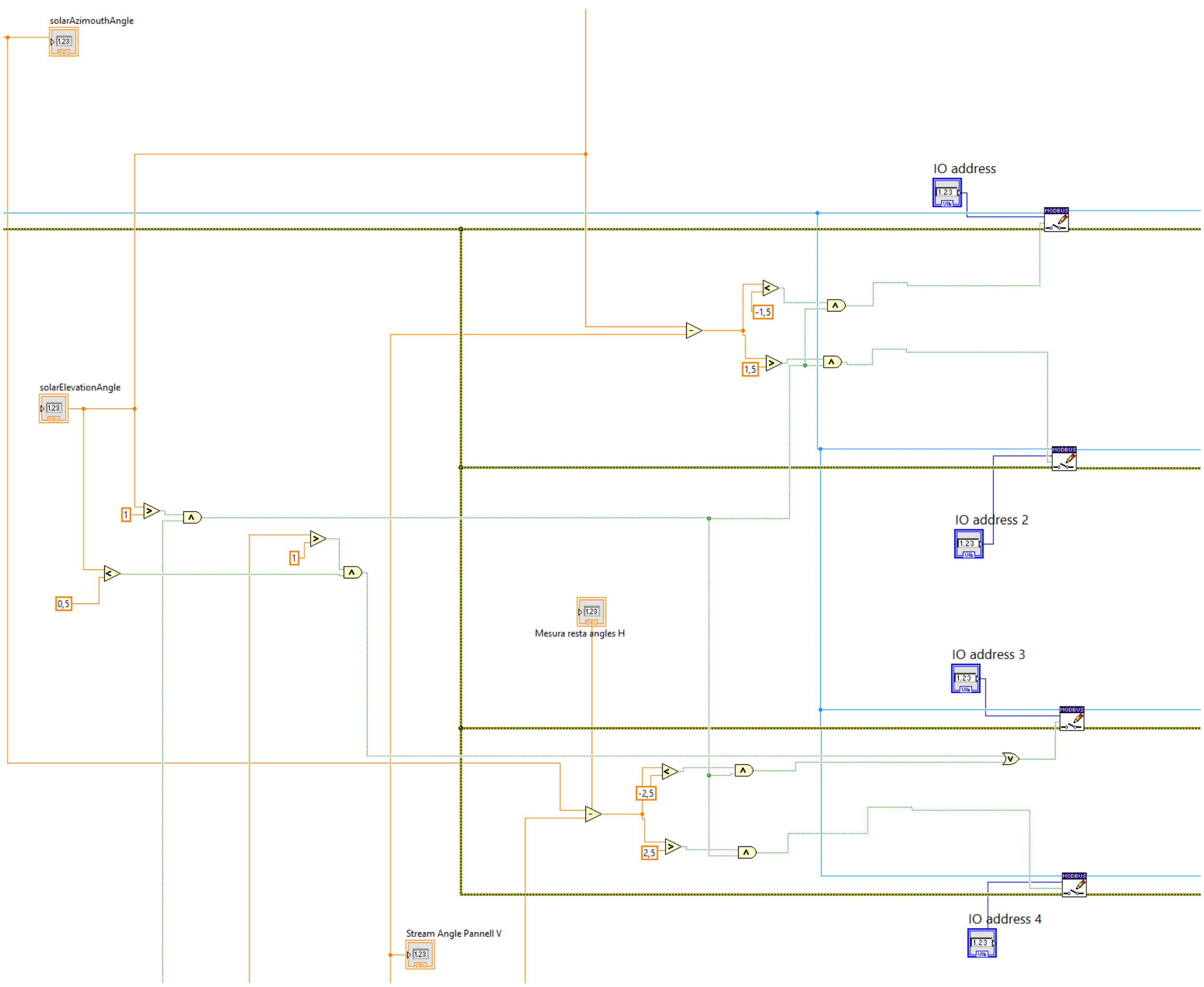

Figure 22: Sun tracking program (part 2)

Figure 23 Demonstrates how the connection between Modbus devices is closed. In the case that there is an error, it will show up in the front panel.

Figure 23: MODBUS closing communication

Panels will not be working continuously (it would not be the most efficient way of working). The program will check the sun position and correcting the position of the panel every 10 minutes. This is possible due to a sequence of timers. They send a high signal that will activate the rest of the program. This one lasts 15 seconds and it is sent every 10 minutes. This amount of time is enough to make the panels follow the sun properly. While the signal is low, the program won't do anything, and the panels will stay in "rest" mode. But when the signal is high, the sun tracking program will be activated, sun position is going to be checked and panels are going to be adjusted.

