Comparison of Solar Thermal and Photovoltaic Panels

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Abstract

The aim of the thesis was to assemble and to make a comparison between a solar photovoltaic and a solar thermal panel installed system. The main differences related to the complexity of equipment needed for correct functionality of each system were documented and real–time measurement of the energy generated obtained.

The communication parameters for each device were gathered and tested using QModMaster software. With successful communication between devices established on the Modbus RTU network, a programme was designed, within LabVIEW software, to extract and store data from the sensors. Initial laboratory testing before formal roof installation demonstrated LabVIEW software to be successful in communicating with all the sensors using Modbus RTU.

For the roof mounted photovoltaic system, data for five consecutive days were obtained. These data demonstrated the difference in power output between a sunny and a partly cloudy day, as well as the relationship between the solar irradiation and the power generated. Estimation for the efficiencies was also calculated.

However, the complexity of installing the roof mounted solar thermal panel system, resulted in a lack of time to fully test the software simultaneously for both assembled systems.

Language: English

Key words: solar photovoltaic panels, solar thermal panels, Modbus, LabVIEW.

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1 Introduction

The challenge of generating electricity more sustainably with a lower carbon footprint is of increasing importance as consequences of Global Warming are more noticeable (Meinshausen et al, 2009).

With the average temperature on Earth rising, this will lead to the ice in the poles melting and in consequence, seawater expanding thermally and sea levels rising. (Meehl et al, 2005). In addition, extreme weather phenomena are occurring with greater frequency and rapid changes to ecosystems resulting in the dying out of species of animals and plants, unable to adapt to the changing environment (National Geographic, 2019).

On the search for alternative and less polluting ways to produce energy, two clean and feasible options are Solar PV and Solar Thermal. There are still some GHG emissions linked to these technologies due to the manufacturing of all the devices that form the system. According to some studies, on average the production of a PV panel emits around 50 g CO2eq/KWh (Sovacool, 2014). However, evidence suggests that in the long term they emit significantly fewer fumes than traditional fossil fuels.

1.1 Current status and evolution

The price of solar photovoltaic panels per watt has been reduced drastically in the past four decades (see Figure 1). One of the main reasons has been due to the improvement of the production techniques after the industry has been more consolidated (Saga, 2010). Another reason is the competitiveness in the market. China highly invested in this technology, achieving the lowest prices in the market and forcing companies in other countries to cut down manufacturing costs to catch up.

Lower prices increase the chance of competing against other technologies to generate electricity, opening a wider market that can afford it which at the same time leads to more motivation for the producers to continue developing and improving solar power. Figure 1 represents the exponential evolution of both the price reduction and the global panel installations in a period of 40 years.

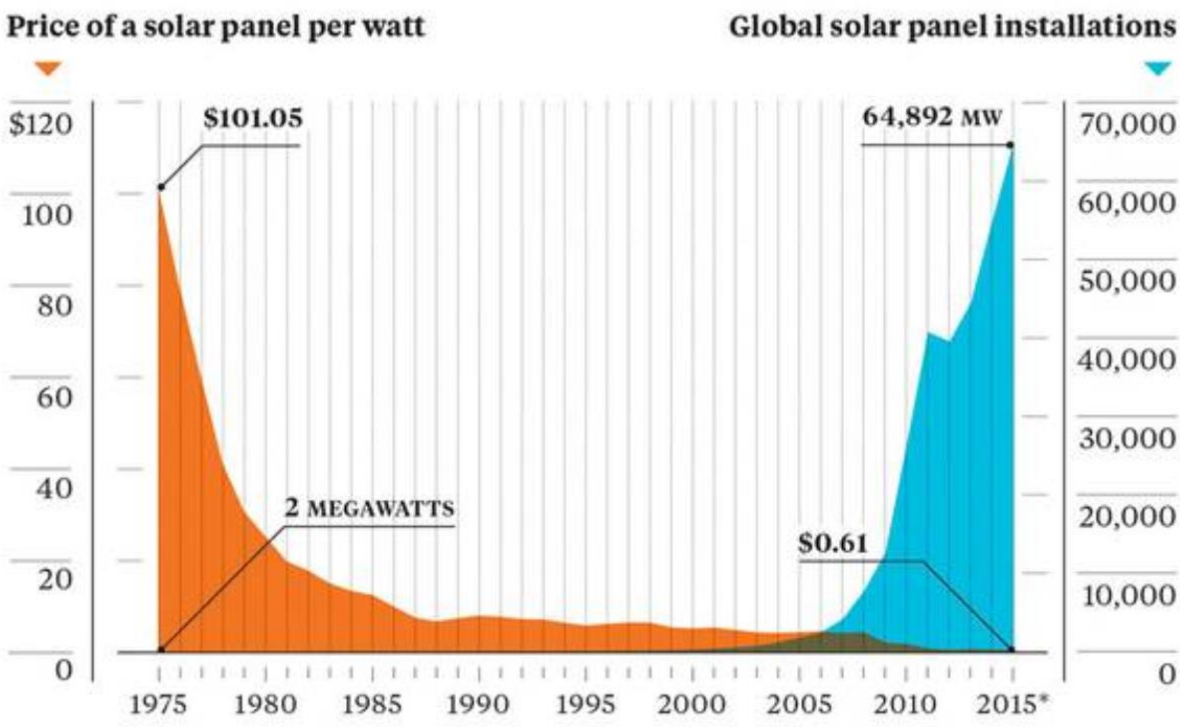


Figure 1. The development of price per watt and installation costs of PV from 1975-2015 (SOLARSW, n.d.).

In May 2019, the price of the mainstream solar PV in Europe (the most common in the market) is of about 0,26€/Wp (this price and other data for the past year can be seen in Figure 2). Other types of PV panels also tend to decrease in price per Wp.

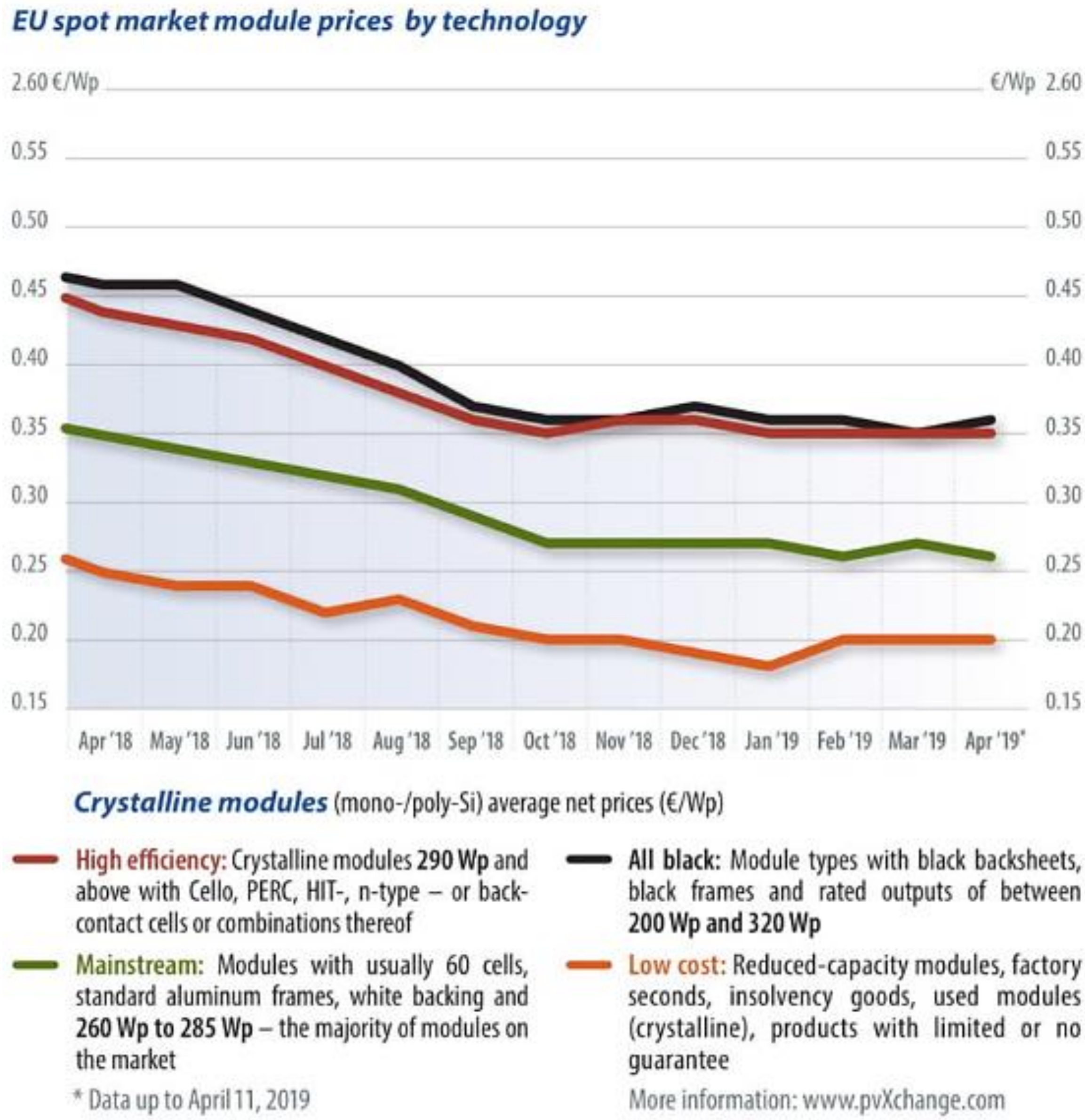


Figure 2. The price of different kinds of PV (PV magazine, 2019).

As the Global Market Outlook for solar power 2018-2022 predicts, the growth in the tendency for PV will continue at least until 2022 (see Figure 3).

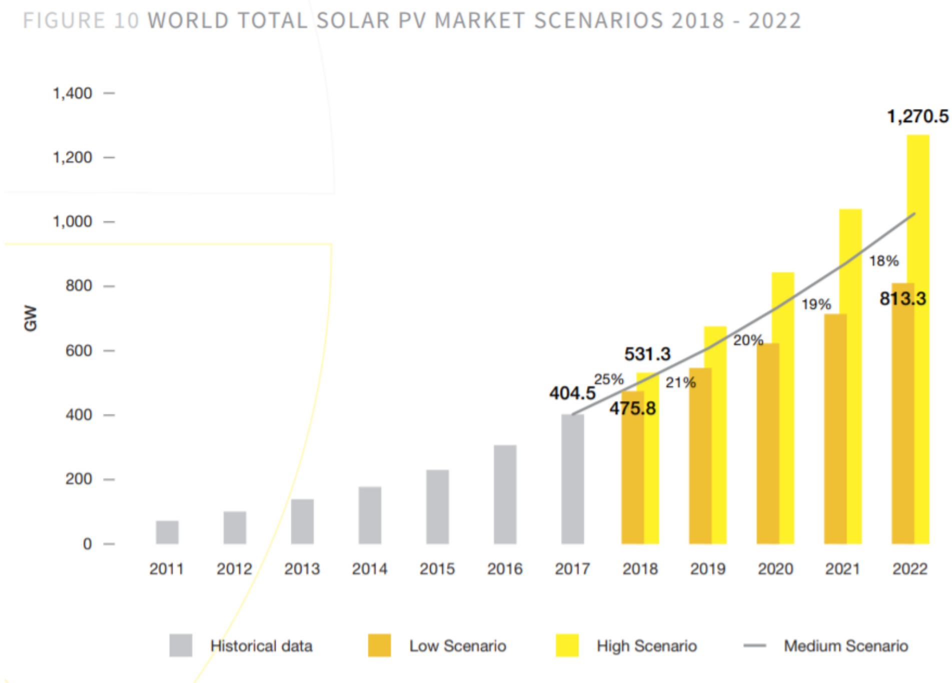


Figure 3. The growth of PV worldwide installation (GW) (Global Market Outlook, 2019).

The amount of surface dedicated to solar thermal in Europe has been increasing year after year since the '90s, but not the rate at which it evolved (see Figure 4). The tendency for annually installed surfaces was growing, reaching its maximum in 2008. After that, the annually new surfaces for solar thermal decreased until 2017, the most recent data available. In other words, it is still growing but at a lower rate since 2008.

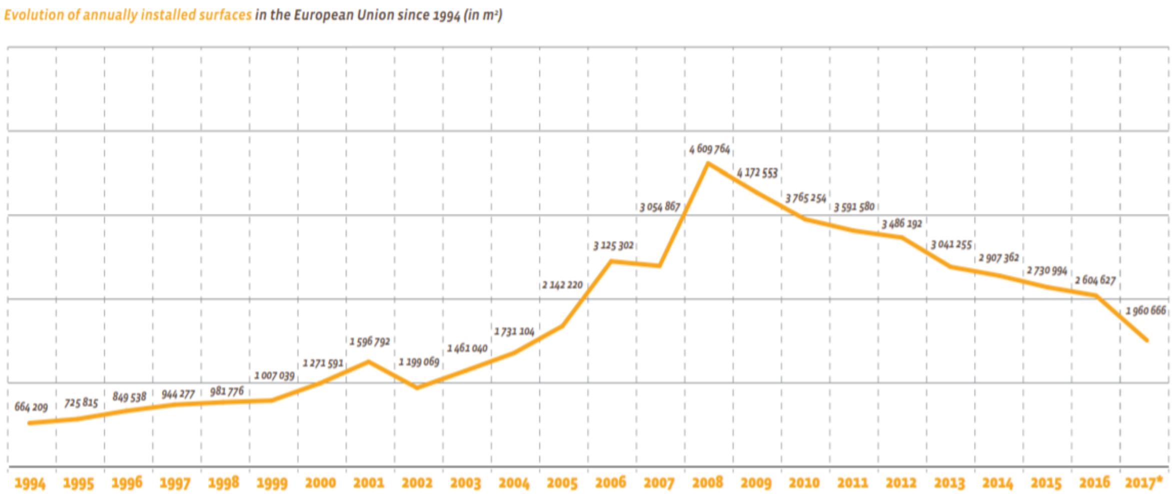


Figure 4. The annual evolution of Solar Thermal installed surfaces (Solar thermal and concentrated solar power barometer 2018, 2018).

This favourable evolution of solar power is one of the main reasons that motivated the topic of this thesis; the comparison of two ways of taking advantage of this source.

Another important aspect that should be mentioned is that they produce different kinds of energy. The PV panel produces electricity (the energy from the current can be measured with an energy analyser), while the solar thermal produces heat (the energy can be known with the temperature difference between the entrance and the exit of the panel and with the flow).

1.2 Aim and objectives

The aim of this thesis is to assemble, install and compare the energy production of solar PV and solar thermal systems over time on a roof space of Novia University of Applied Sciences in Vaasa, Finland.

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

- To document the technical aspects of the components used in these systems.
- To enable real-time energy monitoring using Modbus and LabVIEW.
- To obtain comparison energy data output for both systems.

The purpose for conducting this work is to inform students and other elements of society interested in these types of energy production about the options they have and help them conclude if they are feasible solutions to fulfil their energy needs.

