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# A COMPARISON OF IRRADIANCE MEASUREMENTS USING LOW-COST SENSORS TO HIGH-QUALITY SENSORS

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## ABSTRACT

Solar photovoltaic technology is one of the most interesting options for future energy sources. It has high technical and sustainable potential due to its capability to produce electricity without fossil fuels and with small maintenance expenses. The technology has small environmental impacts and it could be one solution for global energy demand. Photovoltaic cells have been used to provide energy for satellites since the 1950s due to their capability to transform solar radiation straight to electricity. The photovoltaic technology investment has increased due to diffusion policies across the globe. Over 100 countries are using photovoltaics.

The objective of the thesis was to use the Quantitative approach to compare low-cost sensors with high-cost sensors via statistical analysis and give suggestions on how to upgrade a low-cost sensor prototype. The low-cost sensor was a polycrystalline solar cell and two high-cost sensors were a silicon photodiode pyranometer and a thermopile pyranometer. In addition, the interest was to analyse the impact of seasonal variations and temperature changes on measurement values.

The study showed that solar cells and pyranometers have a strong relationship. Seasonal variations and temperature changes had an impact on the measurement values. Results showed that the solar cell is temperature dependent. The low-cost sensors calibration process could be upgraded by concerning the cloudiness of the sky. Longer measurement periods would increase the reliability of the process.



**Keywords**: solar cell, pyranometer, photovoltaics, solar energy

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# 1 INTRODUCTION

Solar photovoltaic (PV) technology is one of the most developable technologies due to its capability to produce electricity in quiet, environmentally friendly, and distributed manner, without fossil fuels and with small maintenance expenses (Strupeit 2017, 273).

The portion of renewable energy sources is expected to grow up to 80% of electricity consumption in Germany by 2050 (Meilinger et al. 2021, 1). Neher et al. (2017, 170) state that photovoltaic (PV) energy has small environmental impacts and it could be one possibility to answer the global energy demand. Due to high solar insolation in developing countries, PV energy is an interesting option for local energy production (Neher et al. 2017). According to Michaelides (2012, 219), photovoltaic cells transform solar radiation straight to electricity and have been used to provide energy for satellites since the 1950s. Solar Cells could be able to produce the entire energy that mankind needs in the future. However, the required technology is expensive, but as fossil fuel prices rise and technology develops, the price of photovoltaic technology decreases. (Michaelides 2012, 219.)

According to López Prol (2018, 1170), Germany is the world's leading country with the highest installed photovoltaic capacity per capita (511 W/capita). The photovoltaics’ potential of global installed capacity will achieve 13% by 2040 due to the new policies, or even more, if countries aim to reach the Paris agreement´s two Celsius temperature target (the International Energy Agency cited in López Prol 2018.) The PV technology investment has increased due to fast cost decline in price and supporting diffusion policies across the globe. PV has the highest technical and sustainable potential of all renewable energy sources and it is considered having the potential to serve as the main energy source in a decarbonized energy system. (López Prol 2018, 1170.)

The thesis commissioner is Hochschule Bonn-Rhein-Sieg the University of Applied Sciences in Sankt Augustin, Germany. The thesis is part of the internship. A low-cost sensor prototype (solar cell) is developed for climate

monitoring in the home garden by Mechanical Engineering Master student Tobias Streckel. Data comparison between low-cost sensors (solar cells) and high-cost sensors (global horizontal pyranometers) is used for the calibration of the low-cost sensor prototype. The prototype's object is to supply an electrical variable that correlates with the radiant power ($W/m^2$). Priority to this sensor should meet the low-cost requirements of the project (Streckel 2023.)

The aim of this thesis is to compare low-cost sensors with high-cost sensors and answer the following research questions:

1. What is the relationship between low-cost and high-cost sensors?
2. What are the primary factors emerging from this relationship so that the low-cost sensors can be upgraded from these factored points?

The quantitative approach of the study aims to compare low-cost and high-cost sensors to each other via statistical analysis and give suggestions on how to upgrade the low-cost sensor prototype.

# 2 LITERATURE REVIEW

This literature review includes the most important topics concerning the content of this thesis. It presents the content of solar energy and photovoltaic system. Solar cells and pyranometers are presented in detail. Chapter 2.5 includes the most important measurement methods and quality aspects. Last chapter shows the importance of the seasonal differences in atmospheric sciences.

## 2.1 Solar energy

According to Michaelides (2012, 195), solar energy is almost equally distributed, available to all countries and a free source of energy. Earth receives the amount of solar radiation power that all mankind on earth needs. This power is approximately 1.73×1014 kW. Incident solar radiation (insolation) indicates a total energy of 5.46×1021 MJ per year. This energy is over 100 million times the amount of energy that humankind is using in a year. However, only a fractional part of this energy has been used by mankind. (Michaelides 2012, 195.)

A monochromatic Sun radiation has the aspects of radiation of a black-body at relatively 7.765 K. A black-body has advantageous radiation properties as absorbed power is constant in all directions. The energy density is a function of the temperature of the black body. The full spectrum of power from the sun can be captured by the various elements such as carbon dioxide, oxygen and water vapour. These elements absorb primarily parts of this spectrum at distinct wavelengths in the infrared part and the visible light of the solar spectrum in the terrestrial atmosphere. Consequently, several parts of the solar spectrum are lost and a portion of the radiation energy has been absorbed before the surface of the earth. (Michaelides 2012, 198.)

According to Michaelides (2012, 198–203), total radiation is the sum of incoming solar radiation (short wave radiation) and outgoing thermal or terrestrial radiation (long wave radiation). Global radiation is short wave radiation which is the sum of the sun’s direct radiation and scattered sunlight (diffuse radiation). The Earth's spectrum on the surface differs considerably from the outer atmosphere. The total power arriving at the surface is considerably smaller than in the outer atmosphere and significantly smaller than the solar constant S. The solar constant is a fundamental quantity that determines the incident insolation or solar radiation. It is the yearly average power that a receiver would collect outside the atmosphere. However, it is not precisely a constant because the distance between the Earth and the Sun varies by approximately 3% in a one-year period. It is approximately comparable to 1.353 kW/$m^2$. (Michaelides 2012, 198-203.)