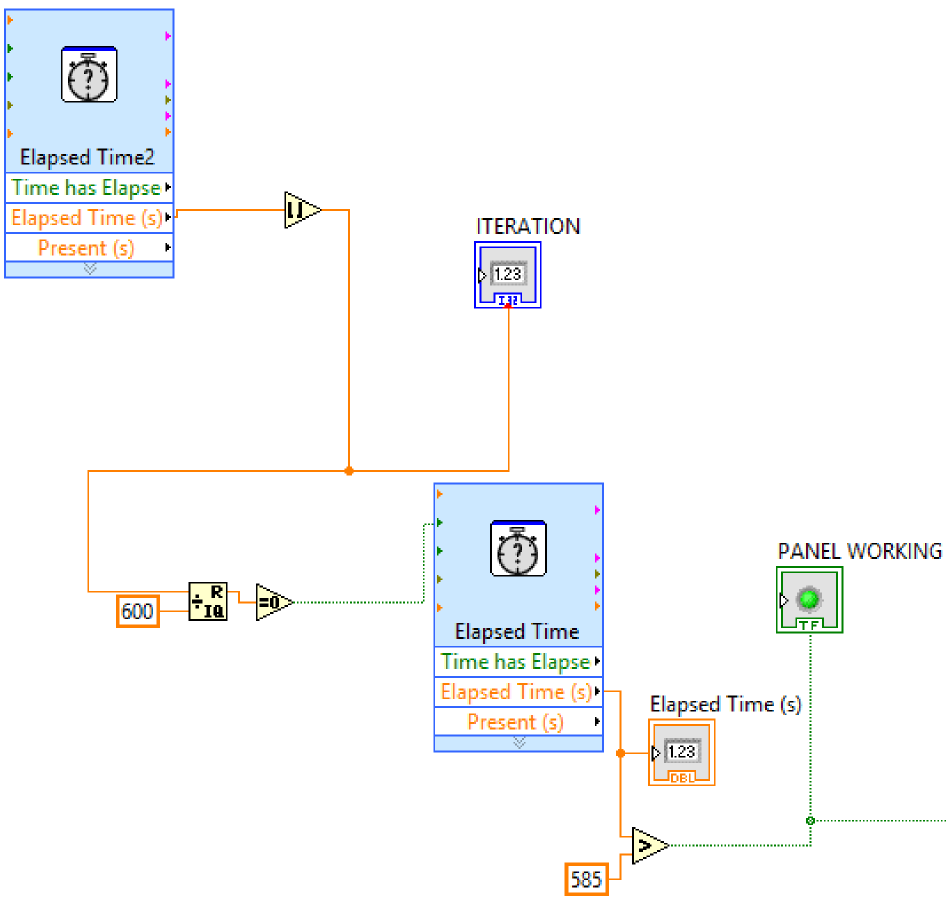

Figure 24: Timer sequence controlling the panels activation time

Figure 25 & Figure 26 illustrate how the front panel looks like for all the connections explained before.