2 Review of literature

2.1 Active and passive solar systems

2.1.1 Active solar systems

This kind of system requires external energy to function, which can be needed for pumping fluids or air that absorb and transport the heat. It can be used both for cooling or heating the interior of a building (Yellowliteno, n.d.). It can be used on a large scale, so producing energy for a whole neighbourhood is an option. Some examples may be PV panels that can be connected with each other to form modules (Matthews, 2019). Aspects to bear in mind are that liquid conductors are better at conducting heat and thus they are more common than the air-based systems. It should also be mentioned that the needed external devices increase the cost, as well as its maintenance. Furthermore, the fluids used should be treated properly, as in case of leakage or disposal they could be highly polluting for the environment (Kang et al, 2015).

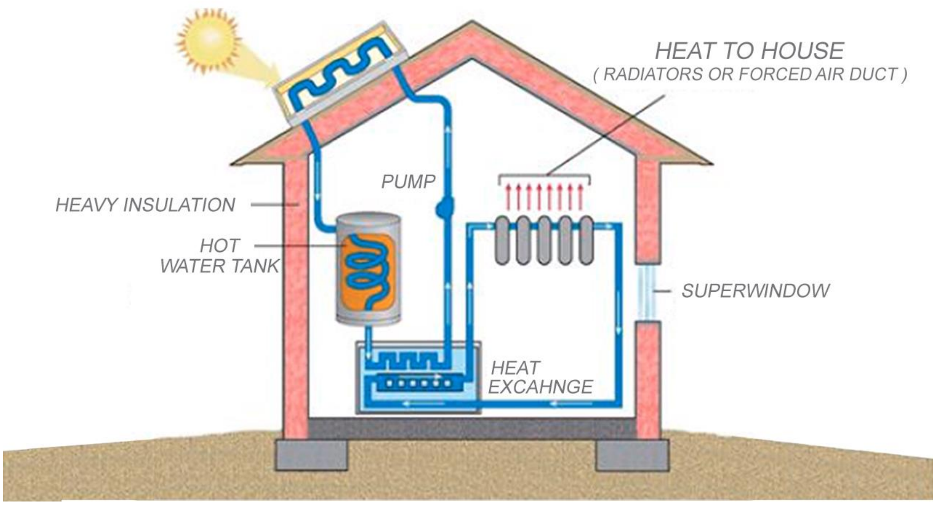


Figure 5. Active solar system example (Solar Energy, n.d.).

2.1.2 Passive solar systems

In this case, there is no need for external energy. The solar energy is captured through passive collectors which absorb and retain it. They work following the laws of thermodynamics, where the heat goes from warmer to cooler bodies. Some examples are passive collectors, greenhouses, solariums or sunrooms (Matthews, n.d.) (Yellowlite, n.d.). The main advantage about this system is that it is less expensive and polluting than the one mentioned before, but some drawbacks are that it has a significant a lower efficiency as it highly depends on the weather (Raquel et al. 2014).

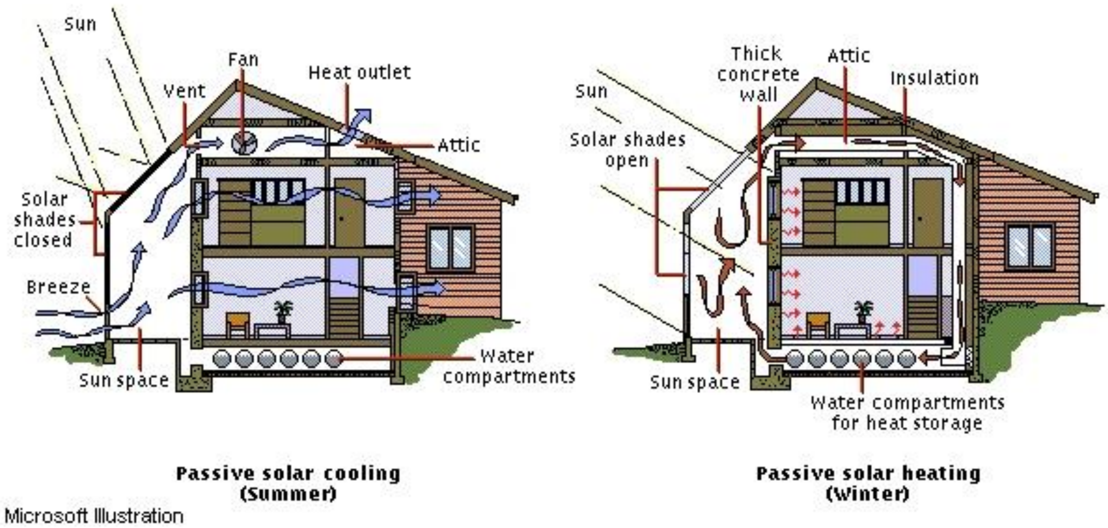


Figure 6. Passive solar system example (Harding, 2014).

To sum up, passive solar systems are a more environmentally friendly option in comparison to active systems, but they are mostly used on a small scale. Given the need for a big amount of energy, active systems may suit better the needs. Finally, given the case that a building is built, passive systems should be considered. An interesting option to take into account is the ZEB (Zero Energy Building), which has the goal of producing the same energy than it consumes in one year (Bautex Systems, n.d.).

Some measures are quite easy to apply such as house orientation, windows that minimize the loss of heat, cool roof with reflective materials, good ventilation systems or highly efficient and intelligent lighting systems. However, it should be connected to a traditional energy source as depending on the weather it is possible that all the energy needed it is not covered (Gillies, 2015).

2.2 Modbus

One of the key factors used in this project is Modbus. This short summary will just cover the information needed for this project, as it can also be used with other combinations or assemblies.

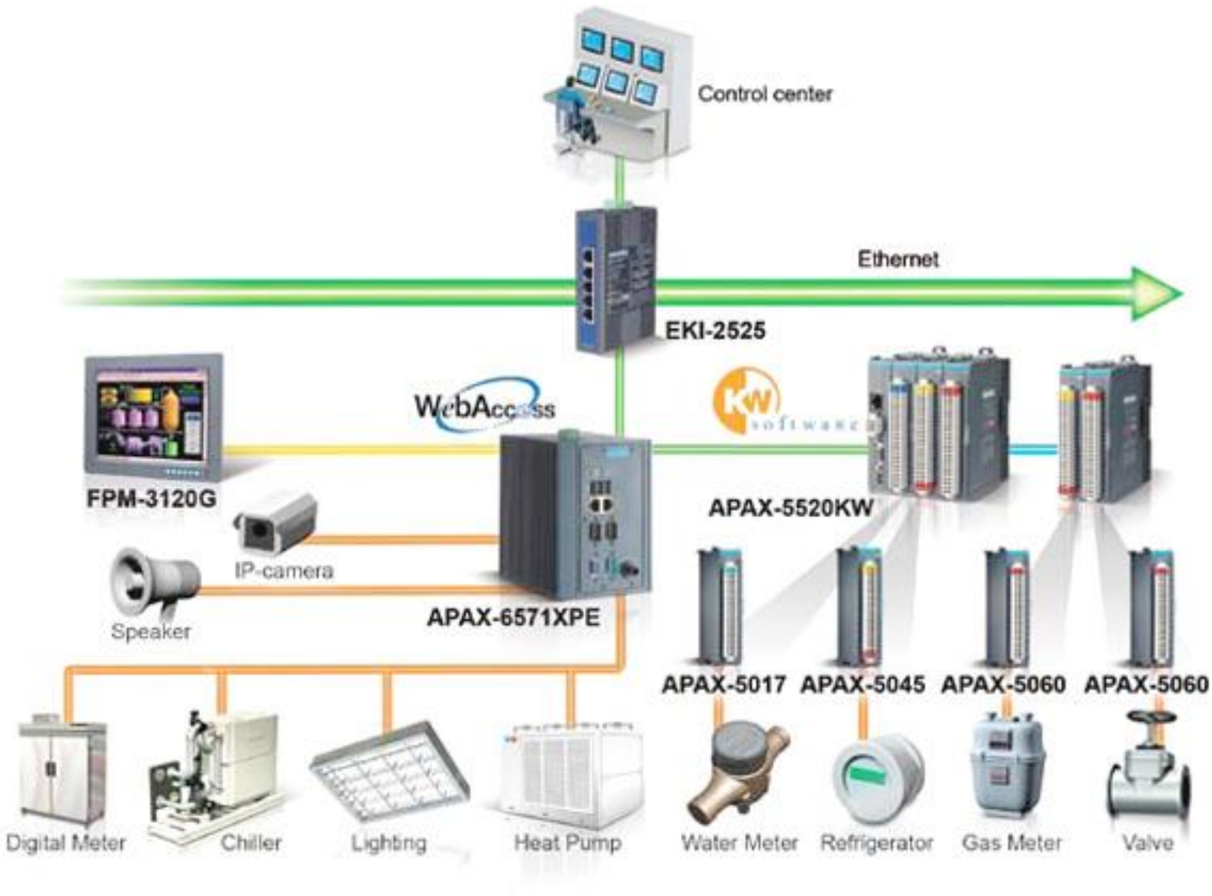


Figure 7. Modbus RTU system.

2.2.1 History

It was developed by the PLC manufacturer Modicon in 1979 (Schneider Electric, n.d.) with the objective of communicating with several electronic devices over a single pair of twisted wires. First, the Modbus interface ran on RS-232, but later the serial line

RS-485 appeared allowing longer distances for communication and higher speeds. RS-485 is used in this thesis.

2.2.2 What is it?

It is a method to transmit information between electronic devices, through Programmable Logic Controllers (PLC's). The device which requests information is the master also called Modbus Master. The suppliers are the slaves, which in this project are sensors, but they can also be PLC's or Programmable Automation Controllers (PAC). There is one master and up to 247 slaves (Simply Modbus), each one with a specific Slave Address.

2.2.3 Uses

It is easy to use and openly published protocol. Thus, it is and has been broadly adopted in the industrial sector. It is used to transmit signals from sensors and control devices to the main controller or data gathering system.

One example is their use of solar farms. In order to detect incidents or to calculate performance, data acquisition must be done. Modbus is the protocol used to get data from inverters, combiner boxes, weather stations, battery banks, and transformers. The most common type of Modbus and the one used in this thesis is using a Remote Terminal Unit (RTU), where is possible to connect a data acquisition device to a computer. Other more advanced versions are connected through the internet (Modbus TCP).

On the whole, it is used in systems with a supervisory unit such as a computer which collects the data that the slaves send. In this thesis, the interesting values are related to the amount of heat produced by the thermal panel and the electricity output from the photovoltaic panel. To know the amount of heat, LabVIEW (master) will ask data periodically to the thermometers and flow sensor (slaves). Similarly, the energy meter (slave) will transfer the data related to the amount of energy in the current generated by the photovoltaic system.

2.2.4 RS485 connectivity

The master initiates the communication with the slave as far as RTU is concerned, but for instance, in TCP Modbus, the communication can also be started by the slave. Data can be sent to the slaves (write) or requested (read). The slaves do not send any data if the master does not ask. The general specifications of this system are a top speed of 10 Mbits/second and a maximum network length of about 1.200 m.

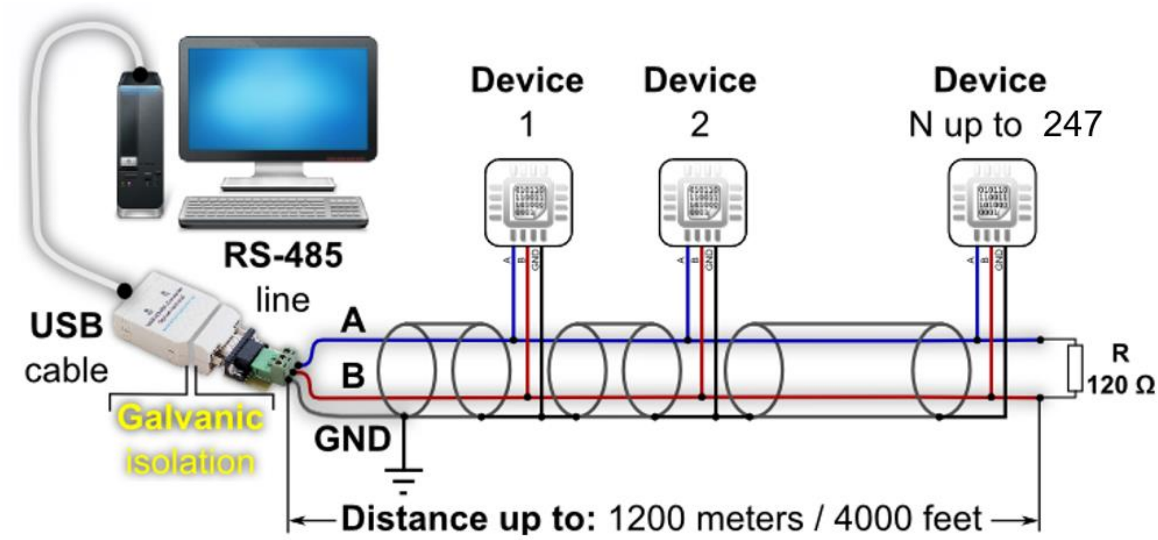


Figure 8. RS-485 wire connectivity (Ozeki, 2009).

The content of a message from the master to the slaves contains:

- Slave address
- Type: read/write
- Index: command to be executed
- Data
- Error checking

An answer from the slave to the master contains:

- Slave address
- Type of answer
- Data
- Error checking

The serial port parameters (baud rate, parity, etc.) must be the same for all the devices in a single Modbus network. The Modbus RTU (Remote Terminal Unit) communicates using binary code, reducing the message size. All the devices must use the same serial transmission mode. Two configurations:

- Half duplex: two wires. The data can be sent or received, not at the same time. Lower wiring costs and the nodes can communicate between themselves.
- Full duplex: four wires. Simultaneous bi-directional communication. Only master-slave communication.

2.2.5 What does each value mean when we use the program?

Two simple softwares used to communicate with Modbus are *MU Terminal* and Q*ModMaster.* Both of them send a message with the same information needed for communication.

- The first value is the slave address in hexadecimal, which can be found in the manual of the device. It has to be written in hexadecimal.
- The second one is the function, which is also found in the manual. Normally the manual gives several options, such as reading, writing or both at the same time. The proper one should be chosen depending on the purpose.
- The next two are the high and low values for the starting address, which tell the starting location of the data inside the device from which the action will take place.
- The following are the high and low values for the number of points. That is, how many locations will be read/written after the starting address, including it.
- Then, using an online converter, it has to be changed to the CRC code, which is used to detect mistakes in data communication. To do it online converters can be of great help. It is important to outline here that this value acts like a little-endian (flips the order).

The answer from the slave consists of:

- Its slave address (same than in the question).
- The function number (same than in the question).
- The data found in the objective addresses, but as a CRC code, which needs to be converted into decimal and operate it as the technical datasheet shows.

2.2.6 Common mistakes and how to detect them

In these kinds of software, the data input has to be precise. It is important to check the datasheet properly to avoid problems. Otherwise, the slave may not give the desired answer, or in most cases, if there is a mistake in the input it will reply with an error message.

Once detected that there is a mistake, the challenge is to find it. Each value should be checked, the first one being the CRC value, as it is sent as a little endian. But a general protocol that can be carried out when an error is found:

- Illegal function. The slave cannot support the function for a particular address. It must be changed to a valid one. It may vary for each address and Modbus device.
- Illegal data address, or data value. That address or value does not exist or is not acceptable for the slave.
- Slave device failure. The problem may be in the connexions from the devices in the Modbus network. If the problem is not in the connections, it may be due to the device itself malfunctioning. Changing the device for a similar one and testing again may be the solution.
- Late response. The message can be correct but errors may occur because of taking too much time to communicate. It can be busy with a previous message.
- Another simple but common mistake is choosing the appropriate number system to represent the data. Different softwares ask for different bases, so the data may have to be converted. For example, QModMaster asks the slave address in hexadecimal, while the programme designed in LabVIEW only asks values in decimal base.