Michaelides (2012, 195–219) states that the time of the day has a major impact on the amount of radiation. At night-time there is no radiation and solar power reaches maximum value at the solar noon when the sun is at its highest point on the horizon. A solar installation that transforms the incident solar power into electrical energy works year-round and needs to be estimated based on the total energy. The best indicators of solar energy potential are the yearly averages of energy and power. It should be noted that local insolation is influenced by humidity, cloudiness, pollution and other temporal variables at a particular location. That is why insolation and solar energy characterization can be seen as

predictable or a periodic variable. The cloudiness or clarity of the sky impacts the local insolation. Cloudy locations collect lower power from the sun because clouds reflect received radiation. Clouds and fog scatter a part of the radiation. The solar radiation diffusion spreads the radiation back in all directions in the atmosphere. This secondary radiation is called diffuse radiation which is part of the total radiation. Even though diffusion and absorption decrease power, they also contribute to the total power received in several locations, notably during foggy periods. In addition to cloudiness, the geographic latitude of the location, the day of the year, and the angle of the collector have an effect on the total supply of solar energy collected. (Michaelides 2012, 195–219.)

## 2.2 Photovoltaic system

According to Michaelides (2012, 219–226), the engineering system that is developed for the harnessing of solar energy is called photovoltaic system (PV). The photovoltaic method is based on the photoelectric effect where inbound radiation on a sensor triggers an electric current that is comparable to the radiation flux density. Solar cells convert energy to electricity using the same method. However, this method includes both advantages and drawbacks. According to Emeis (2010, 98), the main drawback of this method is that it depends on the wavelength of the incoming radiation. Another drawback is that Michaelides (2012, 225) states that the production of a PV cell requires the amount of energy that it can produce in four to five years. As an advantage Kosyachenko (2011, Preface XI) states that the solar power is pollution-free energy source in a time when there is a growing demand for renewable energy sources. The manufacturing of solar cells has developed significantly in recent years and over 100 countries are using photovoltaics. A common use for solar cells is solar panels, which are formed from solar cells that are electrically attached together. Photovoltaic assemblies are used for electric power in cars, boats, radio stations, and water pumps. The main intended use is based on grid-connected power generation. (Kosyachenko 2011, Preface XI.)

According to Lorenz et al. (2022, 593–606), radiance measurements are needed for the input data for multiple applications, as well as to build a basis for model

improvement, development and verification. The installed PV capacity in Germany was 52 GWp in 2022 and the use of PV power as the electricity supply is constantly increasing worldwide (Lorenz et al. 2022, 593–606). In the future PV technology demands innovative solutions such as flexible generation and new storage technologies. The system integration techniques advancements are assumed to develop the durability, efficiency and performance of PV which will decrease the costs. Novel crystalline and thin film cell concepts are promising technologies. (Strupeit 2017, 273.)

Kalogirou (2014, 486) states that the photovoltaic effect appears when a photon arrives at a photovoltaic material by reflection, absorption, or transmission through it. A valence electron of an atom makes the photon absorb. The electron‘s energy grows with the amount of the photon‘s energy. If the amount of photons energy is bigger than the semiconductor‘s band gap, the electron jumps into the conduction band and there it can move without restrictions. The absorbed photon causes an electron to come loose from the atom. A p– n junction allows extracting the electron by an electric field over the photovoltaic material. When the electric field is removed, the electron rejoins with the atom. When the electrical field exists, it runs through and generates a current. If the energy of the band gap is bigger than the photon‘s energy, the electron will not have enough energy to jump into the conduction band. Then additional energy is changed into electron‘s kinetic energy, which raises the temperature. The reason for the photovoltaic cells‘ low efficiency is that only one electron can be freed. (Kalogirou 2014, 486.)

The p–n junction is a junction formed of a p-type and n-type semiconductor. An electric field is formed across it by electrons and holes, which spread across this junction's boundary.  The movement of the photons creates free electrons in the n-layer. Pairs of electrons and holes are generated when sunlight‘s photons hit the surface of a solar cell and are absorbed by the semiconductor. The p–n junction’s electric field will separate the charges and the electrons move to the n-type side and holes to the p-type side if the pairs are near enough to the p–n

junction. An electric current will run when sunlight is shining to the cell and both sides of the solar cell are linked through a load. (Kalogirou 2014, 484–486.)

### 2.3 Solar cells

Most of the solar cells are silicon solar cells in mono crystalline form or large-grained polycrystalline form (multi crystalline silicon). Silicon is an elemental semiconductor with advantageous properties such as a well-balanced set of electronic, chemical, and physical properties and good stability. The successful use of silicon in microelectronics formed an industry that the photovoltaic industry has benefited from. (Willoughby 2014, 65.)

Pure monocrystalline silicon is raw material for monocrystalline silicon cells. It has a single constant crystal lattice structure and it does not contain almost any impurities or defects. The monocrystalline cells' major advantage is great efficiency which is approximately 14–15%. Premium modules have an efficiency of around 20%. (RENI 2012 cited in Kalogirou 2014, 498.) According to Kalogirou (2014, 498), a disadvantage is the complex manufacturing process that causes proportionally high costs. However, bigger raw material manufacturing capacity has lowered the cost which makes the price more competitive. Monocrystalline modules are often used on residential and commercial rooftops. (Kalogirou 2014, 498.)

According to Price and Margolis (2010, 498), polycrystalline cells are made from multiple grains of monocrystalline silicon. The manufacture of polycrystalline cells is cheaper than monocrystalline cells, because of the easier manufacturing process. Polycrystalline cells are less efficient, with approximately the efficiency of 13– 15% (Price and Margolis 2010 cited in Kalogirou 2014, 498) and premium modules' efficiency is around 17% (RENI 2010 cited in Kalogirou 2014, 498). Kalogirou (2014, 498) states that poly- and monocrystalline cells’ have a relatively high temperature coefficient. Polycrystalline modules are widely used in different applications such as ground- and roof-mounted arrays because of high efficiency and a reasonable cost. (Kalogirou 2014, 498.) The operating temperatures and PV power systems strongly influence the electrical efficiency of

a solar cell (Zou et al. 2019, 306–307). The electrical efficiency and power output have a linear dependency on the operating temperature. A lower operating temperature increases electrical efficiency and PV power output with a comparable incident solar radiation flux. (Dubey et al. (2013) and Bayrakci et al. (2014) cited in Zou et al. 2019, 306–307.)

The study of Chander et al. (2015, 41–42) states that the major parameters of the efficiency of a solar cell are the spectral distribution of the temperature, irradiance and total irradiance. The spectral response (SR) of the solar cell is the sensitivity of a solar cell which is comparable to the light of different wavelengths during a measurement of short circuit current per unit light power. It is measured with spectrally clean light including a wide range of wavelengths corresponding to the solar radiation’s spectrum. The difficulties of spectral response measurements have an impact on the variance of the solar spectrum and the efficiency of the different types of solar devices. In an ideal situation, every photon would form electron-hole pair in an optimal solar cell and these photo carriers would move to the depletion region where the separation and gathering happen. The photons which do not have the same amount of energy as the band gap cannot form photo carriers and even with the needed energy, it is not crucial for contributing the photocurrent. (Chander et al. 2015, 41–42.)