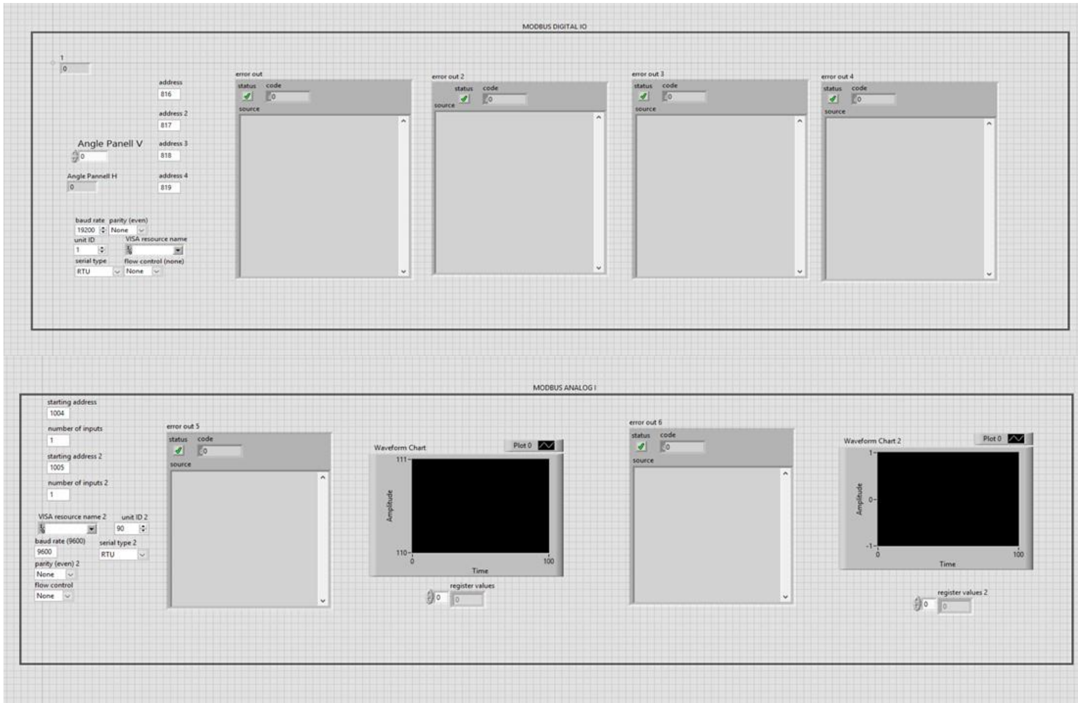

Figure 25: MODBUS communication in Front Panel

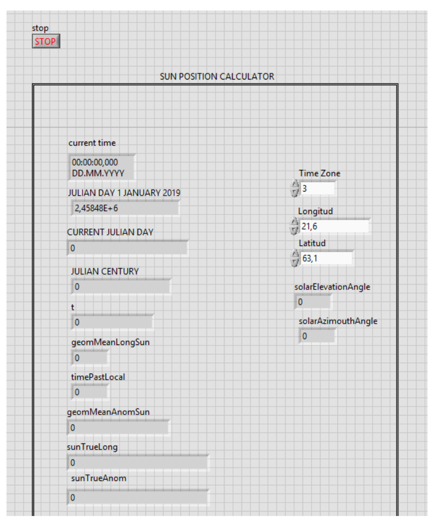

Figure 26: Sun position calculator results in the Front Panel

This was all the programming for the panel. Apart from that, there is also some more programming done in order to take the measurements. An energy-meter and a pyranometer are used for the measurements (both connected to the PC through Modbus). LabVIEW task here is to read the measurements taken by the devices and store them into an EXCEL file as it has been explained in the section before. Full program to read and write the data is located in Appendix 5.

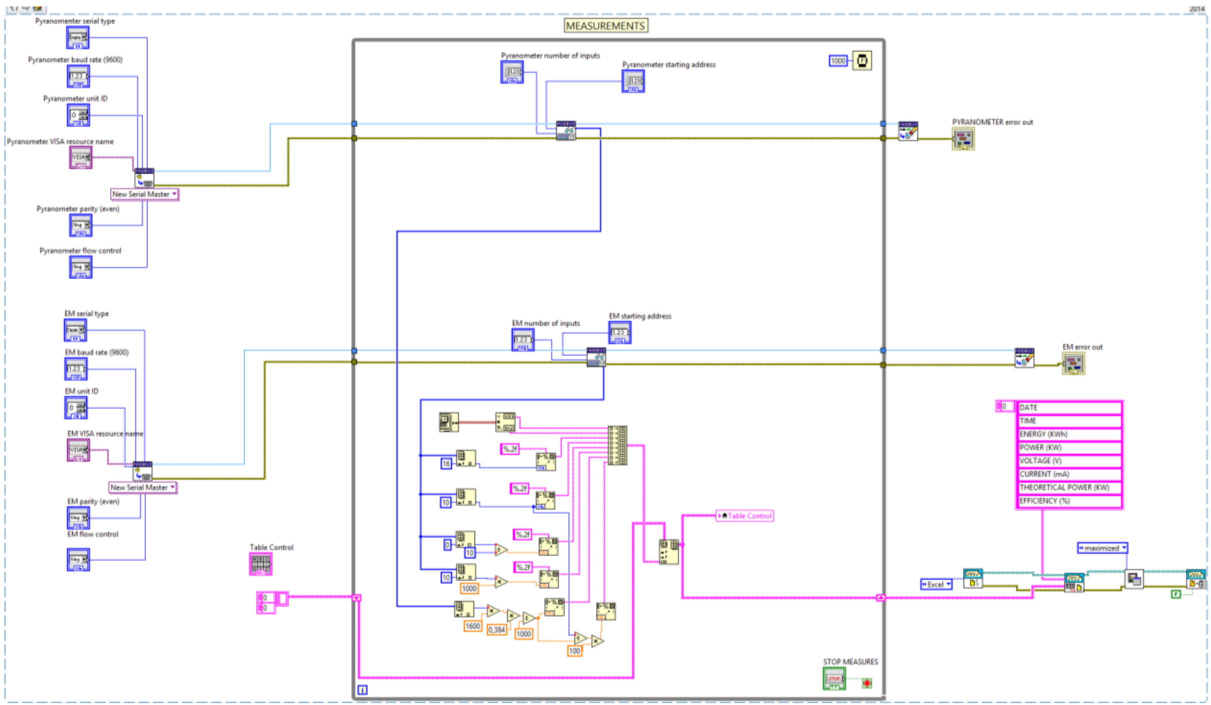

Figure 27: Pyranometer and energy meter measurement acquisition program

3.7 Testing with artificial and real data

Once the structure of the panels was built and all the connections in the electrical box were made it was time to start testing the full device and start getting some data from the energy meters so all the necessary corrections could have been made. All this data could not be collected, and all the testing was a complete failure due to the lack of time and the quality of some of the devices used which stopped working right after the connection of everything together.

The initial intention of the project was to have the panels working for a whole day in some sunny place near the laboratory and once the device would work as desired, the idea was to place the installation on the roof of the building of NOVIA so the panels could have a fully functioning cycle of all day and could generate data to be stored and studied at a student, non-professional, level.

3.8 Results

Right before taking the measurements, the Analog Input device stopped working. While doing some final tests, the panel position measurements obtained by that device started to have some weird fluctuations in the computer. After testing the connections, the potentiometers and the program, the device was tested separately from the rest of the system and it was found to be damaged in some internal way that would result in the lack of transmission in some of the inputs needed. The solution to this problem would have been to replace the device for a new one, but the amount of time that it would have needed to arrive in Vaasa made it impossible for the correct installation and testing timeframes. Because of this, the panel could not follow the sun as desired, and the comparison part of the project was at the end impossible to be done in a practical way.