A practical example can be found in Appendix 1 (Error with the programme QModMaster).

2.3 LabVIEW

In this thesis, the software used to obtain and to store the data from each sensor by communicating through Modbus is LabVIEW (Laboratory Virtual Instrument Engineering Workbench), which is a programming environment for a visual language designed by National Instruments.

During the last years, the software has helped the engineers simplifying the testing and simulating part for all kind of situations which otherwise would potentially take more time, be more expensive and have more risk.

The graphical interface made the software popular. It is more intuitive and provides a wider perspective, facilitating the design and understanding of codes.

2.3.1 Applications

LabVIEW’s most common uses are Automated Manufacturing test of a component or system, Automated product design Validation, Control and monitoring of industrial equipment and Condition monitoring of machines.

Automated Manufacturing test: it is the final step before selling the product, so it is very important the verify everything so as not to have problems and affect the reputation of the enterprise or the product. LabVIEW offers a wide range of options to test it, like manufacturing test systems or solutions to obsolete techniques.

Automated product Validation: with LabVIEW, it is easier to test a product under different conditions with a lot of cycles. There is some software for testing them, as well as some hardware for the most common needs.

Control and Monitoring of industrial equipment: another key aspect when designing a product, as LabVIEW offers software and hardware from a wide range of situations.

In case a special software or equipment is needed, NI Instruments can develop a programme that meets the needs of the final purpose.

Condition monitoring: it is a quite unknown topic which tends to be forgotten in most projects, but for example having online access when controlling a process can be really helpful. Some of the main applications are in the fields of Manufacturing Processes, Energy systems, and Transportation. (View Point USA, n.d.)

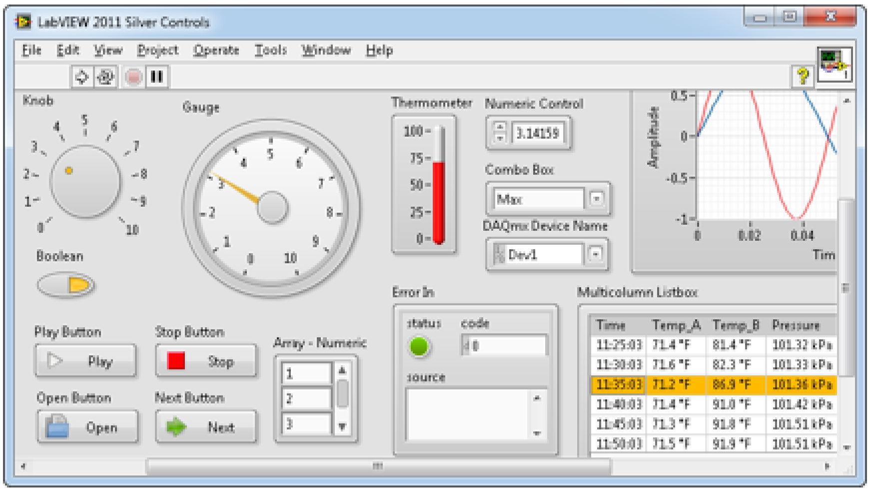


Figure 9. The range of different visual options that LabVIEW offers (Techtip, 2019).

Another interesting feature that LabVIEW offers is its large compatibility with physical hardware like USB, GPIB, and Serial with a large number of drivers available. They can be downloaded from NI Instrument Driver Network (IDNet), as well as from different forums of NI Instruments where there is a flow of information between users. In case of having problems while designing a certain product, is highly recommendable to search for information in these forums as other users may have had similar problems and a solution can be found. Libraries not officially published by NI can also be found, such as the Modbus Library used in this thesis.

2.3.2 License fee and annual cost

Although LabVIEW offers a wide range of advantages, its price is quite high in comparison to other similar programs. It offers three options. LabVIEW base, which is the most basic option, costs 400€/year and includes some basic functions to work with arithmetic operations as well as some drivers to communicate with certain devices. LabVIEW full costs 3,350€/year and has more advanced arithmetic tools and some functions for signal processing. Finally, LabVIEW professional costs 5,580 €/year and include some more functionalities for code validation as well as some engineering extensions which can be essential for the development of certain processes. (LabVIEW, n.d.)

2.3.3 Interface

To begin with, we can see that the programme has two different panels: The *Front Panel* and the *Block Diagram*. The first one (Figure 10, on the left) can be described as the user interface, where he can give inputs and see the graphs or the values generated by the programme. The *Block Diagram* (Figure 10, on the right) is where the graphical coding of LabVIEW is placed.

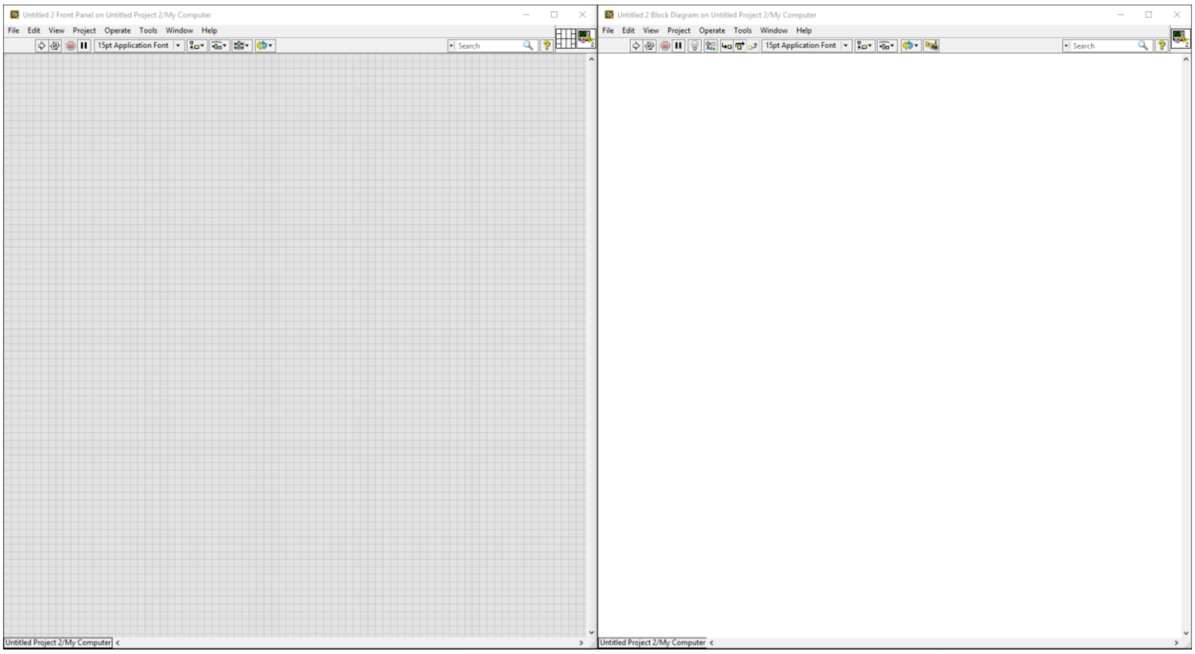


Figure 10. LabVIEW interface.

Some of the most useful functions from the *Block Diagram* can be listed as *Structures* (such as *While Loops, For Loops or Clusters*), *Boolean* and *Numeric* for logic and mathematic operations, and *Timing* options. Also, some functions related to the treatment of the data and *Report Generation* of the obtained results.

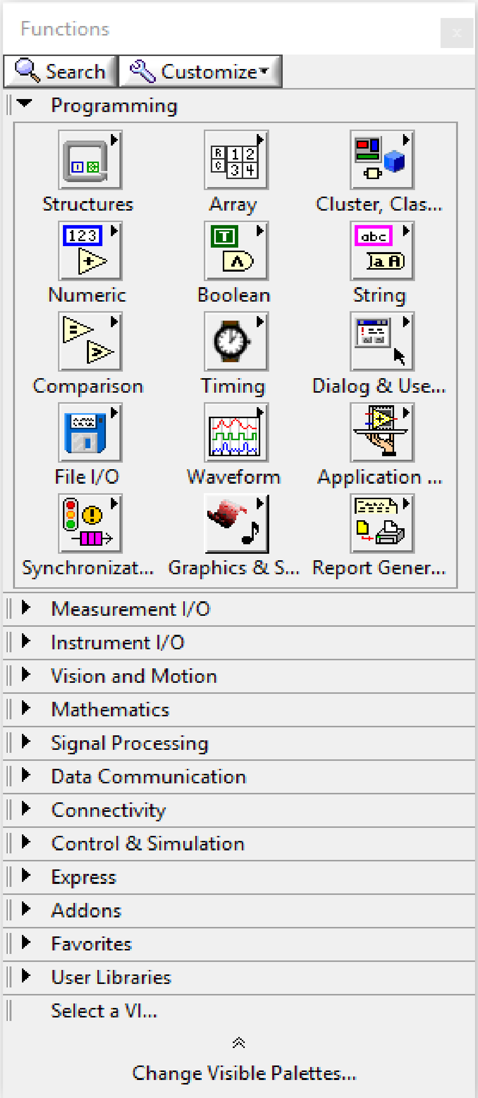


Figure 11. Functions from the Block Diagram.

The *Front Panel* has functions related to the user interface: *Numeric* and *Boolean* controls and output representation, G*raph* options for the display of the results as well as the creation of T*ables, Arrays, Matrix or Lists.*

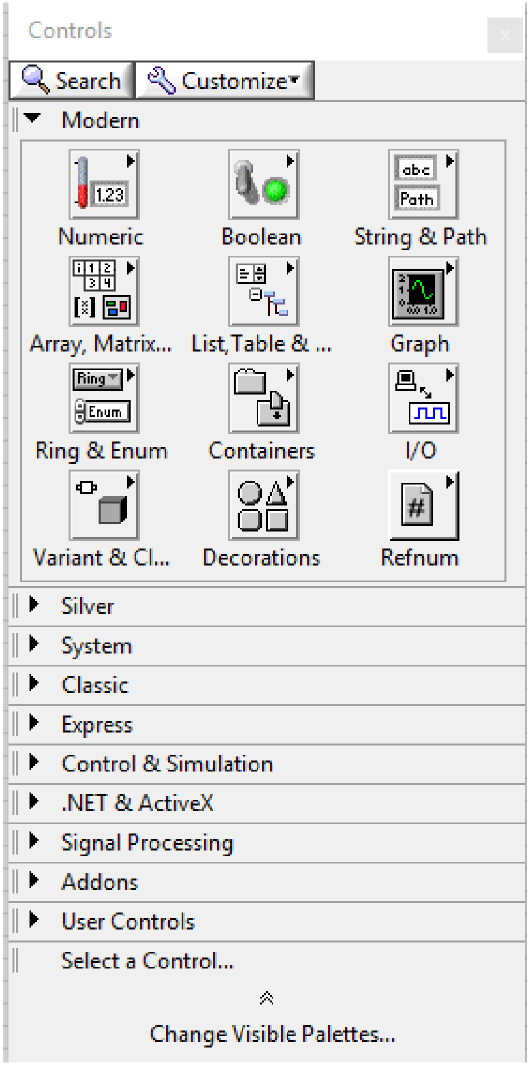


Figure 12. Controls from the Front Panel.

It should be mentioned that LabVIEW is not the best programme for complex mathematic problems. Due to its graphical interface, it needs a lot of space on the screen and it lacks certain operations like integrals or derivatives. To sum up, this programme is not thought to be used for solving extensive problems with the need for huge amounts of functions (Seuma, 2018) and (Essick, 2009).

An example of communication with Modbus can be found in Appendix 2. Communication through Modbus RTU in LabVIEW.

2.4 Description of the equipment needed.

The Modbus RTU communication parameters of the devices can be found in Appendix 3.

Kamstrup MULTICAL 6M2

This device has two temperature sensors, which are placed in the inlet and outlet entries of the solar heater, and a flow sensor. With the data from these sensors and the thermal properties of the fluid it is possible to determine the energy absorbed inside the panel. This model is able to work with fluids in the range of temperatures from -40°C to 140°C. It has a digital interface which displays the current values of the different sensors and other values calculated from them. Some of the values which shows depend on constants set from the factory; therefore, this information may not be reliable if the device is not correctly calibrated.

Electrical connections:

The power supply used is 24 VAC. Red cable on the positive terminal and the black cable on the negative. It cannot be powered by 24 VDC. Therefore, in most cases, an adapter for the current is needed.

The flow sensor (Figure 14) is connected to terminals 11-10. The temperature sensor T1 in the inlet (red label) and T2 in the outlet (blue label) are connected to terminals 5-6 and 7-8 respectively. The polarity is not important (Multical 6M2, n.d.).

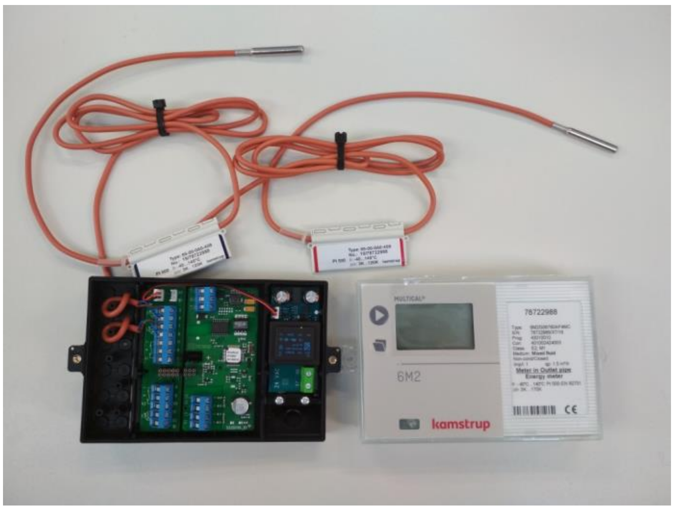


Figure 13. Energy meter Kamstrup MULTICAL 6M2 used in the solar thermal system.

GWF Single-jet volume meter UNICO

This is the tool used to determine fluid flow. It consists of a rotational device which is rotated by the liquid. It also has a physical interface which shows the accumulated volume of liquid which has passed through. It is mainly used for solar thermal installations (GWF, n.d.).

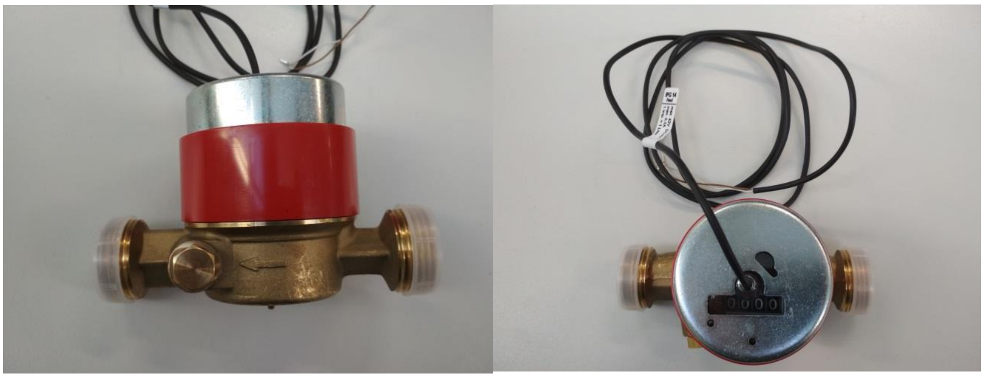


Figure 14. Flow sensor for the thermal system energy meter.