The quantum efficiency is a parameter that shows the sensitivity of a solar cell. It shows the efficiency of equipment to generate electronic charge from incident photons. It is a measure that shows equipment’s response value with different wavelengths and it is assumed to be zero if the photon’s energy is smaller than the absorber band gap energy. (Chander et al. 2015, 42.)

## 2.4 Pyranometers

Pyranometers can measure horizontal solar irradiation at ground level. Together with the satellite data, the ground level measurements can present more accurate values, because of fewer systematic errors. The ground-level data is compared with satellite data so that the errors are recognized and decreased. The disadvantages of the diffuse and direct horizontal irradiation ground

measurements are the expensive and complex values to measure. That makes the access of these measurements limited, particularly in developing countries. (Nunez Munoz et al. 2022.) According to the ISO 9901:2021, the technology used in pyranometers is usually related to the pyranometer type such as photodiode or thermopile pyranometers. The requirements of standards affect the choice of the accuracy class. The accuracy classes A, B and C are defined at the ISO9060:2018 standard. These classes determine the metrological requirements for equipment uncertainties and measurement errors inside specific limits under specific measurement conditions. ISO determines two main types and an independent sub-category for pyranometers. The spectrally flat pyranometers includes the most of the thermoelectric pyranometers. The non-spectrally flat pyranometers are photodiode pyranometers and further sub-category is fast response pyranometer. (ISO9901 2021.)

The most of the thermoelectric pyranometer's spectral selectivity in the 0,35 µm to 1.5 µm range is under 3%. Usually, these pyranometers are more accurate over wide range conditions and applicable for the horizontal measurement of global horizontal irradiance (GHI) as well as reflected irradiance, plane array irradiance and artificial solar sources. These pyranometers are used to measure the typical solar energy measurements with the same calibration, which is usually done with the clear sky conditions, without considerable fall of accuracy. These pyranometers almost have a zero spectral error. (ISO9901 2021.)

ISO9060:2018 does not classify silicon photodiode pyranometers as spectrally flat pyranometers. The spectral errors of photodiode pyranometers can be determined for clear sky conditions solar spectra alone. However, the spectral error is not based only on the classification. The non-spectrally flat sensor's factory calibration is usually made for clear sky conditions. It should be noted that the different conditions have an impact on the pyranometer, and it can change the sensitivity and uncertainty of the sensitivity of the equipment. (ISO 9901 2021.)

## 2.5 Measurements and quality

According to Emeis (2010, 3–28), in meteorological research, measurements are mandatory for any further enhancement of knowledge. Measurements are crucial for monitoring, analysis and documentation purposes. The weather and climate prediction models are based on input data from the weather and climate. Measurement data is used for climate predictions, air quality assessment and monitoring, as well as control of limit and threshold values. High-quality measurement devices are mandatory for these purposes. The major force for the development is more precise research and monitoring requirements, as well as improvement of measurement techniques and equipment. These measurement devices catch the chemical or physical condition of the perceived system and make a comparison between a chosen state variable of the system (e.g. global radiation) and a predefined scale for the chosen variable (e.g. radiation power). This comparison results in a number that shows a relationship between the state of the perceived system and a comparison system that serves a scale. (Emeis 2010, 3–28.)

Emeis (2010, 3–28) states that the amount of measurement values collected from a measurement needs to be judged by considering the specific measurement method or technique. The technique limitations and features need to be recognized and it should be noted that the equipment's temporal and spatial resolution is always device specific. The input signal of a sensor detector is documented, conducted, and amplified by the measurement equipment. The output signal is saved to the storage medium. The energy needed for this process can be performed electrically. Measurement of irradiance with a radiometer is a passive measurement method which uses remote sensing. (Emeis 2010, 3–28.)

The statistical or systematic deviation of a measurement value is called an error. Random or statistical errors cause discrepancies in measurement values that can be above or below the correct value. The average measurement value (the expected value) from a longer period is expected to be close to the true value. Systematic errors can show values that are one sided. Taking the average value

increases the scatter of the measurement values without the mean value getting closer to the true value. It should be noted that a bias exists between the true and mean values. The equipment or methods' defectiveness and restrictions are causing systematic errors, but a calibration process of the equipment may decrease the bias. (Emeis 2010, 3–28.)

The measurement value is an electrical value as voltage or current. When the measurement equipment supplies an analogue value, the input signal needs to be converted to a digital value and included in a calibrating process. Data loggers save the data at a defined sampling rate. The last data set has to be inspected for homogeneity. Standard deviations and mean values should not include inexplicable deviations. If there are outliers that are outside of a predefined span of the standard deviation, it needs to be checked and justified manually. The data series trend is caused by equipment drifting and needs to be recognized. The data evaluation should only include measurement data whose origin and quality are confirmed. (Emeis 2010, 3–28.)

The quality control and accuracy assurance practices ensure the reliability of the measurements. Quality control includes monitoring ongoing measurements and data evaluation. The evaluation conducts the observation of equipment failure and running data control. Before the first measurement, the spatial and temporal resolution of the data needs to be determined. The expected accuracy and range of the data have to be determined before the measurements. These elements affect the selection of equipment and measurement platform. The equipment needs to be tested before starting the measurements. Regular maintenance should be considered depending on the chosen equipment. (Emeis 2010, 3–28.)

Emeis (2010, 3–28) states that the selected study area affects the success of the measurements and obstacles should not impact the measurements. Obstacles should not arise over 3° above the horizon and that is why optimal study areas are on the top of high buildings. Radiation equipment requires maintenance and, for example, the glass or domes need to be wiped on regular basis, because raindrops and dust impact the results. Moreover, plastic parts age and birds

might attack the equipment or defecate the surface of the equipment and precipitation and wind can have a major impact on the behavior of the sensors if domes are not used. (Emeis 2010, 3–28.) According to Lorenz et al. (2022, 593–606), the aim of quality control is the observation of systematic effects such as shading, soiling, calibration issues, and data logging problems. The observation of outliers and defective measurements can result in dew or snow on the pyranometers. As a result, there are quality flags that can help to screen defective measurements. Furthermore, continual problems in the measurement data need to be recognized and corrected in maintenance when observed. (Lorenz et al. 2022, 593-606.)

According to Emeis (2010, 3–28), the calibration of equipment before, during, and after the measurement can remarkably decrease the bias of the results. Limitations with the equipment or a measurement method can cause systematic errors. Time increases the measurement error which is caused by the chemical or mechanical aging of the materials and compounds. Calibration and regular maintenance can reduce these errors. The slope of the calibration line is the sensitivity of the equipment which shows if there is a linear dependency between the measured variable and the output value of the equipment. The sensitivity indicates the equipment’s ability to catch the small-scale difference in quantity. (Emeis 2010, 3–28.)

