SCIENTIFIC INSTRUMENTATION

Development of instrumental device to measure the Solar irradiance

PRELIMINARY PROJECT

DF0820 - Scientific instrumentation

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1 Introduction

In the present document the problem statement for the project of the scientific instrumentation subject will be presented. This project is based in the build of a solar irradiance sensor to monitor photovoltaic systems.

2 Content

2.1 Problem statement

In the recent years, one of the major issues in the world is the climate change. Human activities, in particular burning fossil fuels, have released carbon dioxide and other greenhouse gases to the atmosphere affecting the global climate. The Intergovernmental Panel on Climate Change (IPCC) said that in the last 130 years, the world has warmed by approximately 0.85 °C [7]. According to the World Health Organisation (WHO) this problem affects many of the social and environmental determinants of health - clean air, safe drinking water, sufficient food and secure shelter [8]. Extreme heat can cause cardiovascular and respiratory diseases and could even lead to death among elderly people, i.e Robine et al. determined that in the- summer of 2003 in Europe due to the heat wave, more than 70.000 deaths were recorded [9].

Looking to face this problems, the governments have been developing different policies and regulations in order to reduce the CO_2 emissions and to maximise the efforts to reduce climate changes problems. By this way, the Paris Agreements were established that are the first-ever universal, legally binding global climate change agreement, adopted at the Paris climate conference (COP21) in December 2015 [10]. This agreement look for set out a global framework to avoid dangerous climate

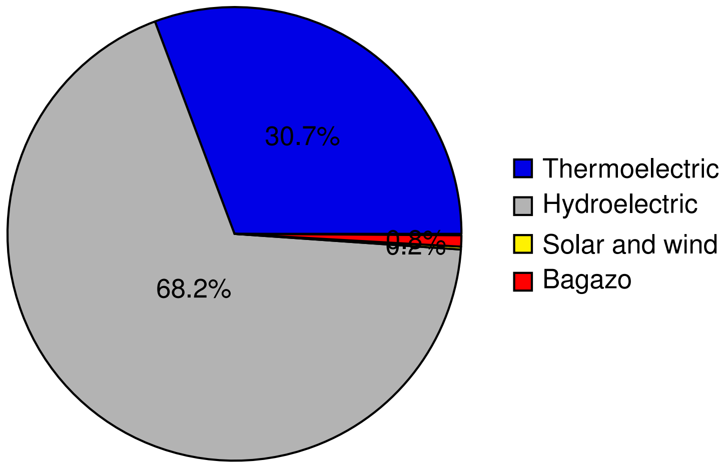

Figure 1: Electric generation matrix in Colombia up to 2018, information taken from [1].

change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. It also aims to strengthen countries ability to deal with the impacts of climate change and support them in their efforts.

Colombia, by becoming member of this agreement, aims to reduce its emissions by 20% for the 2030 [11]. To achieve this goal more than 100 options to mitigate the emissions were identified to implement in the different sectors like Agriculture, forestry and other land, Industry, Residuals, Energy, Transport and Housing that are the most important sectors of the national economy. In the energy sector, the energy generation in Colombia is mainly based on the Hydroelectric generation with a 68.2% of the generated energy followed by the Thermoelectric generation with a 30.7% as shown in Figure 1.

In the last place of the generation matrix is the Solar and Wind energy with only 0.2%. This is supposed to change in the future as can be seen in Figure 2 where is shown the prognostics of the increment of installed power of renewable energies in two different scenarios.

To optimize the performance of the photo-voltaic systems, the solar irradiance must be measured in different places to estimate the potential energy generation and in this way improve the performance of the overall solar systems. The instrumentation for this kind of systems is generally very expensive. For this reason is proposed the development of an instrumental device to measure the solar irradiance reducing prices.

2.2 Objectives

In this subsection, the general objective and the specific objectives of the project will be presented.