Resol FlowSol B HE pump station

Pump station designed for a solar thermal system. It has two lines, one for the hot fluid coming from the solar heater and the other one (where the pump is located) for the cold fluid. It has a flow rate of 1 to 10 l/min and a maximum pressure of 6 bar (Resol, n.d.).

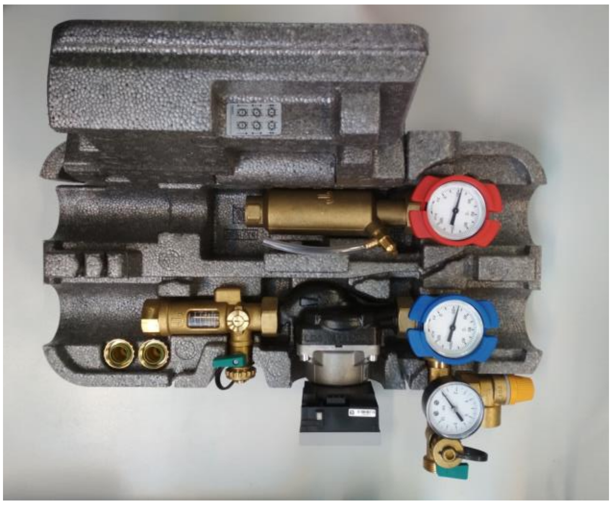


Figure 15. Resol FlowSol B HE pump (cold line in blue and hot line in red).

Resol DeltaSol SLT

Solar and heating controller. It has pre-programmed optional functions which can be combined and parameterized. It also contains 27 pre-programmed basic systems (Resol, n.d.). It is used to control the pump, as the device detects which is the optimal moment to activate it. With the energy meter mentioned before (Kamptrup Multical 6M2) it is also possible to control the pump, but a programme to do so should be designed. Due to a lack of time, it has been decided to use the Resol DeltaSol SLT instead as a time-consuming study to design the mentioned programme would have been necessary.

Figure 16. Resol DeltaSol SLT pump controller.

Hukseflux SR05-D1A3 pyranometer

It measures solar radiation from a 180° field of view angle (hemispherical solar radiation). It provides a reference to compare how much energy the panels are receiving from the Sun and the output they are generating. It also senses the body temperature of the sensor, which may not be the same than the environment temperature; when the irradiation is the higher the internal temperature quickly escalates, distancing from the actual atmospheric temperature.

Electrical connections:

It requires an external power supply between 5 and 30 VDC. More than 30V could damage permanently the sensor. It can be used directly with the RS-485 connection as it has an output of 10 V. The connections for the power supply and data transfer over the RS-485 Modbus RTU network are:

Brown cable → VDC [+]

Black cable → VDC [-]

White cable → RS-485 B/B’ [+]

Grey cable → RS-485 A/A’ [-]

Yellow cable → shield

(Hukseflux, n.d.)

Figure 17. Hukseflux SR-05-D1A3 pyranometer.

Resol SP10 overvoltage protection

Overvoltage protection in case an unexpected voltage peak occurs, e.g. due to a thunderstorm. It is designed in housing for protection against humidity and other adversities, allowing an outdoors use. It avoids fatal consequences to other devices connected to the network (Resol, n.d.).

Figure 18. Resol SP10 overvoltage protection.

Talesun TP660P-275 polycrystalline photovoltaic panels

This is the module used for the solar photovoltaic system. Its main characteristics are listed in Table 1. Two of them are installed (see Figure 19).

Table 1. Principal characteristics of the Talesun TP660P-275 panel.

Type	Polycrystalline	**Maximum Power**	275 W
Operating Voltage (Vmpp)	31,7 V	**Operating Current (Impp)**	8,69 A
Open Circuit Voltage (Voc)	38,7 V	**Short Cicuit Current (Isc)**	9,17 A
Module Efficiency	16,8 %		

(Talesun, n.d.)

Figure 19. Photovoltaic panels Talesun TP660P-275 installed on the Novia roof.

ENVERTECH EVT500 Microinverter

It converts the DC current generated by the solar modules to AC current. Two panels were not powerful enough to use an inverter, so a microinverter was chosen. Its main characteristics are listed in Table 2.

Table 2. Principal characteristics of ENVERTECH EVT500 Microinverter.

Input		**Output**	
Recommended maximum input power	300W*2 panels	**Rated output power**	500 W
Operating range	18V ~ 54V	**Nominal voltage range**	220V/230V/240V
Maximum input current	9,5A*2 panels	**Maximum output current**	2,17 A
Other			
EURO weighted efficiency	95,1 %	**Operating temperature range**	-40°C ~ +65°C

(ENVERTECH, n.d.)

Figure 20. Installed ENVERTECH EVT500 Microinverter.

Carlo Gavazzi Type EM111 energy meter

It measures data from the output electrical current from the microinverter such as power, intensity or voltage. It also provides the total energy generated in a period of time. It has an LCD display with an integrated touch screen. It also shows technical information for its communication with the Modbus protocol (Carlo Gavazzi, n.d.).

Figure 21. Energy meter Carlo Gavazzi Type EM111 (center of the picture) installed in a protection box.

3 Methodology

3.1 Description of circumstances under which the experiment is done

The first tests with the equipment were conducted inside the Energy Technology laboratory in Technobothnia (Vaasa, Finland) to ensure a correct functioning. The solar panels were installed on the roof of the main building of Novia University of Applied Sciences in Vaasa (coordinates: 63°06'19.4"N 21°35'44.7"E).

Before going into the technical aspects of the experiments, a fast analysis of the weather of the region where the experiments are carried out is of interest. This thesis only regards data from several days at the end of May, but for further research in the same location in other periods of the year, it may be useful.

Vaasa is characterized for having the known *Dfc* weather or subarctic weather which has long, cold winters and short, mild and moderately rainy summers. It is widely influenced by the warm flow of the Gulf of Bothnia. The lowest temperatures are registered during the month of February (they can reach -35°C) and daily temperatures remain below 0°C from the 24th of November to the 21st of March. The annually mean variation is shown in Figure 22.

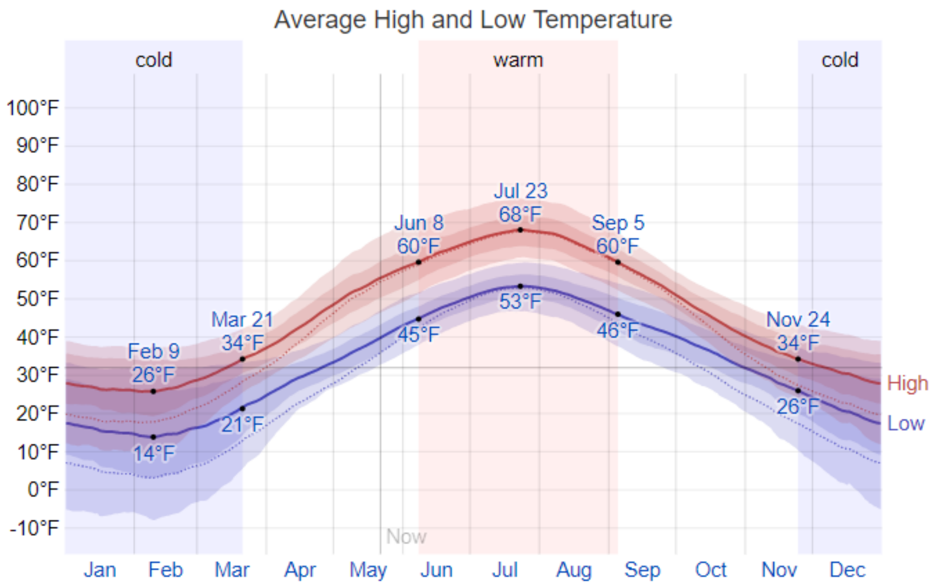


Figure 22. Daily average temperature in Vaasa. The red line is the warmest and blue line is the coldest (Weather Spark, 2019).

The clouds on the sky depend largely on the season of the year. In general, the sky is clear from April to October as it is at least partly cloudy around 54% of the days. On the other hand, the period which goes from November to March only 24% of the days is at least partly cloudy (Figure 23).

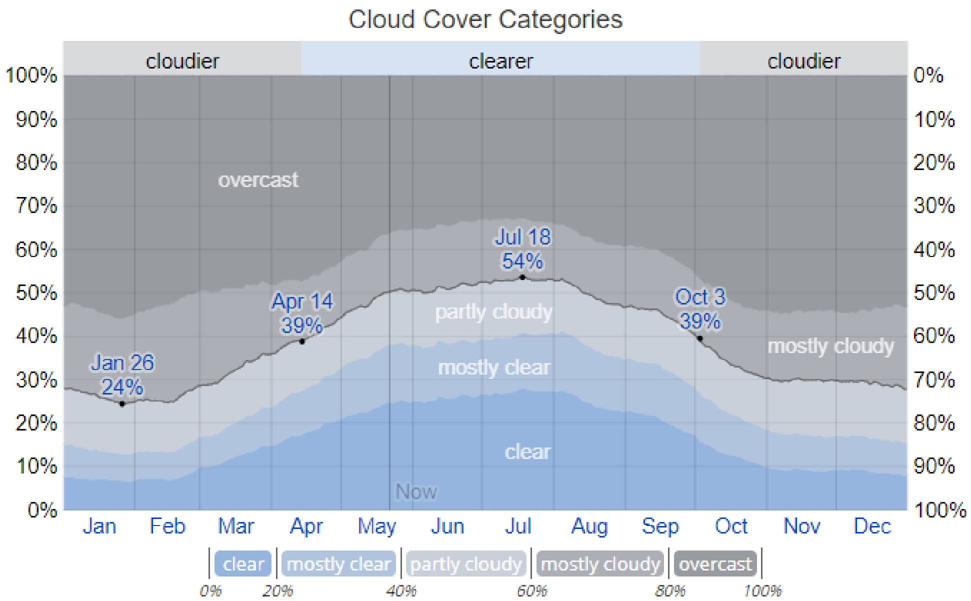


Figure 23. Percentage of each category of cloud cover in Vaasa (Weather Spark, 2019).

Finally, Sun irradiation is another key factor for the PV and solar thermal panels' energy production. The length on the day varies a lot throughout the year. The shortest day on December the 22nd has 4 hours and 40 minutes of sunlight while the 21st of June has 20 hours and 23 minutes (Figure 24). In addition, winter is the season where less solar power is available and the energy demand is higher. This means that other sources of energy are needed. Contradictorily, in summer solar power has a wider impact on the energy production spectrum (Weather Spark, 2019*)* (Kostova, 2014).

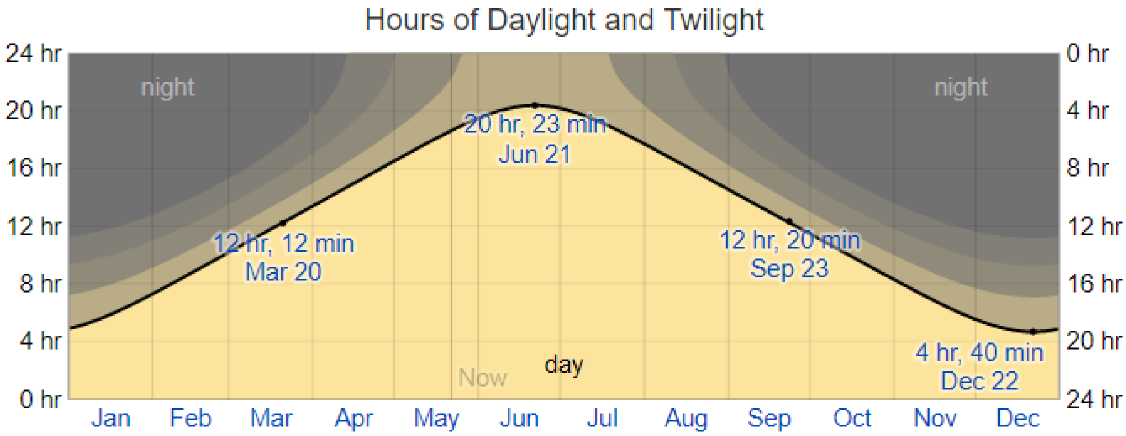


Figure 24. The number of hours daylight and twilight in Vaasa (Weather Spark, 2019).

3.2 Assemblies of the systems

3.2.1 Photovoltaic system

The assembly of the photovoltaic system is simpler than the thermal system. The main components are five: the structure, the solar panels, the microinverter, the energy meter, and the pyranometer. The panels are connected to the microinverter, followed by the energy meter which then transmits the data to the computer. Finally, the electricity goes to the grid (see Figure 26). The pyranometer is connected directly to the computer.

Figure 25. Photovoltaic system assembled on the roof.

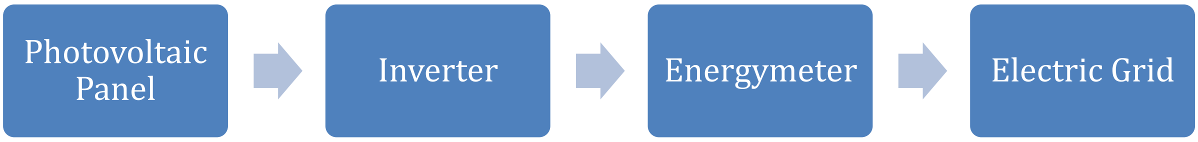


Figure 26. Scheme of the photovoltaic system.

The photovoltaic panels are set with an angle of 60° (see Figure 27), instead of 50° which is optimal for the latitude of Vaasa (Solar Electricity Handbook, *2019*). The reason why 60° is chosen over 50° is that it is harder for the snow to accumulate in winter, which blocks the sunlight, and the rain still cleans the surface. Furthermore, with 50° it would generate more power over the whole year, but 60° produce more power over winter when the energy demand is higher.

Figure 27. Metallic structure for the photovoltaic panels with an angle of 60°.

The basement of the structure consists of horizontal wooden planks and metallic legs of different heights to keep a horizontal angle, as the roof has a slope. The metallic legs consist of two parts screwed together which pinch the metallic sheet from the roof (see Figure28) (Knuuti, 2013).

Figure 28. Basement of the structure for the photovoltaic system.

3.2.2 Solar thermal system

At the end of this thesis, the solar thermal system could not be completely assembled due to lack of time. However, the sensors to be used for the system were tested in the laboratory with artificial data.

The system was thought to follow the structure showed in Figure 29, although modifications could be done upon assembly.