## 2.6 Seasonal differences

According to Michaelides (2012, 196), the angle of inclination of the globe leads to differential energy absorption by the two hemispheres leading to seasonal variations and local changes in seasonal weather, the temperature and local wind patterns. The seasons and seasonal variations between the climate and weather are caused by the two hemispheres of the earth that get different amounts of solar radiation with an exception for two equinox days. Two motions, the motion of the globe around the sun and the rotation of the globe around its polar axis cause significant predictable variations in the intensity of the solar energy received in different locations. Solar energy can be received during daytime hours based on annual and diurnal timescales. (Michaelides 2012, 196.)

According to Rehman Tahir et al. (2021, 1–6), a monthly basis performed statistical analysis on subdaily data can be used to determine seasonal changes‘ effects on the datasets. The monthly and seasonal climatic variations, such as clouds and aerosols, have an important part in sky clearness affecting the amount of solar radiation delivered on the surface. If these changes are not considered, these can cause varying errors in the data. The clearness of the sky is changing, because of seasonal and monthly anomalies such as summer monsoons, dust, rainstorms, heavy rainfall, and thunderstorms. The clearness of the atmosphere is affected by the seasonal factors that are causing the variation of atmospheric transmittance. The monthly analysis can be used to understand the varying errors in different months and seasons based on seasonal anomalies and factors. (Rehman Tahir et al. 2021, 1–6.)

# 3 MATERIALS AND METHODS

This chapter presents the study area and the technical details of the low-cost and high-cost sensors along with temperature sensors. Statistical tests as correlation, t-Test: Paired Two Sample for Means and a linear regression model were used. Other methods include the 90th percentile calculation which was used for finding the solar noon and analysis of solar cell’s temperature dependency.

## 3.1 Study area

Study area was in Sankt Augustin, in North Rhine-Westphalia, Germany. All the equipment were located on the roof top of a high building surrounded by parking lots and smaller buildings (Figure 1).

Figure 1. Study area in Sankt Augustin (Borenius 2023)

In this study, the considered rooftop equipment included two pyranometers, a solar cell and two temperature sensors. There were no distractions such as shadows due to other buildings or trees that would have a negative effect on the study area.

### 3.2 Solar cells

In this study, the low-cost sensor is a solar cell. In the begging, the idea was to use monocrystalline and polycrystalline silicon solar cells (Figure 2).

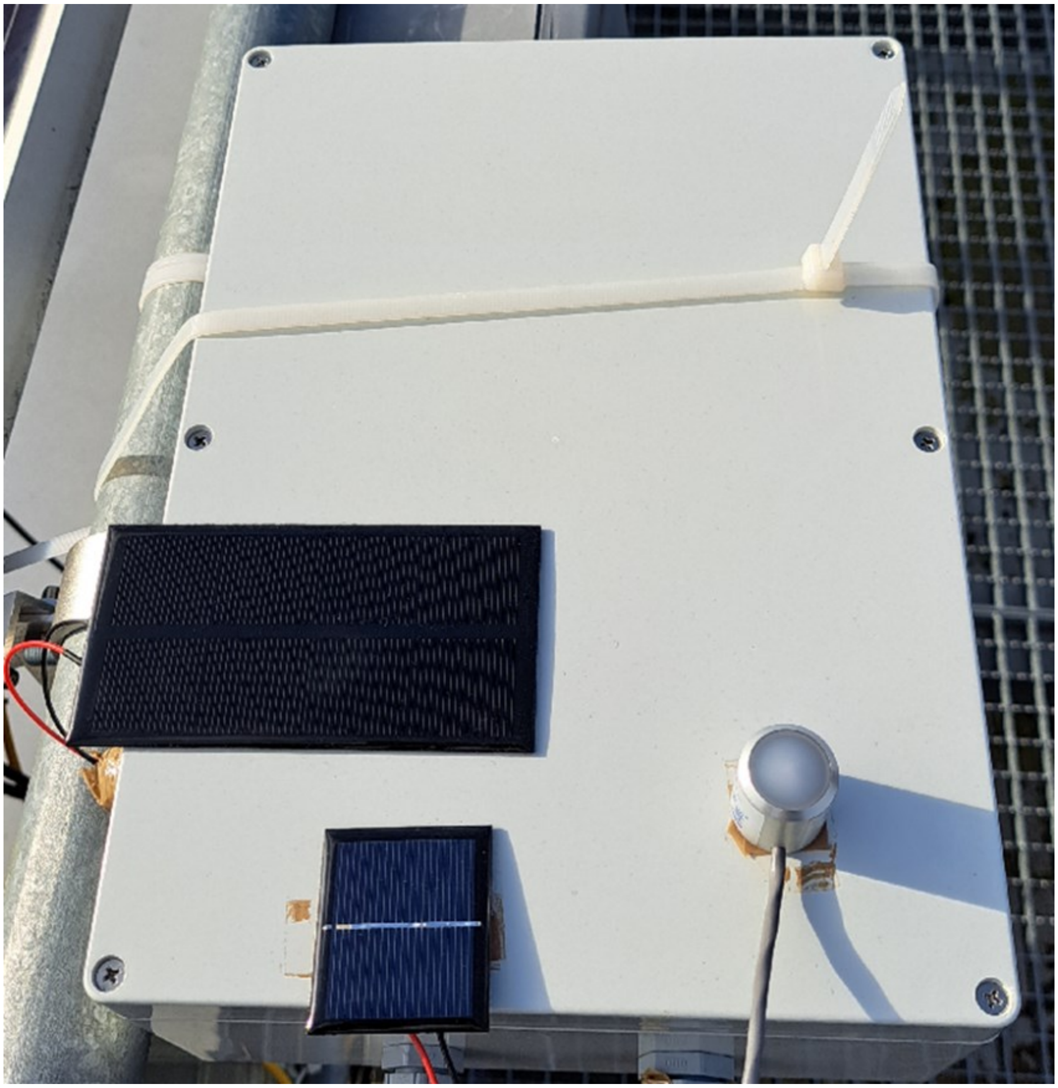

Figure 2. Monocrystalline solar cell SOLAR SM2380 on the top and polycrystalline solar cell SOLAR SOL1N below it (Borenius 2023)

However, the comparison of these solar cells was not possible because of the limitations of the solar cell data. Solar cells were not on the rooftop at the same time, so comparison was not possible due to the different seasons of the measurement times. During the correlation analysis both solar cells had the same nature with high-cost sensors. The monocrystalline solar cell SOLAR SM2380 showed better correlation with high-cost sensors compared to polycrystalline solar cell SOLAR SOL1N, as was expected. However, polycrystalline solar cell which had a longer period of data and better data quality was chosen to represent the low-cost sensor. Technical details of Velleman's SOLAR SOL1N are shown in Table 1.