However, the program was ready to take measurements of both steady and tracking panels. Also, it was reading the radiation with a pyranometer in order to calculate and compare the efficiency of both panels. The results for building and programming the system went as good as expected. At the end of the project, a tracking solar panel was built and programmed successfully as, tested in the computer screen, the LabVIEW program worked perfectly well and gave all the measurements in the Excel files.

Figure 28 and Figure 29 demonstrate the final structure of both static and tracking solar panels with their respective electrical box with all the devices and the connections.

Figure 28: Panel's final structure

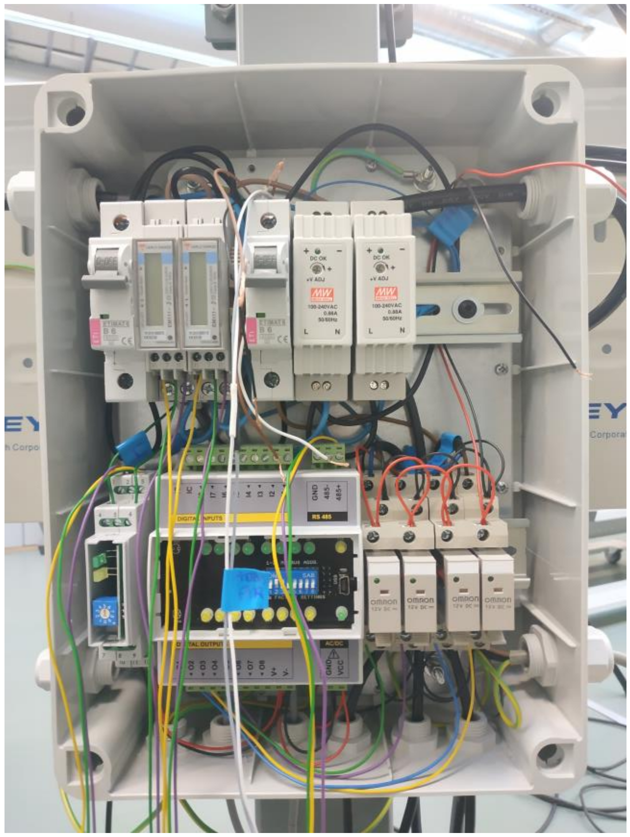

Figure 29: Connections inside the electrical box

In Figure 28, both tracking and steady solar panels can be seen. The one on the top is the tracking system and the one below is the steady one. Also, the pyranometer is placed on the top of the structure to get values of the solar radiation for the calculation of efficiency.

Figure 29 exhibits the connections inside the electrical box. This one is placed below the tracking solar panel and behind the steady one. All connections were made following the electrical schemes presented earlier in this document.

4 Discussion

With respect to the original thesis aim and objectives:

In completing the assembly and installation of both fixed and tracking solar panels, together with ancillary equipment, the first object was successfully met. Furthermore, the second objective, of developing a fully functional control measurement interface using Modbus and LabVIEW was also, in theory, successfully met.

With respect to the limitations of the work, there have been a number of challenges with the biggest issues found during the realization of this project have been time delays in several fields. The building and programming of the system took a lot more time than the one initially expected as the program for obtaining a good position of the sun was very big and slow. Also, in the beginning, when testing the first devices there were some issues related to the devices and communication due to the lack of experience and the quality of some of them. Digital Output Module was responding to the commands given by the computer but was not giving enough current in order to make the motors run so it had to be changed several times until the correct one was found. This whole process made the project to be stuck a lot of time and was one of the main reasons why in the end the full comparison and the final objective could not be completed. As mentioned in the previous section, the Analogic Input Module device stopped working right before starting to take measurements that were planned to be taken before the authors left the country. If there had been fewer delays in between the project, maybe there would have been time for the issued device to be replaced.

According to some post by Energy Central, there is no general rule to evaluate the technical and economic efficiency of a solar tracker, because its effectiveness can vary from place to place and from time to time. Thus, there is also no general rule to compare the efficiency of solar trackers with steady solar panels. However, studies have demonstrated that solar trackers can be 20-60% more efficient, depending on the zone of the world. (White, 2015). As a case study, the example of DEGER has been taken. DEGER is a German company that develops tracking solar systems. Their systems can be 45% more efficient than steady panels, according to their webpage (Deger, 2019).

Going back to the main theme of the thesis, it is clear that according to the text in the previous paragraphs, and according to the knowledge gained and the data from external sources, tracking solar installations are much better than steady ones and the increase of power output makes it worth due to the direct affectation in the reduction of payback times. Values of the electricity generated for tracking installations are much less fluctuant than for fixed solar panels. In the middle of the day the output of both is almost the same but in the initial and final phase of the day is where a big difference is produced and where tracking solar systems prove its worthiness by increasing the values of power output and efficiency in very interesting values that, in the end, reduce the idea of a very big initial investment and make this kind of installations to be the future mostly in counties where sun is not very abundant.