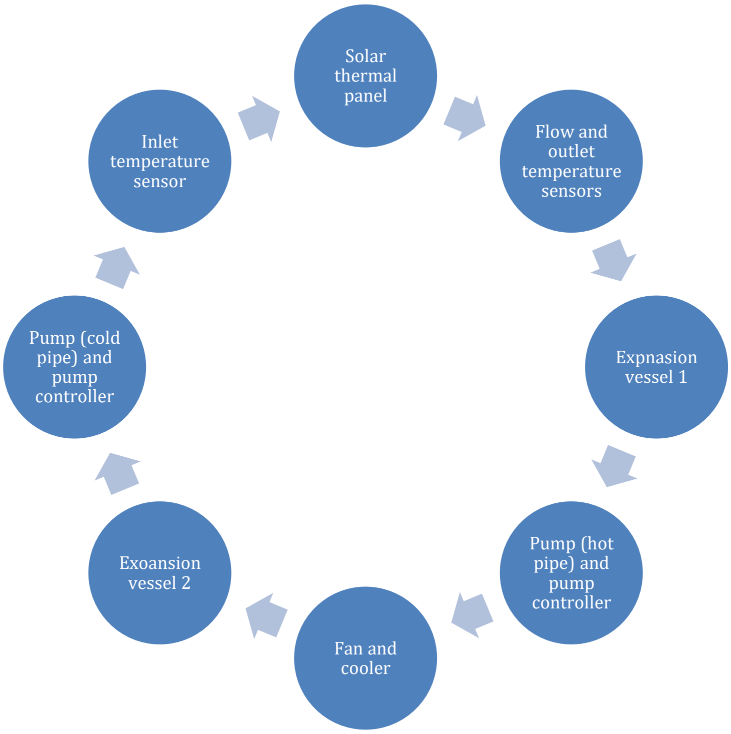


Figure 29. Scheme of the solar thermal system.

First of all, it should be mentioned that in this case this system is designed for an educational purpose, so the cooling fan has the function of cooling down the fluid before entering again into the panel which otherwise would have a purpose. Normally, this heat would be used in a heat exchanger to, for example, heat water. The liquid expected to be used as the freezing point below -40°C, as in winter the temperatures can reach less than -30°C and if frozen the equipment could be damaged.

As a result, the energy meter used is configured according to the properties of the fluid to have a more precise response.

The fluid circulates in a closed circuit. Starting in the solar panel, the liquid is heated by the Sun. Then it goes through an expansion vessel, which in case the pressure is too high releases the vapors into the atmosphere. After that, it enters the pump through the hot line (see Figure 15), but it is not pumped in this stage. Then the heat could be used for any kind of application that requires it, but in this case, the fluid is cooled down to continue with the cycle, as mentioned before. After, it goes in another expansion vessel before being pumped by the pump (entering through the cold line).

The temperature sensors are placed in the inlet and outlet pipes of the solar heater in order to know the temperature difference. With that, the flow and the thermal properties of the fluid, the power generated can be calculated by the energy meter.

The pump is planned to be controlled by the device *Resol DeltaSol SLT*, as it has pre-programmed functions that determine when it needs to be activated and with what power. It also has temperature sensors in the cold and warm lines, and the properties of the liquid are needed to be set.

On the last days of the experimental part of this thesis, the thermal panel was installed on the structure (see Figure 30), but the other components were not. The structure was the same than for the photovoltaic system.

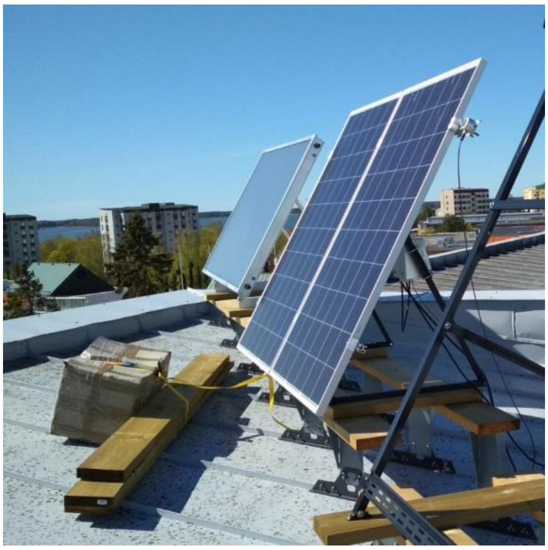


Figure 30. Solar thermal (in the back) and solar PV (in the front) panels on the roof of Novia.

3.3 LabVIEW programme

3.3.1 Block diagram

The main function of this LabVIEW programme is to communicate with the sensors through Modbus RTU protocol, to gather the data and to store it in an Excel file.

In short, the programme first asks for the Modbus RTU communication parameters. The *While Loop* executes the code inside every given time. Inside the loop, first is executed the Modbus function *Read Holding Registers*, which is the same for all the devices and addresses. Once the registers of interest are read, the programme converts the values to the proper units. Next, all these values, as well as the date and time in which the iteration happened, are collected in an *Array* and transferred in real-time to a table in the *Front Panel*. The *While Loop* is repeated until the user presses the *Stop Button*. At the same time, when the condition of the *Stop Button* changes to *True*, the *True* option from the *Case Structure* is executed, generating an Excel report containing the information from all the iterations.

The structure from the programs for the photovoltaic and thermal systems is the same. It can be compared in Figures 31 and 32. The role of the main features is explained further on page 34.

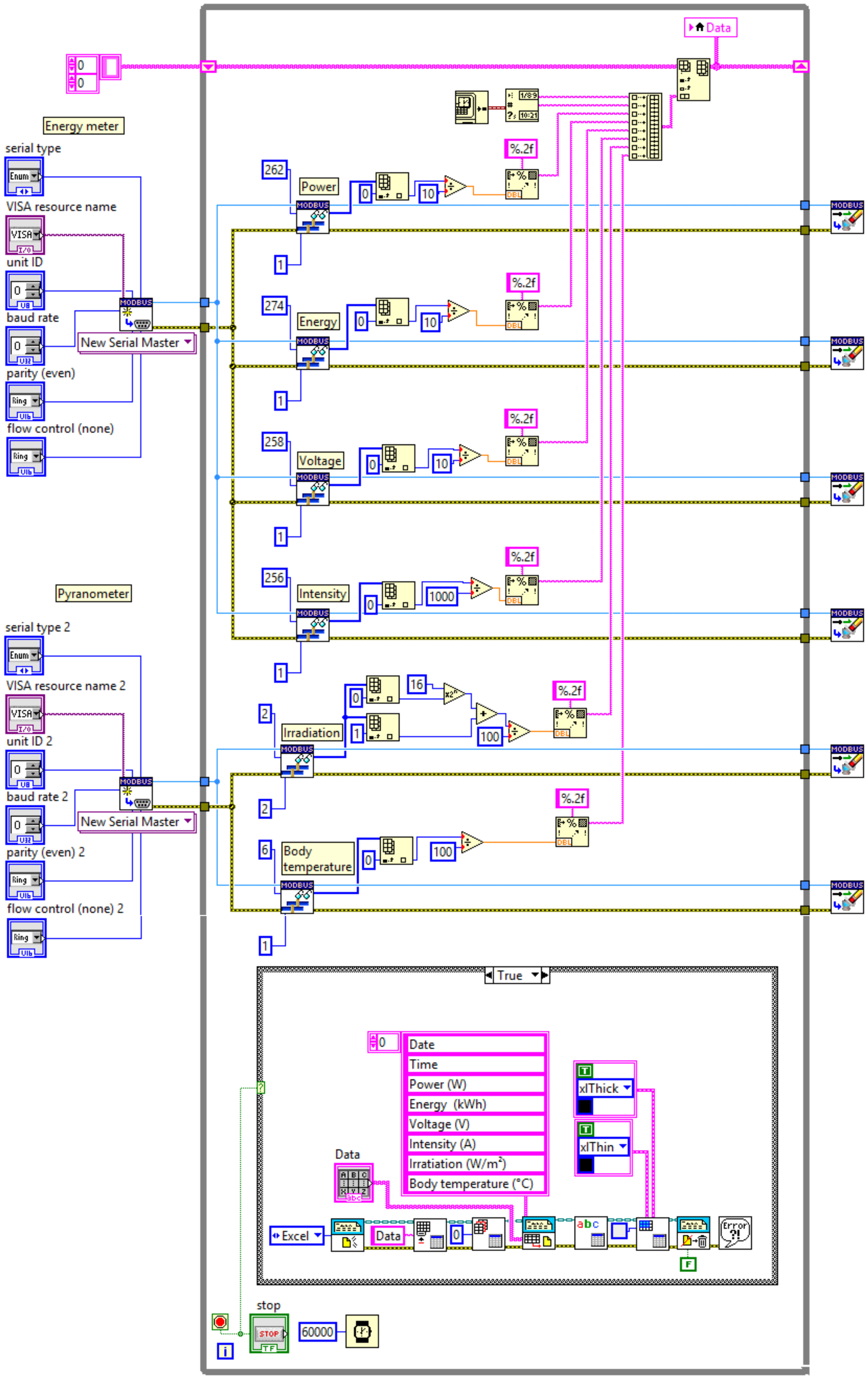


Figure 31. The programme for communicating with the photovoltaic system.

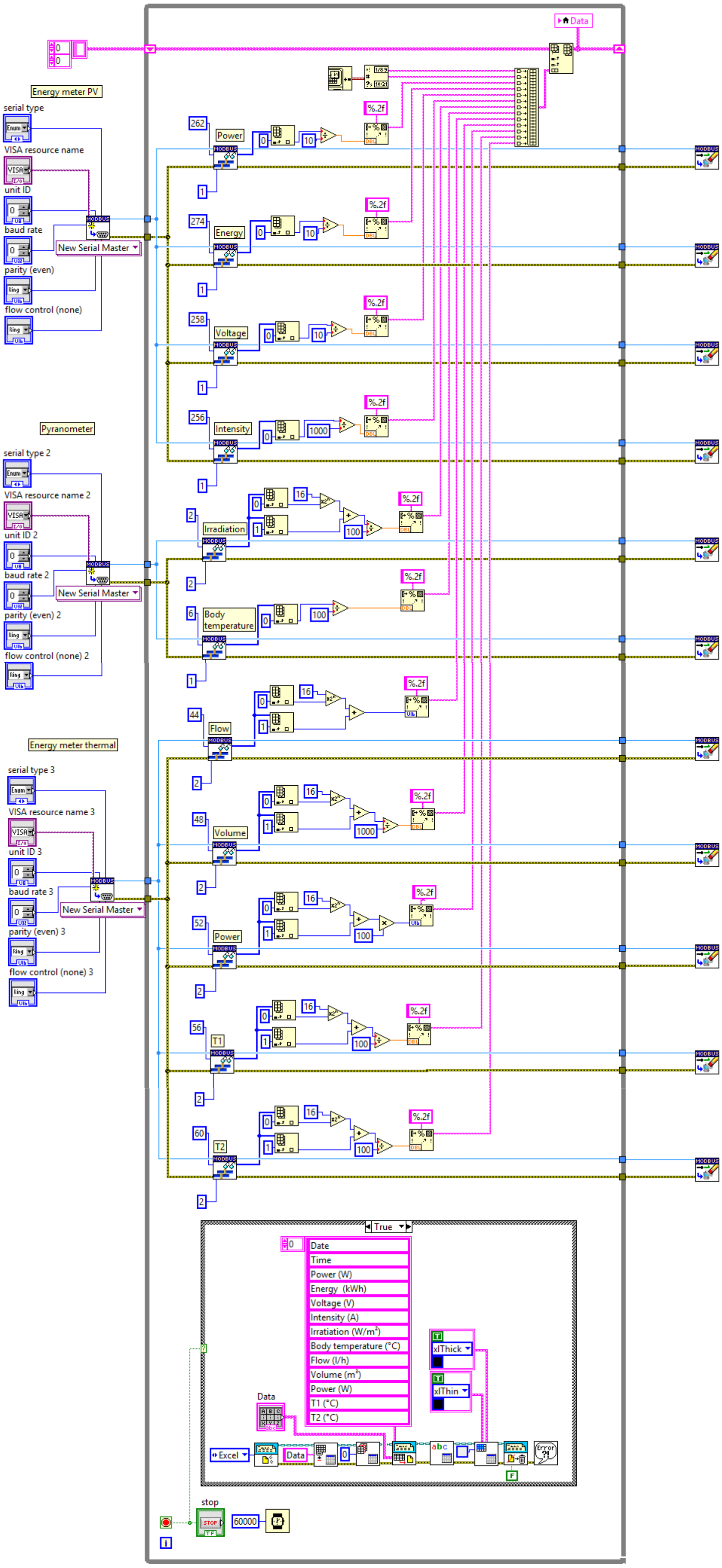


Figure 32. The programme for communicating with both systems simultaneously.

Role of the main features

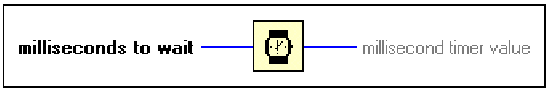
Short explanation about the main features used in this programme to get a better understanding of the whole structure. The figures are extracted from the LabVIEW help tool.

While loop

This loop executes the functions placed inside until a condition is true (when the stop button is pressed, in this case). It iterates every given time, asking the slaves and getting a response once for each iteration.

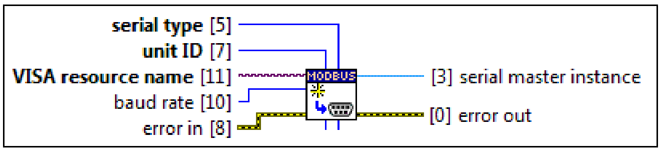
Wait

Period of time between iterations, in milliseconds. In this case, the programme will iterate once every minute (60000 milliseconds).



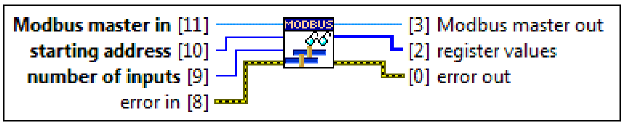
Create Serial Master

This function creates a standard Modbus serial master instance, asking for the parameters needed for successful communication with the slaves.



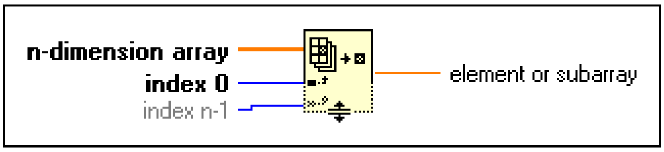
Read Holding Registers

Reads the input address(es) from the slave devices. The number of inputs is how many consecutive addresses are read after the starting address.



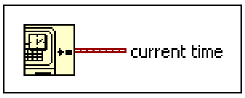
Index Array

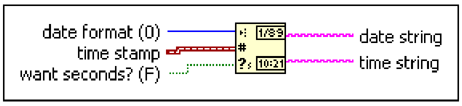
For a given array, only the desired element or subarray indicated with the index returns. The first subarray is identified with the sub-index 0. It is used for extracting just the value which has the information that it is desired (the answer might give more values which are not needed).



Get date and time and convert to string

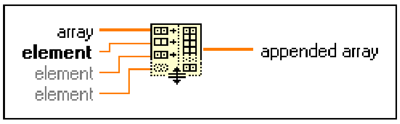
Gets the current date and time to know when reading is made according to the one from the computer, for the when the excel file is generated.





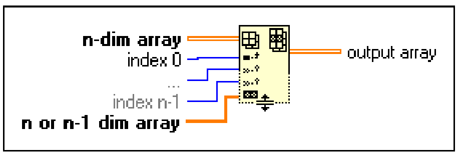
Build Array

It concatenates several arrays or elements in one array, which will store all the information as a matrix. All the data from each iteration of the while loop is collected in this array.