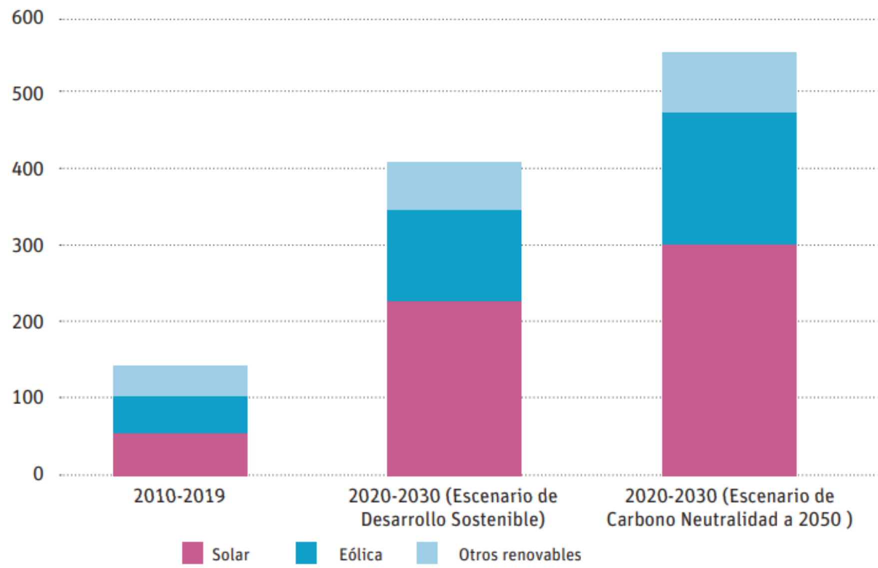

Figure 2: Annual capacity mean increment of renewable energies, figure taken from [1].

2.2.1 General Objective

To develop an instrumental device to measure the solar irradiance based in a solar cell generation to predict and optimize the generation of a photovoltaic system.

2.2.2 Specific Objectives

- To design the instrument folowing the Ulrich methodology.
- To design the electronic of the system to design and obtain the measure of the solar irradiance.
- To develop and calibrate the instrument.
- To evaluate the performance of the instrument when it is installed in a photo-voltaic system measuring the solar irradiance and determining the generated power of the system.

2.3 Project Scope

Next is presented the characteristics of the final instrument developed:

- The instrument developed must be able to measure the solar irradiance.
- The instrument deliver the solar irradiance in a CAN-protocol communication.
- The instrument can be recalibrated and reprogrammed.
- The instrument is capable to resist harsh environments.

2.4 Theoretical frame

In the next subsection the theoretical frame of the project is presented. First will be explained what is the solar irradiance, the common units and its characteristic curve. Then the different ways to measure the solar irradiance will be presented. Finally the most common instruments to measure the solar irradiance will be explained deeply.

2.4.1 Solar irradiance

When installing photo-voltaic systems, one of the main variables to measure is the solar irradiance. Irradiance is the rate at which radiant energy is incident on a surface per unit area of surface [2], so the solar irradiance can be understood as the amount of power of the light of the sun hitting in a square plane each second. This effect happen because of the energy carried by the photons wavelengths from energetic X-rays and gamma rays to visible light to the infrared and radio [3]. The solar irradiance is measured in watt per square meter in SI:

$$G = [\frac{W}{m^2}]$$

The solar constant G_{sc} is defined as the energy received from the sun in a specific unit area of surface perpendicular to the direction of propagation of the radiation at mean earth-sun distance outside the atmosphere [2]. This constant for the earth is 1367 $[W/m^2]$. The solar spectral distribution of the extraterrestrial radiation is useful to know the amount of radiation that wold be received when there isn't atmosphere. The World Radiation Center (WRC) stablished an standard spectral irradiance curve shown in Figure 3. To estimate the solar irradiance based on the wavelength of the light, different methods has been developed. In figure 4 are presented the models of Thuillier 1992, Thuillier 1994 and ASTM E590. Finally, in Figure 5 is presented an approximation of the solar irradiance during a day.

2.4.2 Instruments to measure the solar radiation

1. **Pyranometer:** Is an instrument used to measure the total hemispherical solar radiation, normally is used on a horizontal surface to measure Global horizontal Irradiance (GHI). The shaded from the beam radiation by a shade ring or disc is to measure Diffuse Horizontal Irradiance (DHI) [2]. The Pyranometer has a dome to receive the entire 180 [deg] of the sun trajectory. High-quality glass domes are transparent up to 250 nm - 4500 nm radiation [5]. In Figure 6 is shown a pyranometer and its components.