Table 1. Solar cell technical details (Reichelt Elektronik, n.d.)

| **Name** | **SOLAR SOL1N** |
|---|---|
| Type | Polycrystalline solar cell |
| Manufacturer | Velleman |
| Maximum power (W) | 0.2 |
| Open circuit voltage (V) | 0.5 |
| Short circuit current (mA) | 400 |
| Cost (€) | 2.55 |
| Size (mm) | 45 x 40 x 2 |

The solar cell's maximum power is 0.2 W, open circuit voltage is 0.5 V and short circuit current 400 mA. A cost of the solar cell was 2.55 € and size 45 × 40 × 2 mm. (Reichelt Elektronik n.d.) Solar cell's measurement value is voltage (V). The measuring period of the solar cell was 13 weeks from the begging of August to the end of November 2022.

### 3.3 Pyranometers

High-cost sensors are global horizontal pyranometers which measurement value is radiation power (W/m$^2$). The pyranometers are manufactured by Kipp & Zonen (Figure 3).

Figure 3. SP Lite2 on the left side & CMP11 on the right side (Borenius 2023)

The following values have been considered in the comparison of high-cost sensors: wavelength, resolution/response time, sensitivity, temperature range, temperature dependency, and non-linearity (Table 2).

Table 2. High-cost sensors technical details (Kipp & Zonen n.d.a.& Campbell Scientific n.d.)

| Name | **CMP11** | **SP Lite2** |
|---|---|---|
| Manufacturer | Kipp & Zonen | Kipp & Zonen |
| Wavelength (nm) | 310 to 2800 | 400–1100 |
| Resolution/response time | 5 s | < 500ns |
| Sensitivity | 8.86 μV/W/m² | 68.4 μV/W/m-² |
| Temperature range (°C) | -40 to +80 ºC | -40 to +80 ºC |
| Temperature dependency | (-10 ºC to +40 ºC) ± 1% | -0.15%/°C |
| Cost (€) (Omni instruments n.d.a.& n.d.b.) | 2663,82 | 456,73 |
| Non-linearity | ± 0,2 % 100-1000 W/m² | <1% up to 1000W/ m² |
| Maximum solar irradiance | 4000 W/m² | 2000 W/m² |

CMP11 is a thermopile pyranometer which ISO 9060 Classification is A class (secondary standard). It measures wavelengths between 310 and 2800 nm and non-linearity ± 0,2 % 100-1000 W/m² (Campbell Scientific n.d.). SP Lite2 is a photovoltaic pyranometer (silicon photodiode) which ISO 9060 Classification is Fast Response Class C. It measures wavelengths between 400-1100 nm and non-linearity <1% up to 1000W/ m² (Kipp & Zonen n.d.a). SP Lite2 costs considerably less than CMP11. The measuring period for both pyranometers was two years and eight months.

### 3.4 Air temperature sensor

Two different kinds of temperature sensors manufactured by Kipp & Zonen were used in this study. The first sensor is RT1 Smart Rooftop Monitoring System's plug-in temperature sensor (Kipp & Zonen n.d.b). It was measuring the temperature which is called "pyranometer temperature" in this study. It is affected by the temperature of the measuring equipment. The second temperature sensor is SOLYS2 Sun Tracker's temperature sensor (Kipp & Zonen n.d.c). It was measuring outdoor air temperature and it is called "air temperature" in this study.

### 3.5 Raw data

Raw data was in text document form which was created by the COMBILOG data logger. The data logger's storage rate was 10 seconds. Each file included approximately two weeks of data. This data was combined to bigger files using Total Commander 64-bit software. Modification as organizing the data monthly was done with Notepad ++ software. This software was also used for finding data gaps. The data gaps included gaps on the timeline which were caused by the maintenance measurements and some errors on the data. All data were filtered and analysed using Microsoft Excel. Night time values (0-values) were filtered out from the whole dataset because the interest was in the day time values. In addition, in March 2021 CMP11 had errors in the data which needed more filtering.

### 3.6 Statistical analysis

The main aim of this thesis was to study the relationship between pyranometers, solar cells, and temperature sensors using correlation and regression models. In addition, the interest was to study what kind of impact different seasons have on measurement values. The t-Test: Paired Two Sample for Means was used to analyse the difference between the seasons using yearly data.

#### 3.6.1 Correlation

The correlation test was the first test made and it was used for understanding the relationship between pyranometers, solar cell, and temperature sensors. A high correlation number shows a strong relationship between different variables. The maximum value for correlation is one (100 %). The amount of data was 13 weeks which was the total measuring period of the solar cell.

#### 3.6.2 Regression analysis

A linear regression model was used to explain the relationship between the low-cost sensor, high-cost sensors, and temperature sensors. The solar cell's total measuring period of 13 weeks was used for this analysis. In first scenario solar cell was dependent variable and pyranometers independent variables. In the second scenario solar cell was dependent variable and temperatures were independent variables. The regression test was used for assessing the strength of the relationship between variables. The regression model’s p-value for each independent variable tests if the variable has a correlation with the dependent variable.

#### 3.6.3 The t-Test: Paired Two Sample for Means

The impact of the seasonal variations on measurement values was assessed using the t-Test: Paired Two Sample for Means. Pyranometers CMP11 and SP Lite2 were used for this analysis. The data included two years and eight months. The mean value of each month was gathered on the table yearly and plotted to histogram to see monthly variations in the measured values ($W/m^2$). The

assumption between the measuring devices was that CMP11 would measure higher values than SP Lite2 because it had a better ISO 9060 Classification class than SP Lite2. In March 2021, the figure showed unusual values for CMP11 and after investigating the data set, two different kinds of measurement errors were found. The first error included an unusually high value that was unchanging and constant for several days. The second error had the opposite nature where CMP11 was measuring unchanging and constant unusually low value for several days. The first error was handled by filtering out bigger values than 964, because SP Lite2 maximum value in that month was 963.7 and the comparison to other months and yearly values showed that SP Lite2 was measuring 2021 every month higher values than CMP11. In addition, the second error was handled by leaving out 12 days from the dataset, because filtering out that value would have filtered out also normal values in the same period. These actions decreased the amount of data considerably and have an impact on the result of March 2021.

## 3.7 Solar cell temperature dependency

The relationship between the solar cell voltage and air temperature was studied because the solar cell's efficiency is temperature dependent. The average values of these variables of each week were gathered in a table and plotted to a Pareto histogram. The data included 13 weeks from August to November 2022 when the season was turning from autumn to winter and the temperature started to decrease.