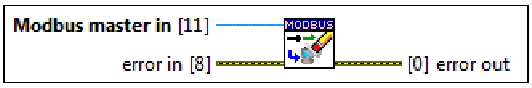
Insert Into Array

Inserts the array generated previously (one row with the data from a single iteration) to the local variable of the table that will later be exported to Excel.



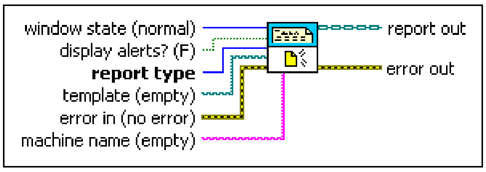
Shutdown

Shutdowns and cleans the Modbus instance after the loop is stopped and in case there is an error during the loop it gives some information about what might have happened. It may be useful to solve it, but sometimes it does not give useful information.



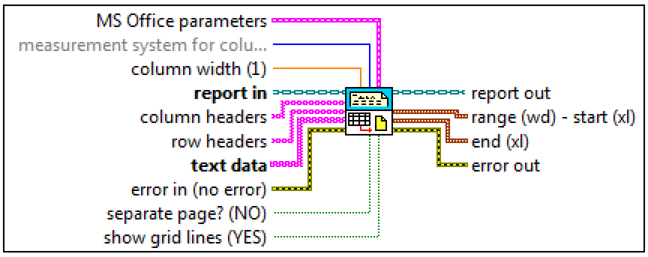
New Report

Used to create a new report, the format type can be chosen and in this case, Excel file is selected.



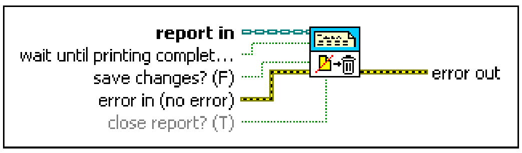
Append Table to Report

The table filled in LabVIEW with every iteration is exported to the generated Excel. It also contains the information for the column headers.



Dispose of Report

It closes the report. After that, no more operations can be done on the report so it must be the last step. Finally, it generates and opens the Excel file which later can be stored in the computer.



Others

Other functions that are not explained are used for appearance reasons, so they are not relevant to the main functionality of the programme.

3.3.2 Front panel

Here the communication parameters, the table with the data and the stop button are placed (see Figure 33). After filling the correct parameters, the program can be run properly. The table is filled with a row every minute (time between iterations). When the stop button is pressed, the programme stops running and an Excel file is generated with the same information than the mentioned table in LabVIEW (see an example in Figure 34).

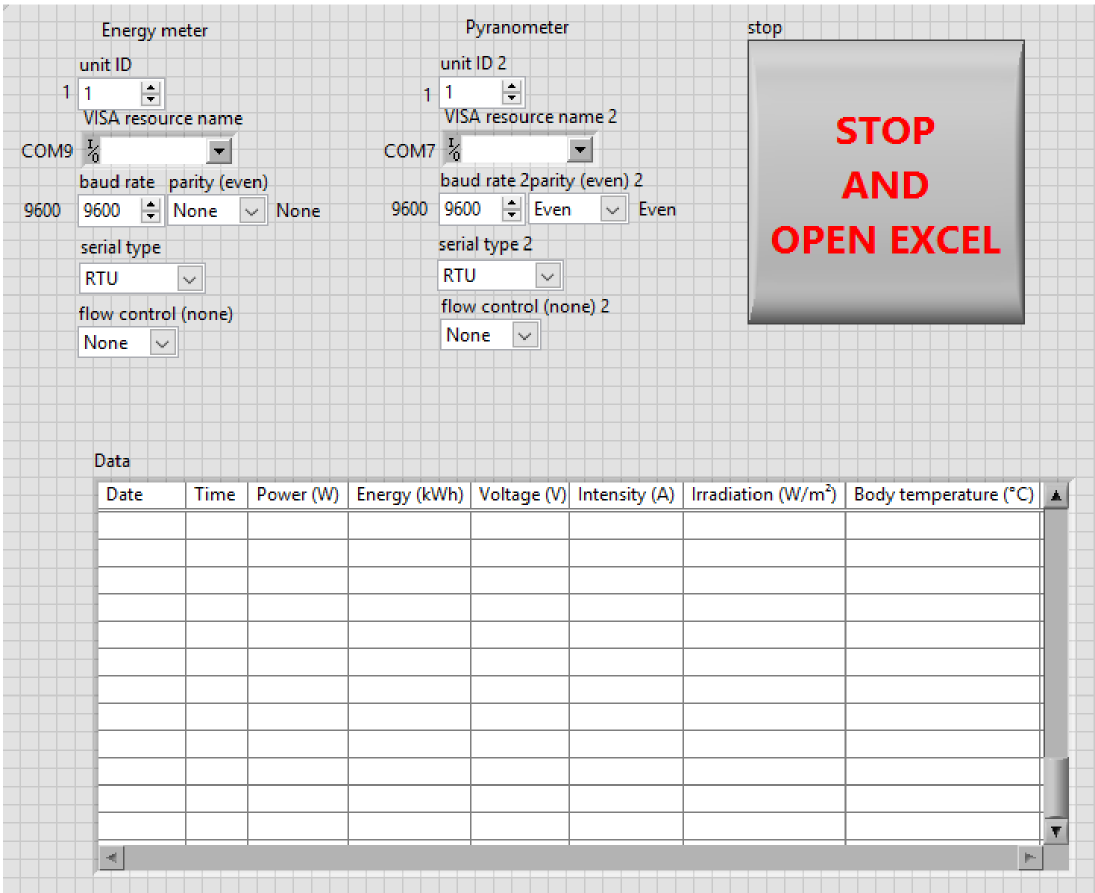


Figure 33. User interface (Front Panel) from the programme in Figure 31.

	A	B	C	D	E	F	G	H
1195	Date	Time	Power (W)	Energy (kWh)	Voltage (V)	Intensity (A)	Irratiation (W/m²)	Body temperature (°C)
1196	18.5.2019	10:50	364,2	9,4	239,8	1,52	760,81	26,56
1197	18.5.2019	10:51	365,3	9,4	240,2	1,53	763,32	26,63
1198	18.5.2019	10:52	366,7	9,5	239,6	1,54	765,84	26,72
1199	18.5.2019	10:53	367,6	9,5	239,9	1,54	768,36	26,78
1200	18.5.2019	10:54	369	9,5	239,7	1,54	771,47	26,87
1201	18.5.2019	10:55	370,3	9,5	240	1,55	774,87	26,89
1202	18.5.2019	10:56	371,8	9,5	239,9	1,55	777,35	26,79
1203	18.5.2019	10:57	373,4	9,5	239,7	1,56	780,78	26,72
1204	18.5.2019	10:58	375,2	9,5	239,6	1,57	783,17	26,72
1205	18.5.2019	10:59	376,3	9,5	239,7	1,57	787,4	26,71
1206	18.5.2019	11:00	378	9,5	239,9	1,58	790,41	26,6
1207	18.5.2019	11:01	379,5	9,5	239,9	1,59	793,14	26,53
1208	18.5.2019	11:02	380	9,5	239,9	1,59	795,32	26,46
1209	18.5.2019	11:03	380,9	9,5	240	1,59	797,21	26,49
1210	18.5.2019	11:04	381,5	9,5	239,7	1,6	798,5	26,6
1211	18.5.2019	11:05	382,8	9,5	239,8	1,6	801,4	26,64

Figure 34. Excel file generated when the programme from Figure 31 is stopped.

The initial idea was to use only one Modbus RTU network, but the LabVIEW programme had trouble handling more than one device per network. Finally, one RS485 network is used for each device (two for the photovoltaic system).

4 Results

4.1 Representation and analysis of the outputs

The data acquired from the photovoltaic panels using the LabVIEW programme is represented using line graphs.

The graph from 18/05/2019 (Figure 35) offers a clear vision of what it is expected to be seen on a sunny day, as it has a very smooth shape. It clearly starts to produce energy at the sunrise until the sunset, and the maximum output is during the midday. Another interesting aspect is the anomalies where the data drops to 0. They are most probably communication errors from the sensors which return value 0 in some isolated cases. Other drops which do not reach the value 0 are due to shadows from clouds, constructions or other bodies blocking the sunshine.

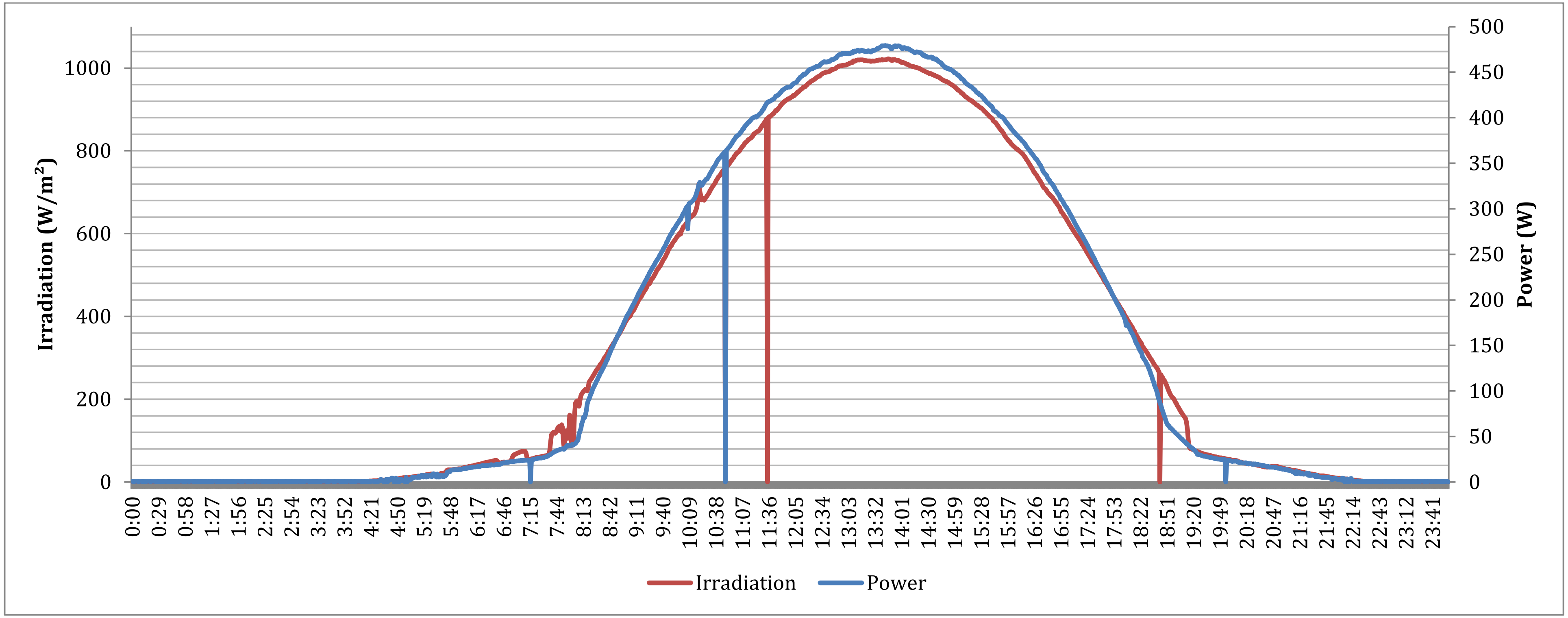


Figure 35. Data obtained from two Talesun TP660P-275 photovoltaic panels (275W each) installed on the Novia roof on 18/05/2019.

In comparison to Figure 35, Figure 36 differs quite a lot as there are a lot of turbulence. The irregular behavior is produced mostly by the shadows from the clouds, so it was a partly cloudy day. The irregularities are followed by the power generated and the irradiation, demonstrating the relation both have. The area under the power graph line is lower than in Figure 35, showing a lower total energy production at the end of the day. Anomalies are detected at around 8:05 and 17:55.

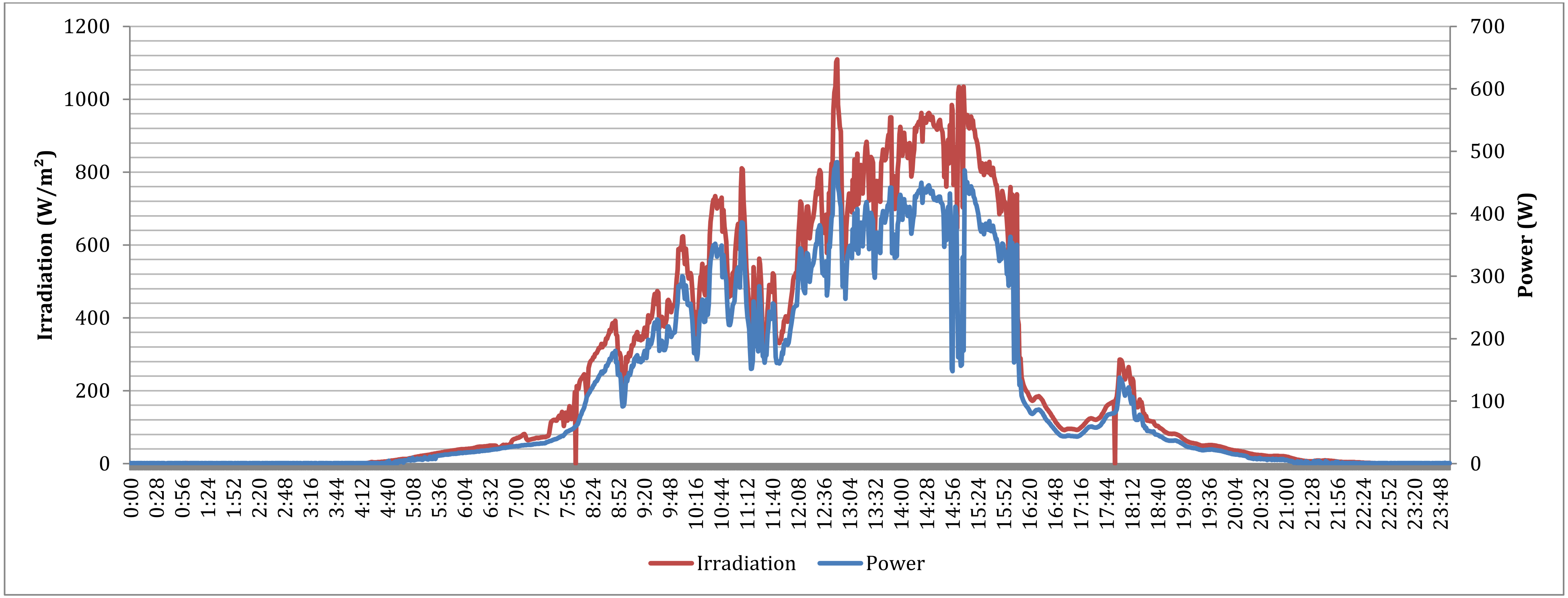


Figure 36. Data obtained from two Talesun TP660P-275 photovoltaic panels (275W each) installed on the Novia roof on 19/05/2019.

The 20/05/2019 (Figure 37) was a day quite similar to the previous one as it was partly cloudy. An interesting observation is what looks to be a period of time with more clouds between 10:30 and 13:30 approximately, dropping the power output at one of the periods of the day with more solar irradiation if there were no clouds (see Figure 35). There is an anomaly at 12:15.