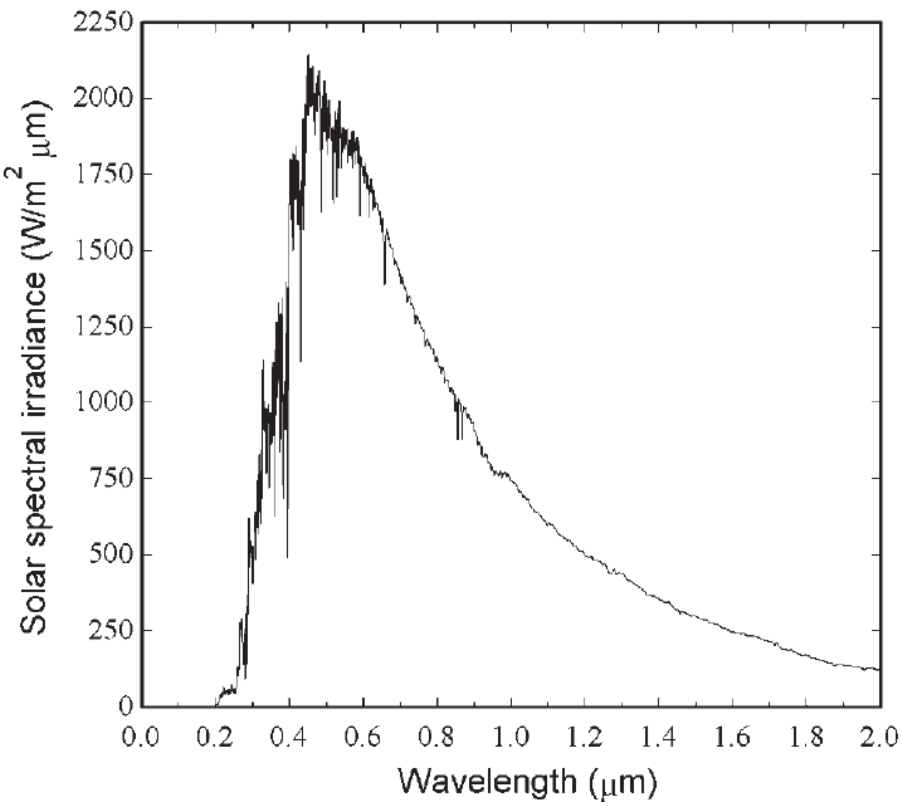

Figure 3: The World Radiation Center (WRC) standard spectral irradiance curve, taken from [2]

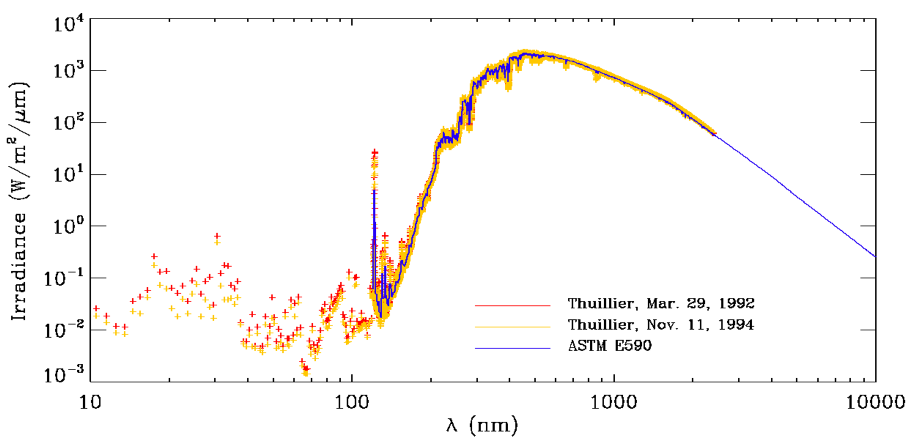

Figure 4: Models to estimate the solar irradiance based in the wavelength, taken from [3]

2. **Pyrheliometer:** Is an instrument that use a collimated detector to formeasure the solar radiation from the sun and from a small portion of the sky around the sun at normal incidence. This instrument is used to measure the Direct normal Irradiance (DNI). To measure the direct beam the pyrheliometer must be pointed normal to the sun, this can be achieved with a two-axis solar