## 3.8 Solar noon

The interest was to find the time of the day when solar power reaches a maximum value when the sun is at its highest point on the horizon. The solar noon was defined using the 90th Percentile calculation to find the highest peaks from the data and these timings were compared with real timings. CMP11 data was used in this analysis. This analysis was done during summer from June to August in 2022 and winter from December 2021 to February 2022. In Excel, a filter was used for choosing higher values than the 90th Percentile value and these values were plotted in a figure. The five highest peaks (timings) were

chosen for both seasons. An average of five timings was used for estimating the time for solar noon in summer and winter. These values were compared with Sun's location data from the Department of Environmental Protection and Urban Climatology Division of Stuttgart (n.d.). The coordinates for Sankt Augustin were 7° 11'E, 50° 46' N which were not the accurate coordinates of the location, but because of the limitations of the data form, it was not possible to use longer coordinates. The real timings for each day and the average of these five timings were compared with real timings.

# 4 RESULTS

This chapter includes the results of statistical tests and seasonal variations. The results of correlation test and regression model are the main results of this thesis. In addition, t-Test: Paired Two Sample for Means shows the variations in different seasons. Chapter 4.4 includes a solar cell's temperature dependency and Chapter 5.5 the result of solar noon.

## 4.1 Correlation

The period for the correlation test was three months between 1 August 2022 – 30 November 2022. These analysis variables included pyranometers CMP11 and SP Lite2, a solar cell, and two temperature sensors: pyranometer temperature (Pyr. temp.) and air temperature (Air temp.). The correlation table shows a very strong correlation between the pyranometers (Table 3).

Table 3. Correlation between pyranometers, solar cell and air temperatures

| **Correlation** | *CMP11* | *SP Lite2* | *Solar cell* | *Pyr.temp.* | *Air temp.* |
|---|---|---|---|---|---|
| CMP11 | 1 | | | | |
| SP Lite2 | 0,99916 | 1 | | | |
| Solar cell | 0,77683 | 0,77279 | 1 | | |
| Pyr. temp. | 0,48546 | 0,48363 | 0,52923 | 1 | |
| Air temp. | 0,61528 | 0,61451 | 0,55179 | 0,95636 | 1 |

CMP11 and SP Lite2 had the strongest correlation at 99.9%. In addition, there was a strong correlation between the solar cell and pyranometers at 77.68% (CMP11) and 77.28% (SP Lite2). The pyranometer temperature and high-cost sensors showed a low correlation at 48.55% (CMP11) and 48.36% (SP Lite2). The correlation was moderate between the air temperature and pyranometers at 61.53% (CMP11) and 61.45% (SP Lite2). The lowest correlation was between a solar cell and air temperature at 55.18% (Air temperature) and 52.93% (Pyranometer temperature). The second highest correlation was between the temperature sensors (95.64%).

These results answered the main aim of this thesis by showing that there is a strong correlation between the solar cell and pyranometers which means that the equipment has the same kind of nature and strong relationship. In addition, the correlation between pyranometers is almost 100%.

## 4.2 Regression analysis

Regression analysis shows the relationship between different variables. In the first scenario, analysis was done between the solar cell and pyranometers, and in the second scenario between a solar cell and temperature sensors. The confidence level for both regression analyses was 95% and the p-value was tested under 0.05 level. Table 4 shows the first scenario where the dependent variable is a solar cell and the independent variables are pyranometers CMP11 and SP Lite2.

Table 4. Regression analysis between solar cell and high-cost sensors

| **Regression statistics** | | |
|---|---|---|
| Adjusted R Square | 0.610262603 | 61.03% |
| Standard error | 0.126600109 | 12.66% |
| Observations | 350373 | |
| **ANOVA** | **df** | |
| Regression | 2 | |
| Residual | 350370 | |
| Total | 350372 | |

| | | |
|---|---|---|
| Significance f | 0 | |
| **Coefficients** | | **P-value** |
| Intercept | -0.02714705 | 0 |
| CMP11 | 0.00299755 | 0 |
| SP Lite2 | -0.00214692 | 0 |

Adjusted R Square in regression statistics shows that the accuracy of the model was 61.0% and standard error 12.7%. There were 350 373 observations. Below ANOVA the regression was two and residual 350 370. Significance f value was 0. In the Coefficients section, the intercept was -0.02714705. The CMP11 coefficient value was 0.00299755, which shows a positive correlation between variables. SP Lite2 coefficient value was -0.00214692 which shows negative correlation between variables. All coefficients' p-values were 0. This result is statistically significant at 95% confidence level based on p-values and the Significance f value.

In Table 5, the dependent variable is a solar cell and independent variables are pyranometer temperature and air temperature.

Table 5. Regression analysis between solar cell and temperature sensors

| **Regression statistics** | | |
|---|---|---|
| Adjusted R Square | 0.304497659 | 30.45% |
| Standard error | 0.169120922 | 16.91% |
| Observations | 350373 | |
| **ANOVA** | **df** | |
| Regression | 2 | |
| Residual | 350370 | |
| Total | 350372 | |
| Significance f | 0 | |
| **Coefficients** | | **P-value** |
| Intercept | -0.16663746 | 0 |
| Pyranometer temperature | 0.000640802 | 0.000218 |
| Air temperature | 0.017749312 | 0 |

Adjusted R Square in regression statistics shows that the accuracy of the model was 30.5% and standard error 16.9%. There were 350 373 observations. ANOVA shows that regression was two and residual 350 370. Significance f value is 0. In the Coefficients section, the intercept was -0.16663746. The coefficient value for Pyranometer temperature was 0.000640802 and for Air temperature 0.017749312 which shows positive correlation for both variables. All coefficients p-values are 0. This result is statistically significant at 95% confidence level based on p-values and the Significance f value.

Both results showed that independent variables had an impact on the dependent variable. Low p-values indicate that the probability that there is no relationship between the variables is small. Full tables are visible in Appendix 1.

### 4.3 The t-Test: Paired Two Sample for Means

According to t-Test: Paired Two sample for Means seasonal variations for radiation power ($W/m^2$) was observed with pyranometers. The total measurement period for CMP11 and SP Lite2 was two years and eight months. Figure 4 shows the average values from May to December in 2020.