With respect to inconsistencies.

The project had both consistent and inconsistent points. The inconsistency was product of the lack of experience in some of the technologies being used. Designing and building a whole system from scratch and using Modbus and other new technologies for the first time were really slowing the project at the very beginning. At the same time, these challenges started becoming consistent points in the aspect that a lot of knowledge was being acquired while leading the difficulties.

With respect to the consistencies.

As this was a project directly related to the engineering field, problems could be solved more easily thanks to the knowledge already acquired in previous engineering courses and internships. Programming skills, logical and electronic knowledge were the main three aspects applied during the project, and where the ones that helped more in developing it. Another consistent point was the help received by Hans knowledge in electronics and Modbus, it helped when struggling with the issues.

5 Conclusion

In relation to the first objective of the project, which was to develop a fully functioning sun tracking solar panel giving feedback and real-time measurements, a LabVIEW program has been created, together with a tracking solar panel structure. As mentioned before, the program has the capability of predicting the position of the sun, reading the position of the panel and adjust it every time to make it equal. It is also able to read the energy given by both panels and compare them in a series of tables generated in an Excel file. Therefore, it can be said that the first objective has been achieved as partially successful due to the fact that it has been so close to success.

The lack of results in this project makes it impossible to extract conclusions about the other two objectives, relating to the relative efficiencies of both installations and differences in Finnish and Spanish scenarios. However, all the data presented throughout the project leads to the conclusion that tracking solar systems are, in the end, much more efficient and worth it for countries in higher latitudes due to the capability of extracting a lot of energy during the initial and final phase of the day. On the other hand, when comparing with different locations, some results in this projects panel would have given an idea of what could actually be extracted from a panel in Finland so a better comparison with panels in Spain would have been easier. Southern European countries have abundant and powerful sun all day, so personal thoughts are that fix solar installations can be paid back in a decent amount of time due to the bigger electricity generation and that there is no need for an investment in solar trackers, at least, at a level of actuation containing personal installations. However, in Finland, the lack of sun during the long winter makes the solar tracker a good investment in order to maximize the output during the summer and reduce its payback time.

The whole project was useful for bringing to practical work the theoretical knowledge acquired not only during the stay in Finland but also during the whole bachelor back in Spain. Modbus knowledge was acquired, and the knowledge already got in LabVIEW was expanded. Working in pairs and being able to combine two different student profiles, mechanical and electrical engineering, was a really profitable way of working.

During this project, the Modbus communication protocol was learned in order to be able to communicate with the devices. Devices were tried and tested in order to know how to connect them and make them work. LabVIEW programming was learnt and a whole sun tracking program was built in order to control the system. Also, the panel was mounted, and all the cables were connected correctly inside the electrical box. All this work was really interesting as "Junior Engineers". General thoughts are that this project could be a good start of our professional career.

The lack of experience in the kind of technologies used during the project made the task much more difficult but, overall, Modbus was found as a good and fast protocol of communication. Nevertheless, trying to connect the whole system using just one single Modbus device, was slowing down the process considerately, probably because of some issues with the program in LabVIEW.

Some conclusions lead to the thought that maybe using another system, for instance, PLC or Raspberry connections for the communication would have been a better idea, but Modbus did a decent job on that. On the other hand, LabVIEW is a really useful tool and quite easy to learn, use and understand. However, when programming more complex things, the user gets across some difficulties. Sometimes, using LabVIEW when trying to program some non-basic things would become complex while writing the exact code in some writing programming language, such as C, Java or Matlab, would have taken just a few code lines.

Overall it was a fun and challenging project to develop and a big well of experience and knowledge for both the authors and the university in order to improve the performance in the following similar projects.

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[Accessed 28 05 2019].