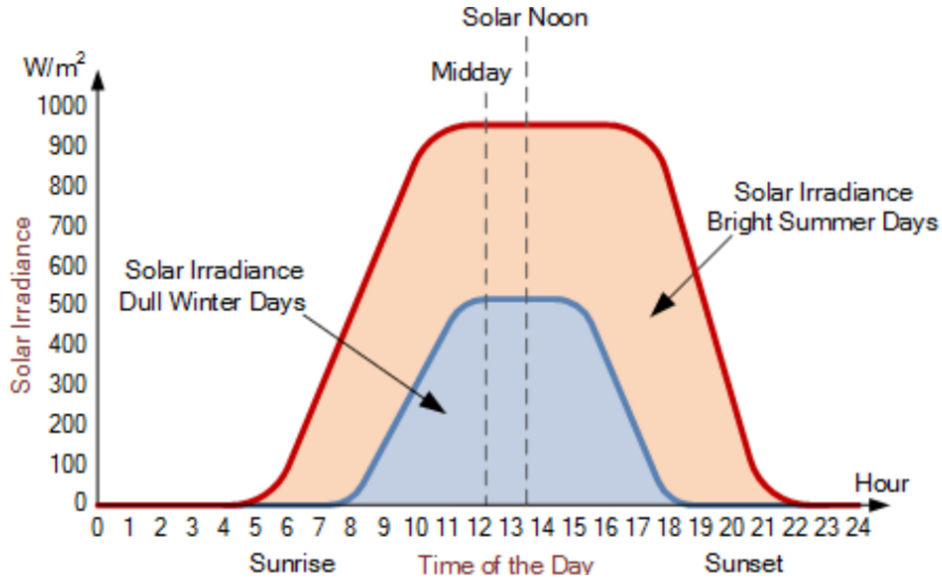

Figure 5: Solar irradiation during the day, figure taken from [4]

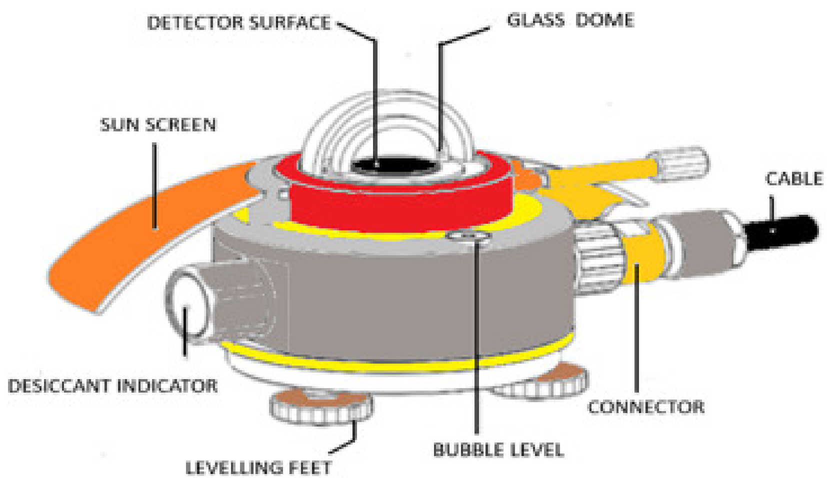

Figure 6: Schematic of the Pyranometer, taken from [5]

tracker. In Figure 7 is shown a pyranometer and its main components.

3. **Multi-Filter Rotating Shadow Band Radiometer (MFR-7):** This instrument is used to measure DHI and GHI using one device with a minimum number of moving parts compared to the Pyrheliometer setup. This sensor is composed by one rotating shadow-band. This instrument has a control unit that calculates the rotation of the shadow-band based on the position of the Sun. In this way, th device moves the shadow-band to the right position four times a minute. First is measured the GHI when the sensor is not shaded. Then the DHI measurement is performed when the shadow-band shades the sensor. In Figure 8 is shown a Multi-Filter Rotating Shadow Band Radiometer (MFR-7) and its main components. [5].

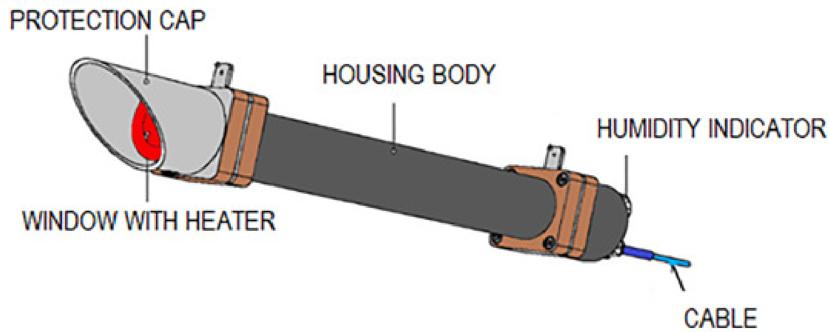

Figure 7: Schematic of the Pyrheliometer, taken from [5]