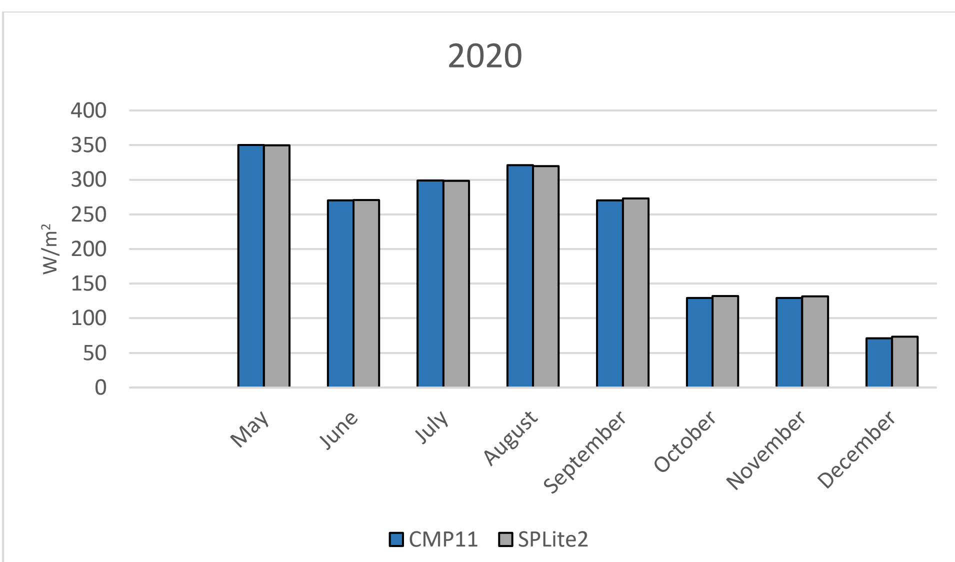


Figure 4. The average radiation power values in 2020 (by t-Test: Paired Two Sample for Means)

The highest values were measured in May 2020 the average value was 350 W/m$^2$ and in August via 320 W/m$^2$. After August the measured values started to decrease and in October and November the average value was 130 W/m$^2$. The lowest value was reached in December with an average value of 73 W/m$^2$. CMP11 was measuring slightly higher values in May, July, and August while SP Lite2 was measuring slightly higher values in June, September, October, November, and December. Pyranometers' values were almost the same every month. (Figure 4.)

2021 was the first full year of the measurement. The difference between the pyranometers increased and SP Lite2 was measuring more than CMP11 every month except in March 2021. The average values for winter months in January were 64 W/m$^2$ and February 181 W/m$^2$. In March, the values for CMP11 increased to 350 W/m$^2$ and for SP Lite2 to 325 W/m$^2$. However, it should be noted that March 2021 had fewer data and more filtering than other months due to errors in CMP11 data (Figure 5).

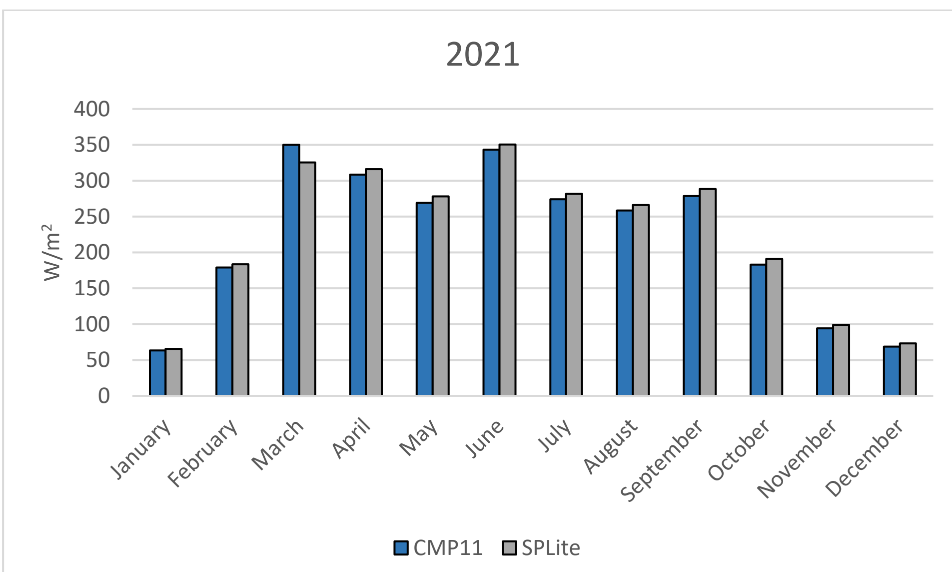


Figure 5. The average radiation power values in 2021 (by t-Test: Paired Two Sample for Means)

Variations in radiation power showed seasonal variations. The average value of April 2021 was 316 W/m$^2$ which decreased in May to 274 W/m$^2$. In June the highest value of the year was measured by the average of 350 W/m$^2$. The values decreased in July and August and increased slightly in September. October's

average value was 187 W/m$^2$ and it decreased in November to an average of 97 W/m$^2$ and in December to 70 W/m$^2$. (Figure 5.)

2022 was the second full year of the measurement. SP Lite2 was measuring slightly more than CMP11 the whole year. The average value of January was 70 W/m$^2$ which increased to 144 W/m$^2$ in February (Figure 6).

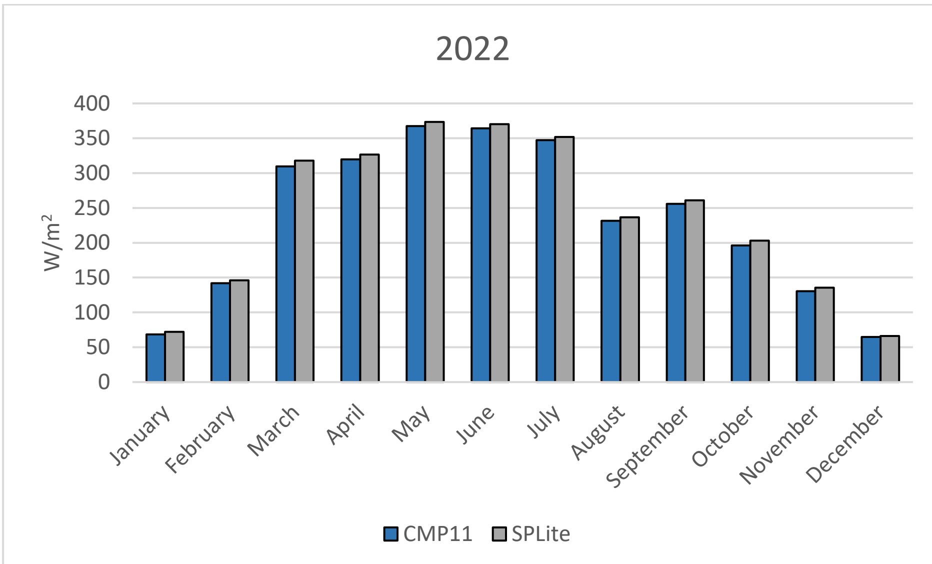


Figure 6. The average radiation power values in 2022 (by t-Test: Paired Two Sample for Means)

In March and April 2022, the measurement values were close to each other with 313 W/m$^2$ and 323 W/m$^2$. During May the highest value of the year was measured as 370 W/m$^2$. In June and July, the value decreased slightly to 367 W/m$^2$ and 349 W/m$^2$. In August, the average value decreased to 234 W/m$^2$ and in September the value increased to 258 W/m$^2$. After September, the measurement values decreased in October to 199 W/m$^2$, in November to 132 W/m$^2$ and in December to 65 W/m$^2$.