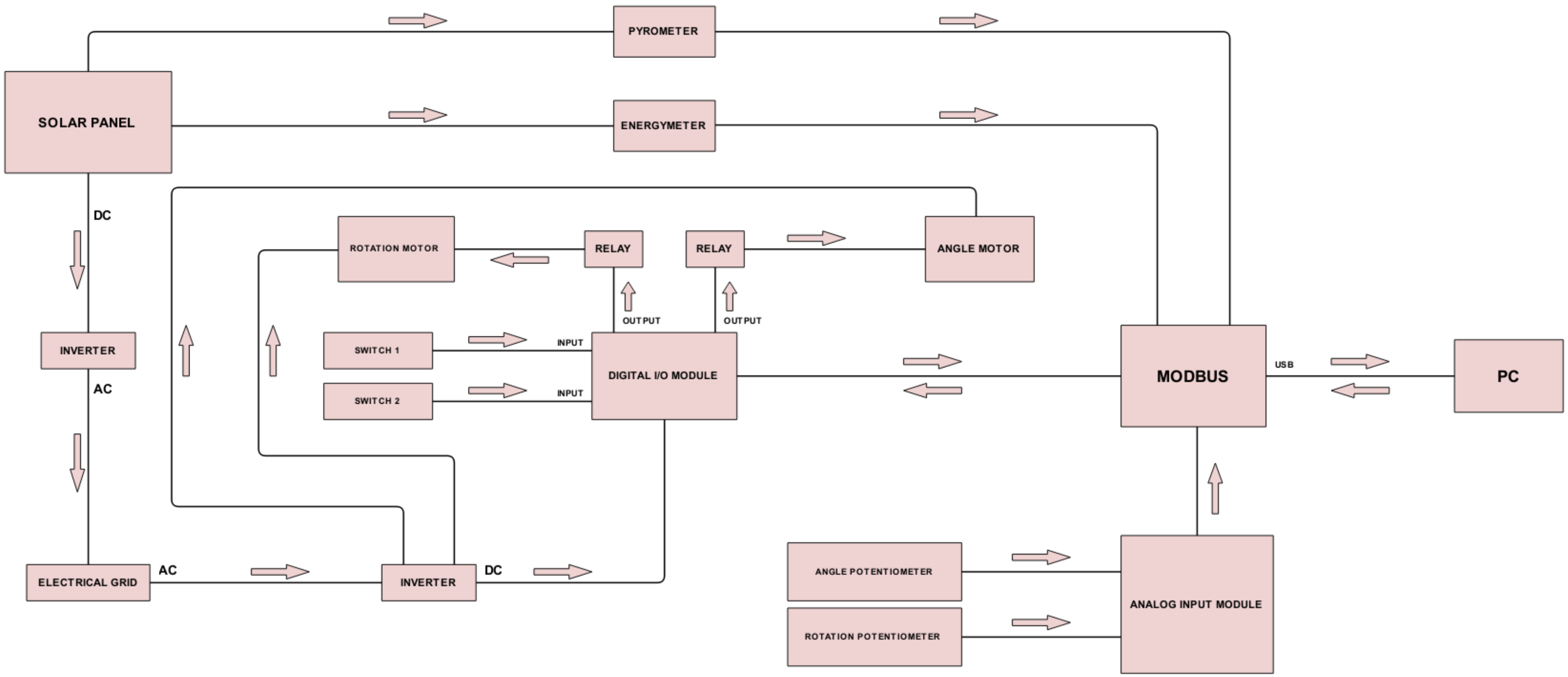
APPENDIX 1: Table of Material

NAME	MANUFACTURER	REFERENCE	DESCRIPTION	PRICE	URL	IMAGE
SOLAR PANEL	MW Green Power	MWG-30	Solar panel designed for the use in personal installations. Capable of working in either high or average powered systems. Dimensions: 545 x 515 mm	40 €	https://fotoogniwa-sklep.pl/pl/p/Panel-fotowoltaiczny-MW-Green-Power-MWG-30W/531	
INVERTER	ENVERTECH	EVT500	Microinverter designed to generate electricity from two solar panels and deliver it directly to the grid through a wall socket.	203 €	https://foest.eu/index.php?main_page=product_info&products_id=348&language=en	
ROTATION MOTOR	YXS Technology	GW31CT	Miniature DC Worm Gear Motor reversible, variable and self-lock, widely used in small and lightweight applications.	56 €	https://spanish.alibaba.com/product-detail/gw31ct-motor-6v-12v-24v-dual-output-shaft-torque-worm-24-v-dc-geared-motor-60342944101.html	

INCLINATION MOTOR	DC HOUSE	L11TGF12V 250-T-1	Stroke linear actuator with sensitive action stable running, the same characteristics of push and pull ideal in these situations.	51 €	https://www.aliexpress.com/item/250mm-stroke-12V-DC-electric-linear-actuator-solar-tracker-1500N-150KG-load-5-7mm-sec-for/32233411617.html	
DIGITAL OUTPUT MODULE	AMPERO	SDM-8I8O	Electronic device that provides an extension of input and output lines in popular PLC.	119 €	http://www.ampero.eu/en/standard-series/26-sdm-8i8o.html	
ANALOG INPUT MODULE	F&F	MR-AI-1	Electronic device with four analogic inputs measuring continuously values of both voltage and current.	53 €	https://www.tme.eu/es/details/mr-ai-1/redes-industriales/f-f/	
TRANSFORMER	MW Mean Well	DR-15	AC to DC voltage transformer that permits the conversion of the 230 volts from the grid to 12 volts DC.	16 €	https://www.mouser.es/ProductDetail/MEAN-WELL/DR-15-24?qs=StI9JdmCm6v0Oj0rDt83uQ%3D%3D	

RELAY	OMRON	G2R-2SNI	Electromagnetic relay which diverts the current to two different outputs depending on its state.	7 €	https://www.tme.eu/es/details/g2r-2-sni-12dc/reles-electromagn-miniaturizados/omron/g2r-2-sni-12vdc-s/	
ENERGYMETER	CARLO GAVAZZI	EM-111	Monophasic energy meter with integrated LCD tactile screen capable of reading other values such as power, voltage and current.	87 €	https://es.farnell.com/carlo-gavazzi/em111dinav81xs1x/contador-energ-a-digital-1-fase/dp/2672854	
POTENCIOMETER	BOURNS	3852A	Rotary potentiometer with no angle limit.	9 €	https://www.reichelt.com/de/en/rotary-potentiometer-100-ohm-linear-6-35-mm-bou-3852a282101a-p232541.html	