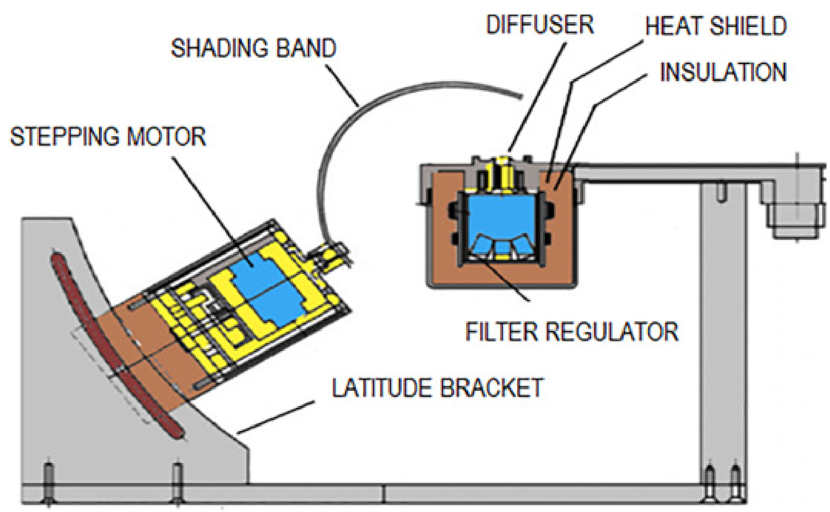

Figure 8: Schematic of the Multi-Filter Rotating Shadow Band Radiometer, taken from [5]

4. **Rotating shadow-band radiometer (RSR2):** This device has the same principle of the device showed before (MFR-7. A control unit periodically shade a pyranometer using a photodiode sensor. DNI values are calculated according to Eq. 1.

$$GHI = DNI * cos(\theta) + DHI \tag{1}$$

Where θ is the incidence angle. In this way, DNI is an approximation rather than an accurate measurement. In Figure 9 is shown a Rotating shadow-band radiometer (RSR2) and its main components. [5].

5. **Silicon Sensors:** Silicon-based sensors are sensor based in a photo-voltaic cell. This type of sensor is implemented to monitor PV plants. Silicon-based sensors have a spectral response between 300–1200 nm. In Figure 10 is shown a Silicon-based sensor and its main components. [5].

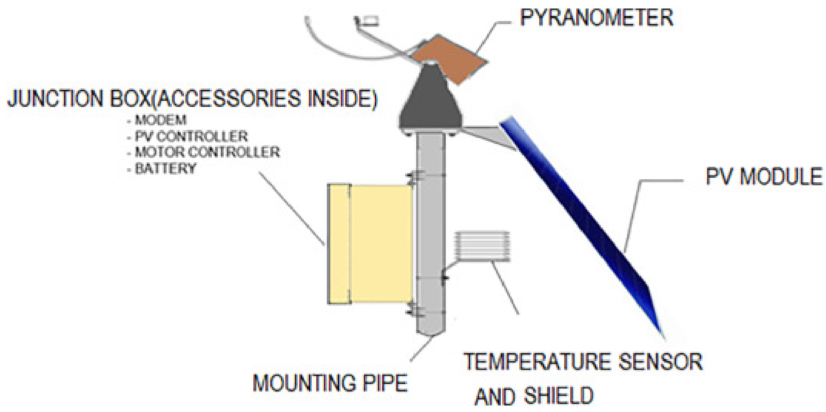

Figure 9: Schematic of the Rotating shadow-band radiometer, taken from [5]

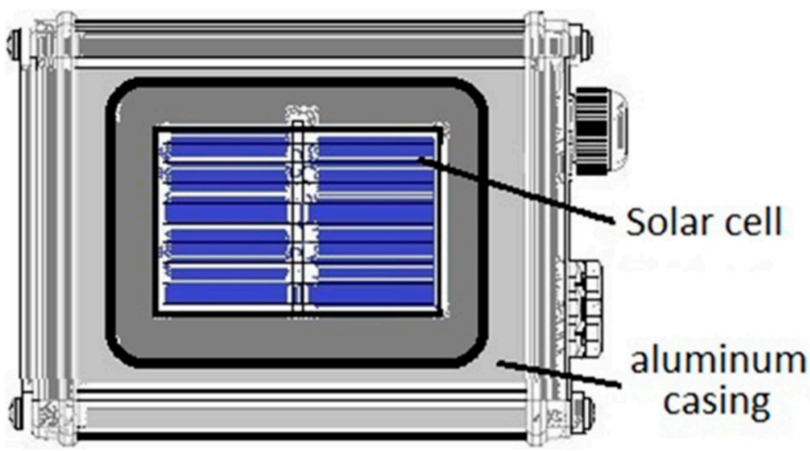

Figure 10: Silicon based irradiance sensor, taken from [6].