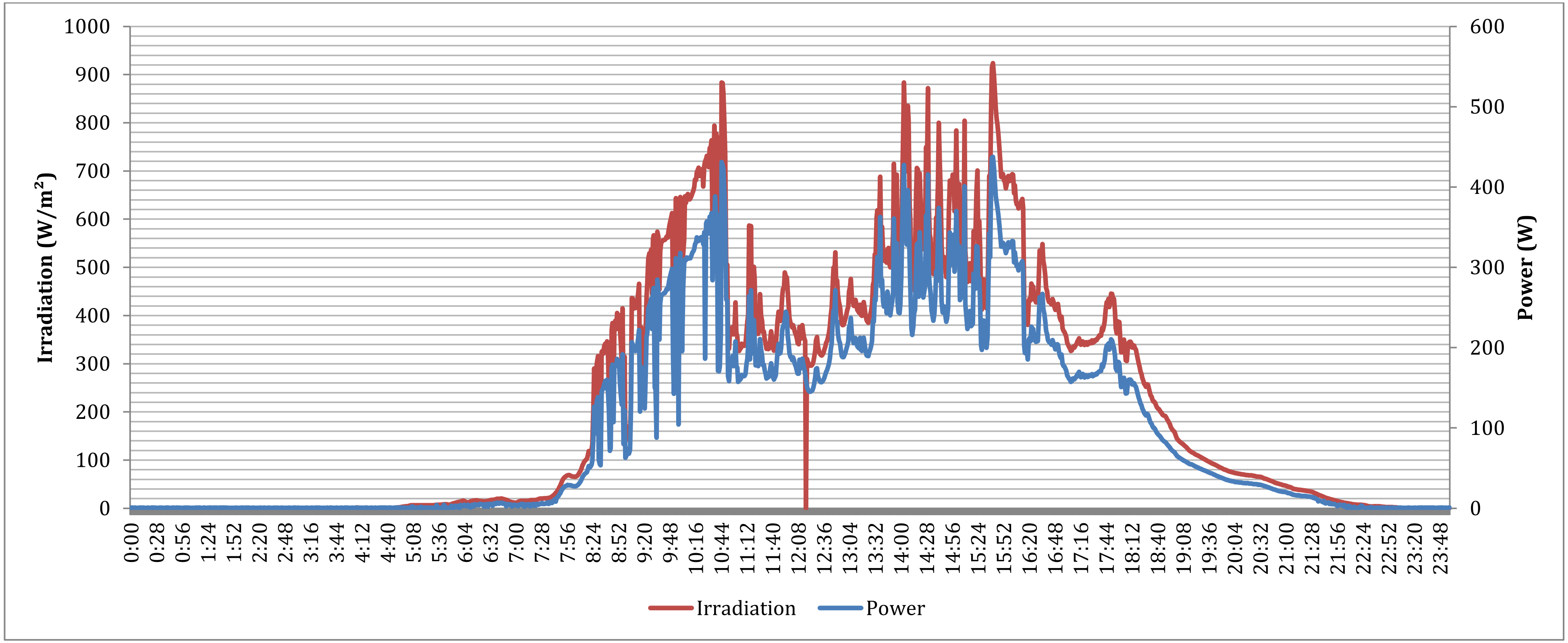


Figure 37. Data obtained from two Talesun TP660P-275 photovoltaic panels (275W each) installed on the Novia roof on 20/05/2019.

Finally, the last analyzed day (Figure 38) was the most irregular one, with sharp changes in a short time. This is evidence of a partly cloudy sky similar to the previous three cases but with the higher frequency of cycles between shadows and sunshine. There is an anomaly on the power output at 16:00.

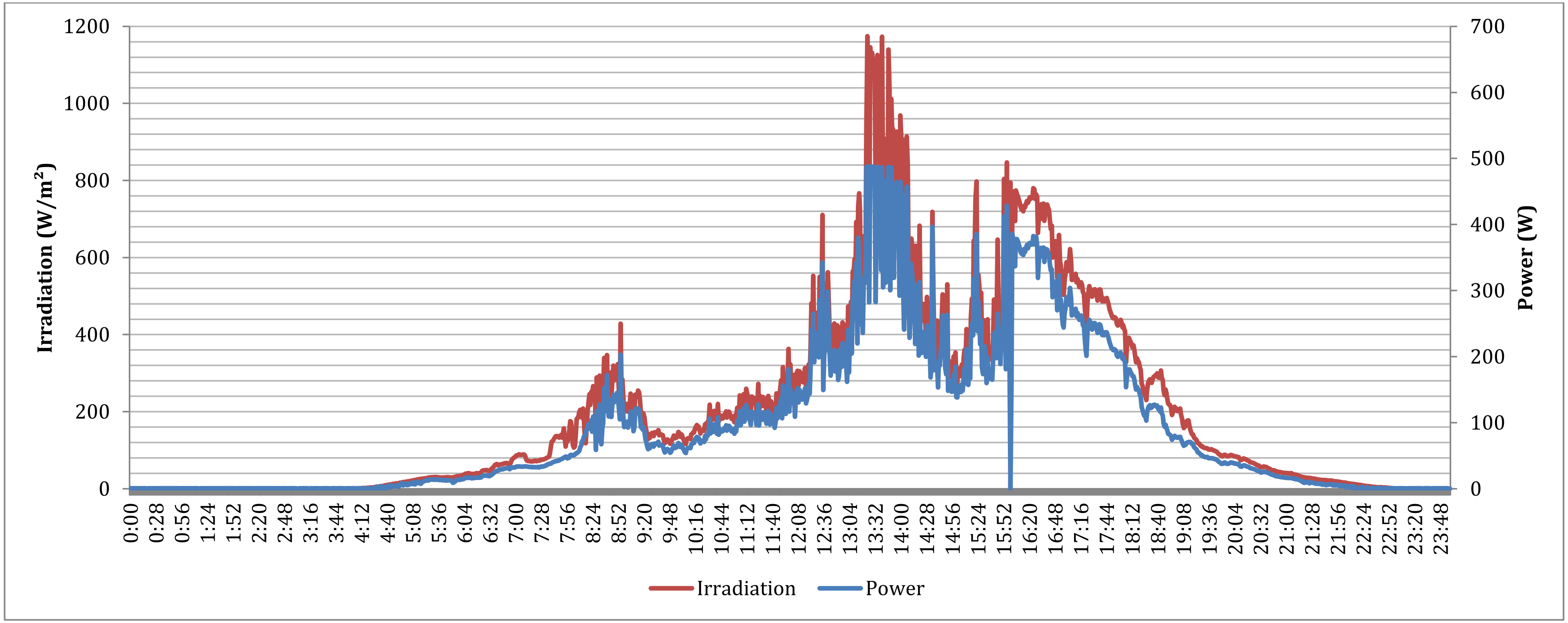


Figure 38. Data obtained from two Talesun TP660P-275 photovoltaic panels (275W each) installed on the Novia roof on 22/05/2019.

4.2 Efficiency calculation of the photovoltaic system

In order to calculate the efficiency of the photovoltaic system, the energy produced per unit of surface from the panels has to be determined. One panel consists of 60 cells, each one measuring 156,75*156,75mm (Talesun, n.d.). Given that, the two panels have a total surface of 2,95 m^2. The energy produced per square meter (W/m^2) is obtained dividing the power (W) by the total surface.

To calculate the efficiency, the power generated per square meter is divided by the energy that the panel receives from the sun (irradiation) and multiplied by 100 to get a percentage. The efficiency calculated from 14:30 to 14:45 on the 20/05/2019 on an Excel file can be seen in Figure 39, at the right on the white cells. The average efficiency for that period is 16,19%.

Date	Time	Power (W)	Energy (kWh)	Voltage (V)	Intensity (A)	Irratiation (W/m²)	Body temperature (°C)	Irradiation (W/m²)	Power (W/m²)	System efficiency (%)
20.5.2019	14:30	415,9	16,5	240,4	1,74	871,61	28,82	871,61	141,08	16,19
20.5.2019	14:31	294,6	16,5	239,7	1,24	631,5	28,93	631,5	99,93	15,82
20.5.2019	14:32	276,8	16,5	239,8	1,16	569,06	29,03	569,06	93,89	16,50
20.5.2019	14:33	268,4	16,5	239,8	1,13	559,71	29,11	559,71	91,04	16,27
20.5.2019	14:34	246,4	16,5	240	1,03	512,01	29,11	512,01	83,58	16,32
20.5.2019	14:35	240,8	16,5	240	1,01	502,46	29,12	502,46	81,68	16,26
20.5.2019	14:36	233,5	16,5	240,2	0,97	485,97	29,03	485,97	79,21	16,30
20.5.2019	14:37	242,4	16,5	240,6	1,01	501,87	28,96	501,87	82,23	16,38
20.5.2019	14:38	259,5	16,5	240,6	1,09	536,6	28,89	536,6	88,03	16,40
20.5.2019	14:39	295,2	16,5	240,7	1,23	603,33	28,84	603,33	100,14	16,60
20.5.2019	14:40	283	16,5	240,7	1,18	591,54	28,84	591,54	96,00	16,23
20.5.2019	14:41	338,5	16,6	240,9	1,41	679,69	28,85	679,69	114,82	16,89
20.5.2019	14:42	374,1	16,6	241,3	1,56	800,28	28,75	800,28	126,90	15,86
20.5.2019	14:43	342,9	16,6	240,9	1,43	714,18	28,64	714,18	116,32	16,29
20.5.2019	14:44	315,4	16,6	240,9	1,32	663,72	28,55	663,72	106,99	16,12
20.5.2019	14:45	257,5	16,6	240,9	1,08	544,06	28,32	544,06	87,35	16,05

Figure 39. Efficiency calculated in the Excel file on 20/05/2019 from 14:30 to 14:45.

5 Discussion

In order to achieve the aim of this thesis, both systems had to be assembled to further compare the energy production for the same period of time. The solar thermal system could not be assembled before the deadline for the writing of this thesis. A reason behind it is that this system needs more variety of devices to function than the solar photovoltaic. An example is the installation of pipes where the fluid circulates, which requires qualified personnel. These increase the difficulty in assembling the system before it is ready to test. However, the energy meter for the solar thermal system was tested in the laboratory with artificial data to ensure that the LabVIEW programme would work once the system was assembled. The photovoltaic system was assembled successfully.

To provide some context for the tests, the location of the experiments and its average weather conditions were analysed.

A LabVIEW and Modbus summaries were completed to give a base to understand how the software and the protocol work, facilitating the reader to follow the thesis.

The devices from both systems were listed and their functionality and characteristics briefly described. The schemes from every system telling the order of the devices were elaborated and the electric connections were described.

An initial objective was to communicate with all the devices through one Modbus RTU Network, but there were communication problems with the LabVIEW software. Quite frequently anomalous values were received from the sensors. Then, one network was used for each sensor and the programme run correctly. Because of that, the Modbus RTU communication parameters did not have to be common in all the devices. After many attempts, the reading from the desired addresses was successful and the values could be converted to the desired units.

LabVIEW was shown to work like a Modbus RTU master. The programme designed communicated properly with the sensors from both systems, which were first tested in the laboratory and then on the roof (only solar PV system). It gathered data for five consecutive days (until stopped), iterated every minute and stored it in an Excel file, as expected. However, there was an issue with the data representation. For irradiation values higher than 655,36 W/m^2, the LabVIEW programme did not give the complete value but only the difference between it and 655,36 (i.e. for irradiation of 700 W/m^2, the output value was 700 - 655,36 = 44,64W/m^2). This is because the data from the sensor came as a signed 32-bit value, and it is represented in two addresses (16 bit each). Only the first address was read, up to 2^{16} = 65536 values (to get the irradiance in W/m^2 this value has to be divided by 100). After that, it started again from 0. However, the data in the Excel file was corrected to represent the correct outputs.

Figures 35 to 38 show the data collected from the Photovoltaic Panel from the 18th, 19th, 20th and 22nd of May 2019. The most noticeable aspect is the relation between the irradiation and the power generated, which clearly shows a proportionality and how it varies every day.

It is also interesting to see that the weather of the different days varied. The first day (18th of May) was a sunny day without any clouds in the sky and both lines (irradiance and power) have a smooth result, almost perfect. On the other hand, the other days were partly cloudy, which leads to an irregular output. Therefore, those days the panel produced lower energy than the 18th of May.

The reliability of the results was contrasted by consulting the weather for those days (Timeanddate, 2019). Analyzing if the relationship between the irradiance and the power is kept may facilitate detecting anomalies. After correcting the data in Excel few anomalies were found, except for the 0 values in some isolated iterations.

Another interesting factor is the total energy generated each day, which can be extracted from the Excel file as the energy meter provided it.

Table 3. Total energy generated during the whole day.

Day	Energy (KWh)
18th of May	3,7
19th of May	2,6
20th of May	2,6
22nd of May	2,4

Table 3 clearly shows the statements mentioned before. The sunny day (18th of May) has a significantly bigger electricity production than the others, which have a similar one between them but quite lower than the first one. From this information, it can be concluded that clouds largely influence the energy produced by photovoltaic panels. Other objects such as the Novia flag on the roof may also affect the output by casting shadow on the panels, but they can be neglected as it is for a short period.

Efficiencies were calculated from the Excel data (see Figure 39), giving an average of 16,19% for that period of time. The datasheet from the photovoltaic panel (Talesun, n.d.) says it has an efficiency of 16,8% (see Table 1). The microinverter has an average efficiency of 95,1% (ENVERTECH, n.d.) (see Table 2). Both combined have an efficiency of 0,168 * 0,951 = 0,16 = 16%, which is close to the calculated one.

5.1 Limitations and suggestions for further research

This thesis had certain limitations in terms of time testing, as in order to be able to extract accurate and reliable conclusions about which is the best kind of technology in this region, the data should be collected for several months. Not only that, but the thermal system could not be assembled. The dependence on external authorized personnel and the requirement of more complex equipment extended the expected time for its assembly.

This thesis can be the starting point for further studies, such as the mentioned objectives that could not be achieved. Both devices could be tested simultaneously for a longer period of time, ideally over the four seasons. To what extent the varying weather conditions and solar irradiation through the year affect each system and to compare between them could be of interest, as depending on the season each system has different efficiency. For instance, PV panels have their highest efficiency at 25˚C (Fox, S), while solar thermal has its best performance when the fluid temperature is as high as possible, reaching temperatures of 200°C. Also, how each system affects the environment from the manufacturing to the disposal by doing an LCA (Life Cycle Assessment), because despite generating clean energy there are still some emissions related to the complete life cycle. Also, the LabVIEW programme could be optimized.

6 Conclusions

To conclude, the thermal systems can be more complex to assemble than expected, so this should be taken in mind when organizing the time. LabVIEW can be used as a Modbus RTU master, achieving a successful communication, although other simpler softwares may be of more convenience. It could also store the data in an Excel file. The output from the photovoltaic panels was proportional to the received irradiance, showing a notable difference between cloudy and sunny days. The calculated efficiency from the photovoltaic system was found to be similar to the combination of the rated efficiencies from the panel and the microinverter.

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Appendices

Appendix 1. Error with the programme QModMaster

As mentioned before, there can be several issues which lead to not receiving the expected answer from the device. A clear example is provided below using the software QModMaster, the most basic for communicating through the Modbus protocol and the used in this thesis when checking the correct functioning of a device for the first time.