APPENDIX 2: System Connections Diagram



APPENDIX 3: Sun Position Calculation Program (JavaScript Version)

```
// Location on earth:
var lat=62.429498;
var lon=21.418333;

// Functions
function toRadians (angle) {
  return angle * (Math.PI / 180);
}

function toDegrees (angle) {
  return angle * (180 / Math.PI);
}

function sinD(angle){
  return Math.sin(angle/180*Math.PI);
}

function cosD(angle){
  return Math.cos(angle/180*Math.PI);
}

function tanD(angle){
  return Math.tan(angle/180*Math.PI);
}

// Time and date
var dt = new Date();
var timeZone=-dt.getTimezoneOffset()/60;
var timePastLocal=(dt.getHours() + (dt.getMinutes()+dt.getSeconds()/60)/60)/24;

// Julian day
julianDate=dt.getTime()/1000/3600/24+2440587.50;
var julianCentury=(julianDate-2451545)/36525;

var t=280.46646+julianCentury*(36000.76983 + julianCentury*0.0003032);
var geomMeanLongSun=(t/360-Math.trunc(t/360))*360;
var geomMeanAnomSun=357.52911+julianCentury*(35999.05029 -
0.0001537*julianCentury);
var eccentEarthOrbit=0.016708634-
julianCentury*(0.000042037+0.0000001267*julianCentury);

var sunEqOfCtr=sinD(geomMeanAnomSun)*(1.914602-
julianCentury*(0.004817+0.000014*julianCentury))+sinD(2*geomMeanAnomSun)*(0.01
9993-0.000101*julianCentury)+sinD(3*geomMeanAnomSun)*0.000289;
var sunTrueLong=geomMeanLongSun+sunEqOfCtr;
var sunTrueAnom=geomMeanAnomSun+sunEqOfCtr;
var sunRadVector=(1.000001018*(1-
eccentEarthOrbit*eccentEarthOrbit))/(1+eccentEarthOrbit*cosD(sunTrueAnom));

var sunAppLong=sunTrueLong-0.00569-0.00478*sinD(125.04-1934.136*julianCentury);
```

```
var meanObliqEcliptic=23+(26+((21.448-julianCentury*(46.815+julianCentury*(0.00059-
julianCentury*0.001813))))/60)/60;

var oblicCorr=meanObliqEcliptic+0.00256*cosD(125.04-1934.136*julianCentury);
var sunRtAscent=toDegrees(Math.atan(cosD(oblicCorr)*sinD(sunAppLong) /
cosD(sunAppLong)));

var sunDeclin=toDegrees(Math.asin(sinD(oblicCorr)*sinD(sunAppLong)));
var varY=tanD(oblicCorr/2)*tanD(oblicCorr/2);

var eqOfTime=4*toDegrees(varY*sinD(2*geomMeanLongSun)-
2*eccentEarthOrbit*sinD(geomMeanAnomSun)+4*eccentEarthOrbit*varY*sinD(geomMea
nAnomSun)*cosD(2*geomMeanLongSun)-0.5*varY*varY*sinD(4*geomMeanLongSun)-
1.25*eccentEarthOrbit*eccentEarthOrbit*sinD(2*geomMeanAnomSun));
var HAsunrise=toDegrees(Math.acos(cosD(90.833)/(cosD(lat)*cosD(sunDeclin))-
tanD(lat)*tanD(sunDeclin)));
var solarNoon=(720-4*lon-eqOfTime+timeZone*60)/1440;
var sunriseTime=solarNoon-HAsunrise*4/1440;    // 0-1   motsvarar tid 0-24
var sunsetTime=solarNoon+HAsunrise*4/1440;     // 0-1   motsvarar tid 0-24

var sunlightDuration=8*HAsunrise;              // minuter
var t=timePastLocal*1440+eqOfTime+4*lon-60*timeZone+1440;
var trueSolarTime=(t/1440-Math.trunc(t/1440))*1440;    // minuter

var hourAngle=(trueSolarTime/4<0?trueSolarTime/4+180:trueSolarTime/4-180);
var
solarZenithHour=toDegrees(Math.acos(sinD(lat)*sinD(sunDeclin)+cosD(lat)*cosD(sunDec
lin)*cosD(hourAngle)));
var solarElevationAngle=90-solarZenithHour;

var approxAtmosphericRefraction=
  (solarElevationAngle>85?0
   :(solarElevationAngle>5
    ?58.1/tanD(solarElevationAngle)-
0.07/Math.pow(tanD(solarElevationAngle),3)+0.000086/Math.pow(tanD(solarElevationA
ngle),5)
    :(solarElevationAngle>-0.575
      ?1735+solarElevationAngle*(-
518.2+solarElevationAngle*(103.4+solarElevationAngle*(-
12.79+solarElevationAngle*0.711)))
      :-20.772/tanD(solarElevationAngle))))/3600;

var solarElevationCorrected=solarElevationAngle+approxAtmosphericRefraction;

solarAzimuthAngle=(hourAngle>0
  ?(toDegrees(Math.acos(((sinD(lat)*cosD(solarZenithHour))-
sinD(sunDeclin))/(cosD(lat)*sinD(solarZenithHour))))+180)%360
  : (540-toDegrees(Math.acos(((sinD(lat)*cosD(solarZenithHour))-
sinD(sunDeclin))/(cosD(lat)*sinD(solarZenithHour)))))%360);

----------------------------------------------------------------------
```