2.5 Methodology

In this subsection, the methodology and the step to develop the device will be presented. This methodology is based in the Ulrich methodology.

1. Design stage: First, both the mechanical and the electronic are designed using the tools of simulations to establish the performance of the designed device.
2. Component selection: Based on the user requirements, the sensors and components will be selected.
3. Prototype: The circuit will be mounted and tested.
4. Software development: The software for the embedded system will be designed and tested in the circuit.
5. Device build: With the circuit ready and the mechanical case adapted, the device is builded.

6. Test and calibration: Finally, test the performance of the instrument and calibrate it based on the measure of a pyranometer.

2.6 Product design specifications

For the product design specifications, the most important necessities were taken into account. The PDS is presented in Table 1. From the PDS, the House of quality is developed as shown in Figure

Table 1: PDS

Necessity	Requirement	Variable	Units	Value
Sense the solar irradiance good	The device must be accurate	Accuracy	%	+-5
The device must be small	The dimention of the device must be less than 10x10x5 cm	Volume	cm^3	<500
The device must be cheap	The cost of the device can't be greater than 100.000 COP	Cost	COP	<100.000
The devece must be light	The weight of the device must be less than 500 g	Weight	Grams	<500
The device will be outside	The instrument must support harsh environments	IP protection	IP	>65

11.

From the House of quality, it can be concluded that the most import functional requirements to fulfill are the price and the environmental resistance of the device. The weight and volume are the less important requirements.

2.7 Technological impact:

The main contribution of this device is the low cost and the communication protocol:

- The cost of the device must be lower than the instruments in the market.
- The communication protocol of the device is CAN improving and opening new markets for the automotive industry.

2.8 Project cost estimate

Table 2: Cost estimation

Components	Aprox. Price
Case	$ 30,000.00
Electronics	$ 60,000.00
Solar cell	$ 10,000.00
Total	**$ 100,000.00**