The example shows both an answer received when there is a wrong input and when all the values are correct. Due to its basic interface, it makes it easier than other software's to locate the error. The main screen (Figures 1 and 2) asks for the Modbus Mode (TCP/RTU), Slave Address, Function Code, Start Address, Number of Registers and data format (decimal/ binary/ hexadecimal). The Modbus RTU Settings (Figure 2) asks for the port in which the terminal is connected, baud speed, data bits, stop bits and parity.

The energy meter Kamstrup 6M2 is used in this example. The correct parameters are introduced except for the baud rate of 9600 instead of 19200 (the correct). An error occurs (Figure 1). Then, the baud rate is corrected and the communication is successful (Figure 3). The data received from the slave device is the room temperature from the laboratory. In this case, the temperature is represented in 32 bits using two addresses (16 bits in each address). The value is low, so only the second address is used. This value must be divided by 100 to get the temperature in °C (22°C).

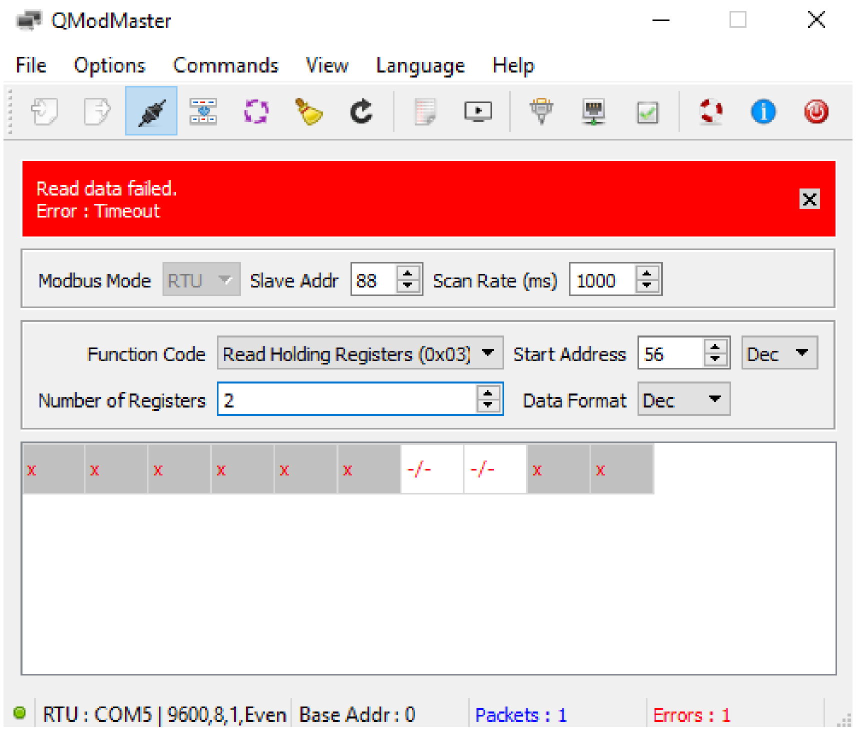

Figure 1. Screen capture of a wrong answer in QModMaster.

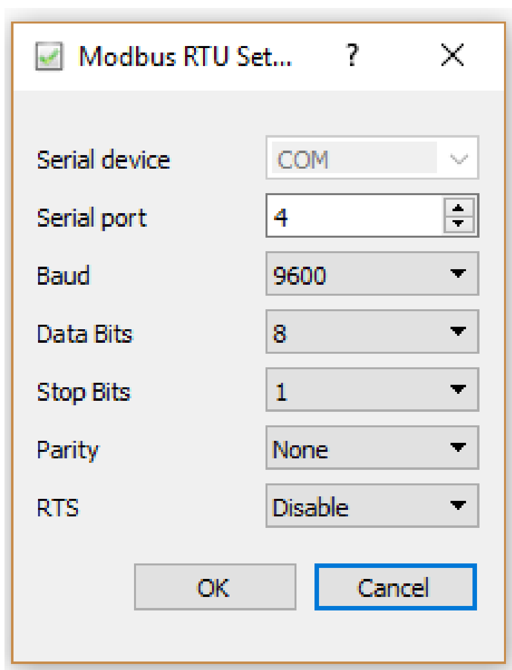

Figure 2. Modbus RTU Settings in QModMaster.

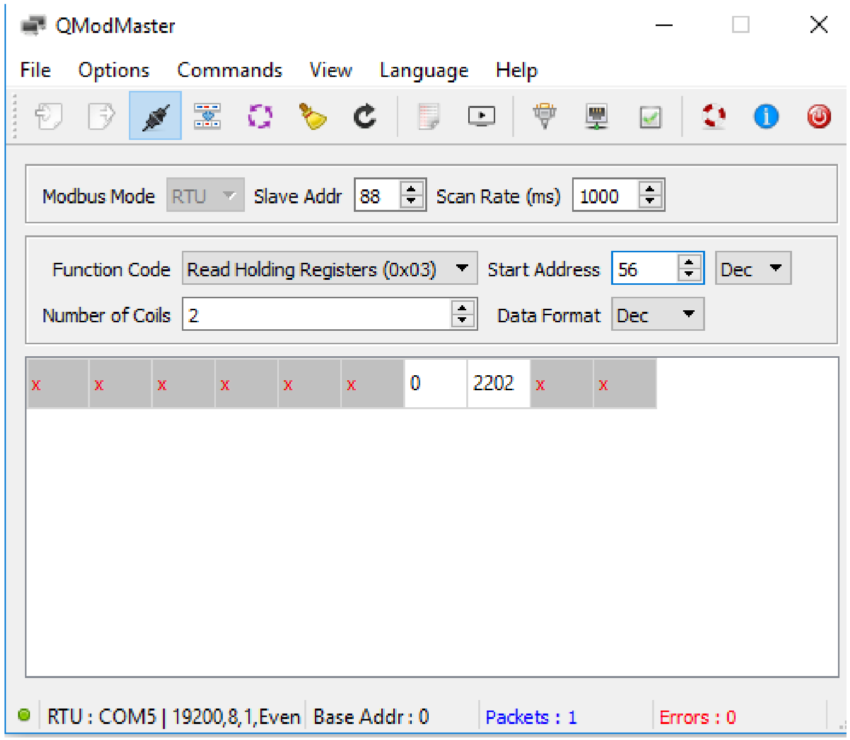

Figure 3. Screen capture of a correct answer in QModMaster.

Appendix 2. Communication through Modbus RTU in LabVIEW

First of all, to be able to communicate through Modbus RTU in LabVIEW a library containing the functions for it must be installed. It is possible to download it from the following link: https://forums.ni.com/t5/Reference-Design-Content/LabVIEW-Modbus-API/ta-p/3524019.

Once installed, the Modbus Library should appear in the Block Diagram (*right click* → *Data Communication* → *Modbus Library*). Inside the library, there is the option to create a *Modbus instance* → *New Serial Master*. This asks for the Modbus RTU communication parameters such as *unit ID, serial type, baud rate, VISA resource name, parity* and *flow control.*

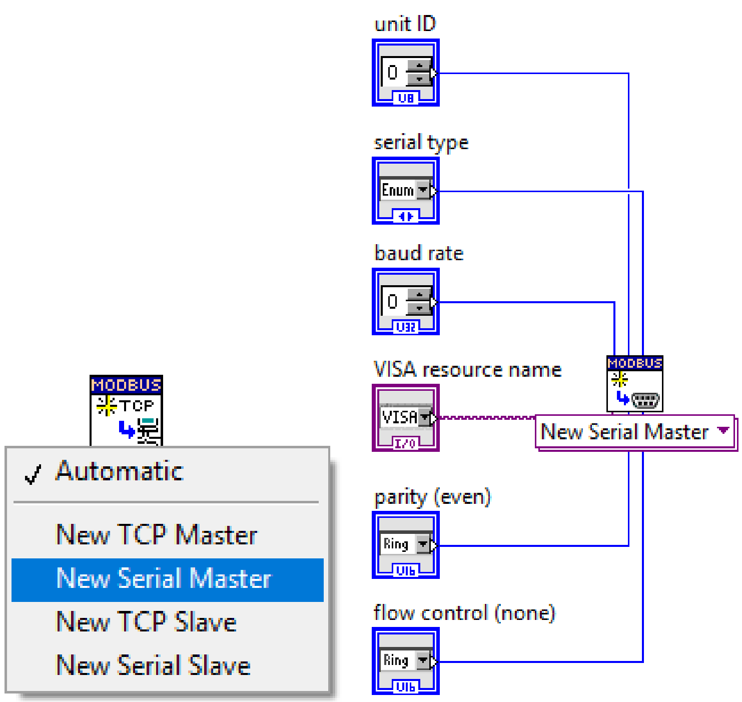

Figure 4. New Serial Master function.

In order to constantly monitor the slave devices, a *While Loop* can be used. It will run the code inside until the stopping condition is true (for example, a stop button is pressed). A period of time between iterations can be set with a *Wait* function.

Read or write Input or Holding Registers are the most common functions used when interacting with the slaves. They are placed inside the loop and connected to the *Serial Master*. Controls or constants can be used to set values at the *starting address* and the *number of inputs*.

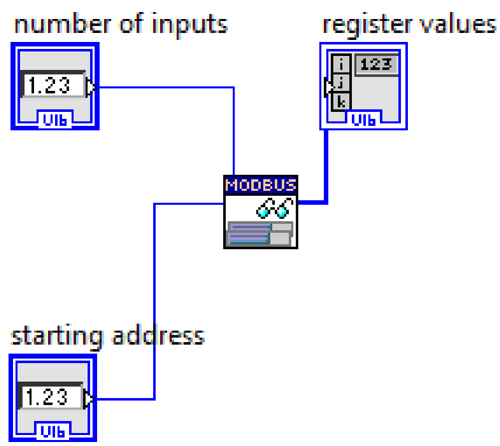

Figure 5. Read Input Registers function.

Finally, a *Shutdown* function is set outside the *While Loop* to erase the Modbus instance once the loop is stopped. The functions are wired as shown in Figure 6.

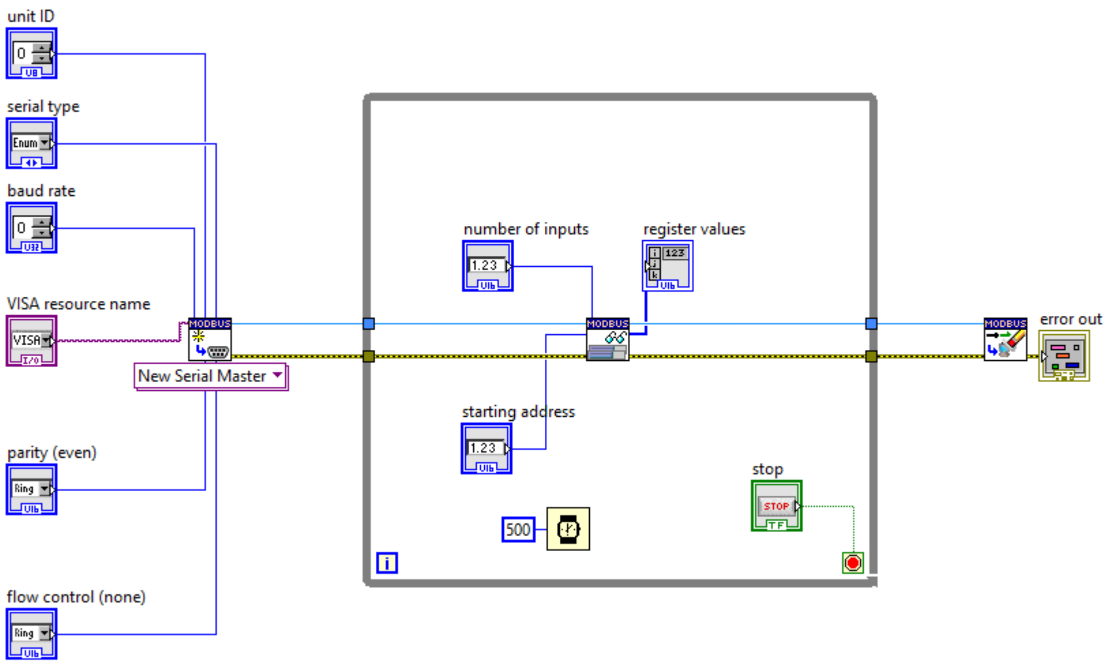

Figure 6. Simple LabVIEW programme able to communicate through Modbus RTU.

This basic programme allows the user to communicate with a Modbus device. It is the foundation for the programme designed in the thesis to transfer data with multiple sensors at the same time. The user interface can be seen in Figure 7.

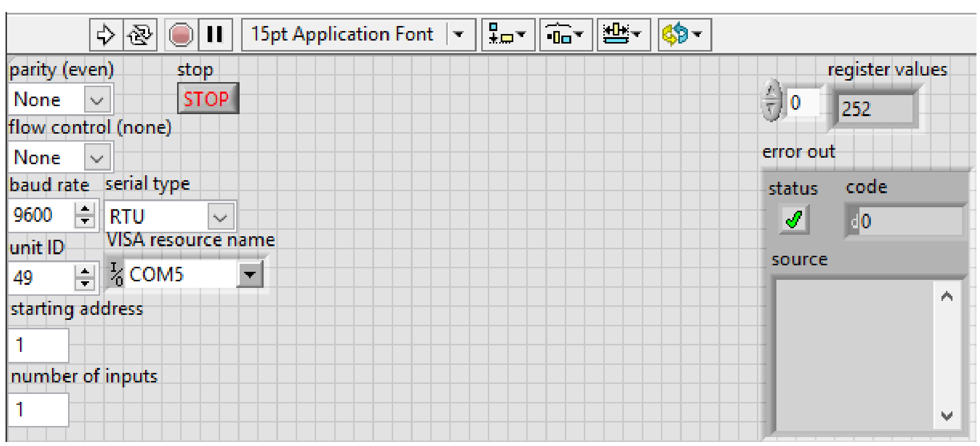

Figure 7. Front panel from the programme in Figure 6.

Appendix 3. Modbus RTU communication parameters of the devices

Kamstrup MULTICAL 6M2

Table 1. Modbus information for the Kamstrup MULTICAL 6M2.

Slave Address	Baud Speed	Data Bits	Stop Bits	Parity
88	19200	8	1	Even

	Function code	Start Address	Number of registers	Response	Units
T1	Read holding registers	56	2	Value/100	°C
T2		60		Value/100	°C
Flow		48		Value	l/h

(Kampstrup, n.d.)

Hukseflux SR05-D1A3 pyranometer

Table 2. Modbus information for the Hukseflux SR05-D1A3 pyranometer.

Slave Address	Baud Speed	Data Bits	Stop Bits	Parity
1	9600	8	1	Even

	Function code	Start Address	Number of registers	Response	Units
Irradiation	Read holding registers	2	2	1st value * 2^16 + 2nd value/100	W/m^2
Internal temperature		6		Value/100	°C

(Hukseflux, n.d.)

Carlo Gavazzi Type EM111 energy meter

Table 3. Modbus information for the Carlo Gavazzi Type EM111 energy meter.

Slave Address	Baud Speed	Data Bits	Stop Bits	Parity
1	9600	8	1	None

	Function code	Start Address	Number of registers	Response	Units
Power	Read holding registers	262	2	Value/10	kWh
Energy		274		Value/10	V
Voltage		258		Value/10	W
Intensity		256		Value/1000	A

(Carlo Gavazzi, n.d.)