Altitude of the sun in degrees is now stored in (angle from horizon, 0 is at horizon, 90 at zenith):

```
solarElevationCorrected;
```

Azimuth of the sun in degrees is now stored in (angle from north, 0 is north, 90 east, 180 south, 270 west):

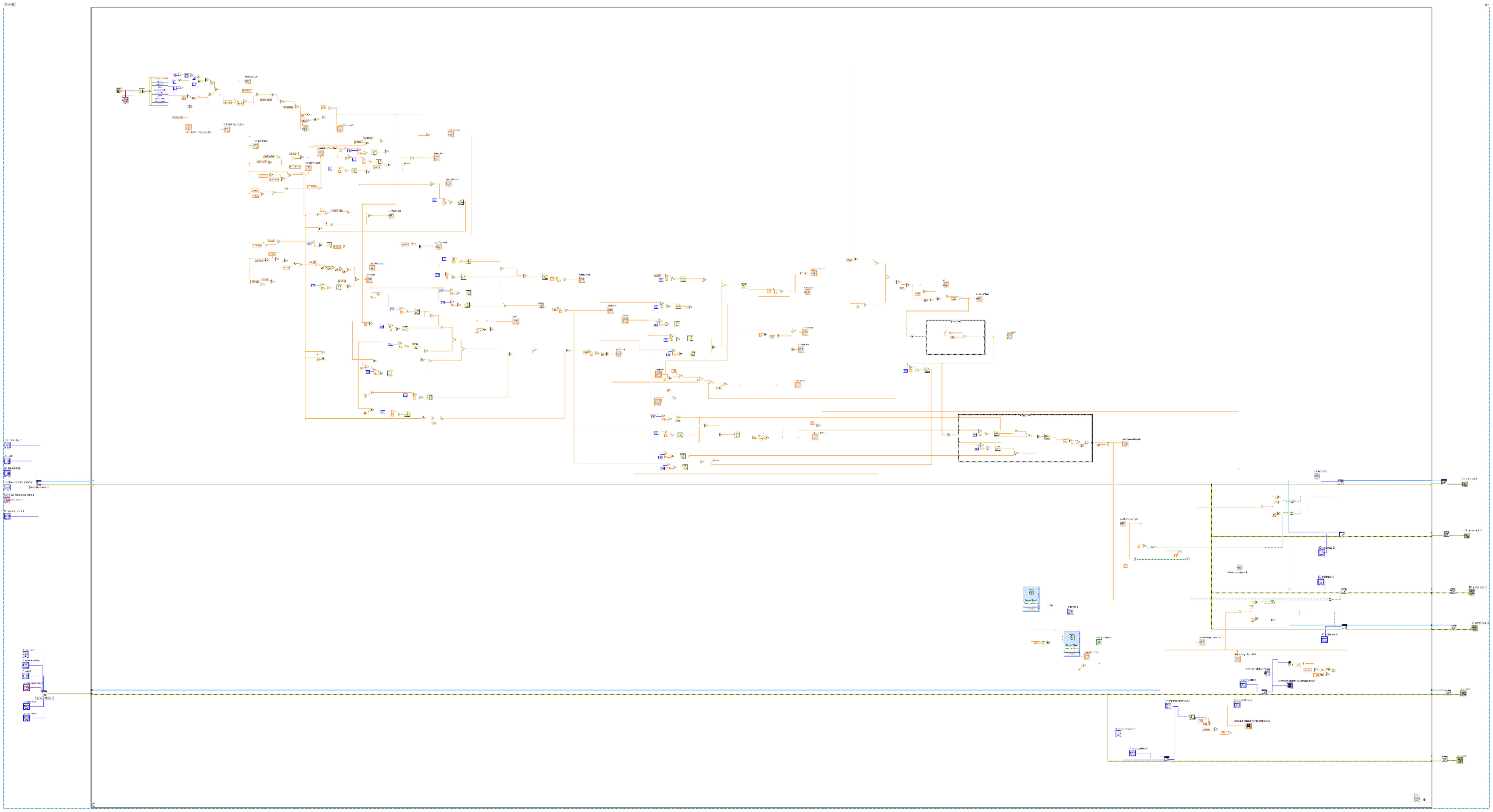
```
solarAzimuthAngle;
```

Javascript and C have a cryptic way of writing conditions within mathematical expressions, the ()?:
Example:

```
a = (x > 20) ? 20 : x;
```

This is equal to:

```
if (x>20) a=20;
  else a=x;
```



APPENDIX 5: Measurements LabVIEW Program