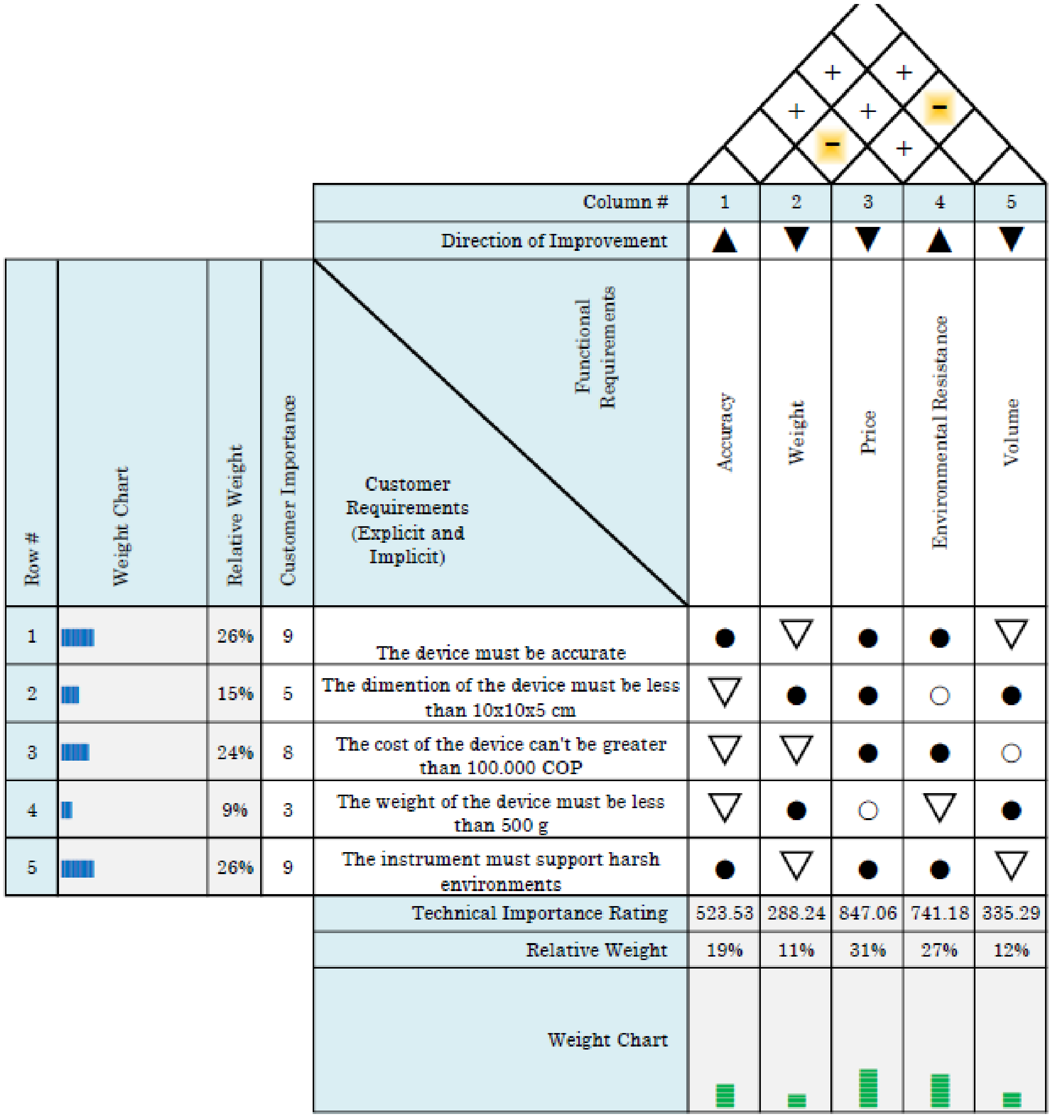

Figure 11: House of quality

2.9 Schedule adherence

Based on the schedule presented in Figure 12, the actual state of the project will be explained. At this moment, the project is delayed mainly because at the moment the selected cell hasn't arrived yet. For this reason the experimental tests have not yet been carried out. To understand better the cells, different measurements with another cell were carried out.

AÑO 2022		Planeado																
ACTIVIDAD	**Fecha de Inicio planeada**	**Duración en Semanas**	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
			14-feb	21-feb	28-feb	7-mar	14-mar	21-mar	28-mar	4-abr	11-abr	18-abr	25-abr	2-may	9-may	16-may	23-may	30-may
To design the instrument folowing the Ulrich methodology.																		
Product design specification	14-feb	1																
House of quality	21-feb	1																
Functional diagram	28-feb	1																
Morphologic Matrix	28-feb	1																
Decisión Matrix	7-mar	1																
Detailed design	7-mar	2																
To design the electronic of the system to design and obtain the measure of the solar irradiance.																		
Design de block diagram	14-mar	1																
Design the conditioning circuit	14-mar	1																
Simulate the circuit	21-mar	1																
Program the embedded system	28-mar	3																
To develop and calibrate the instrument.																		
Build the case of the device	18-abr	1																
Buid the conditioning circuit	25-abr	1																
Test the conditiong circuit	2-may	1																
Test the comunication protocol	2-may	1																
Integrate all the device	9-may	1																
Calibrate the device	9-may	1																
To evaluate the performance of the instrumentem																		
Install the intrument in a photovoltaic system	16-may	3																
Monitor the performance of the instrument	30-may	1																

Figure 12: Shedule

3 Conclusions

During the development of this instrument, we established the importance of the model development and simulations results because even if the selected cell is not available at this moment, preliminary design can be done based on the simulation results. Also it is concluded that to estimate the solar irradiation, is necessary to measure the short current and not the open voltage, because the voltage change in function of the solar irradiance doesn't change significantly and is very difficult to obtain trusted measurement due to the effect of the temperature. On the other hand the current doesn't change significantly with effect of the temperature and the measurements are more reliable. In the future, the model of the specif cell will be adjusted and the experimental curves will be obtained

Glossary

G_{sc}: The solar constant

DHI: Is the amount of radiation scattered in the atmosphere that strikes a given point on the ground.

DNI: The direct solar beam passing through the atmosphere.

GHI: Radiation measurable on a horizontal surface.

Solar irradiance: Instantaneous power density

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