These results show that seasonal variations had an impact on the measurement values. The highest values were measured in summer and lowest in winter. SP Lite2 measured more than CMP11 almost every month, but the difference between pyranometers was small.

## 4.4 Solar cell temperature dependency

The average values of 13 weeks from 1 August – 30 November 2022 were used to analyse the relationship between the air temperature and the solar cell's voltage (Figure 7).

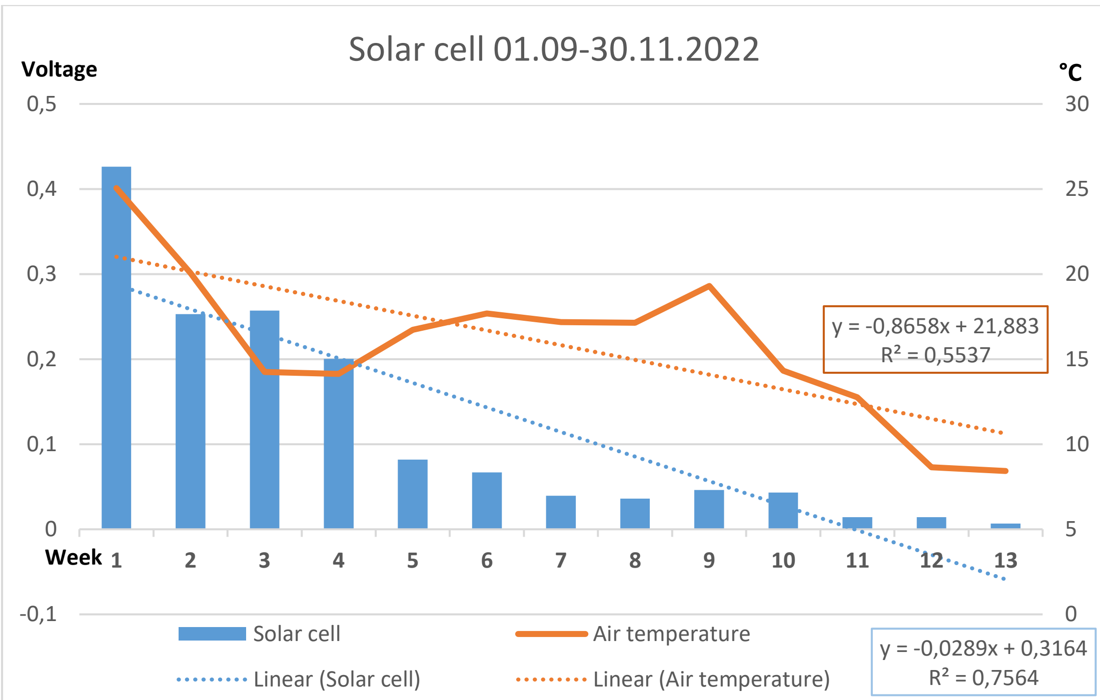


Figure 7. Solar cell temperature dependency 1 August – 30 November 2022

In week one, the solar cell voltage (0.43V) and temperature (25 °C) were at the highest level of the whole measuring period. In week two, the temperature decreased to 20 °C and voltage decreased to 0.25 V. In week three, the temperature decreased to 14.2 °C and the voltage increased slightly to 0.26 V. The voltage decreased from week four (0.20V) to week eight (0.036V). The temperature was 14.1 °C in week four. It increased in week five to 16.7 °C and stayed on the same level between week six to eight (17 °C). In week nine, both solar cell voltage and temperature increased and after that both values started to decrease.

The temperature and voltage had the highest and lowest values at the same time and both values decreased considerably between week one and week 13 when the season changed from autumn to winter. In Figure 7, the trend line $R^2$ value is

higher for solar cell voltage (0.76) than air temperature (0.55) which shows that the solar cell's voltage trend line fits the data better.

## 4.5 Solar noon

Three months of data were used to analyse solar noon in summer and winter. The five highest peaks were chosen from the data by filtering higher values than the value of the 90th percentile calculation and plotting the values to a figure. These chosen peak values were compared with Sun's location data from the Department of Environmental Protection and Urban Climatology Division of Stuttgart (n.d.). Five peaks in summer from June to August in 2022 are presented in Table 6.

Table 6. Solar noon timings' comparison in summer 1.6.2022-31.8.2022

| **Date** | **$90^{th}$ Percentile** | **Real time** |
|---|---|---|
| 6th of June | 13:14 | 13:32 |
| 1st July | 12:24 | 13:35 |
| $2^{nd}$ of July | 12:28 | 13:35 |
| 31st of July | 12:56 | 13:38 |
| 5th of August | 12:26 | 13:37 |
| **Average** | **12:41** | **13:35** |

The first peak was in June and the next three peaks were in July. The last peak was in August. The latest time was on the 6th of June at 13:14 and the earliest time in the 1st July at 12:24. The average of these five peaks was calculated to find the solar noon in summer. The average value was 12:41. The comparison of 90th Percentile values and real-time values showed that in summer, the average value has 54 minutes difference and an individual difference between timing for each date is at the smallest 18 minutes and at the maximum of 71 minutes.

In winter months from December 2021 to February 2022 all the five peaks were between mid-February until the end of February (Table 7).

Table 7. Solar noon timings' comparison in winter 1.12.2021-28.2.2022

| **Date** | **90th Percentile** | **Real time** |
|---|---|---|
| 14th of February | 12:24 | 12:45 |
| 15th of February | 12:02 | 12:45 |
| 19th of February | 11:56 | 12:45 |
| 25th of February | 12:34 | 12:44 |
| 26th of February | 11:58 | 12:44 |
| **Average** | **12:11** | **12:44** |

All peaks were between 14th to 26th February. The latest time was at 12:34 and the earliest 11:56. The average value was 12:11. The comparison to the real values showed that in winter the average value has 33 minutes difference, but the individual difference between timing for each date was in the smallest 10 minutes and at a maximum of 49 minutes. The wintertime analysis was closer to real time. The difference between solar noon in summer and winter had 51 minutes difference according to real time.

## 5 DISCUSSION AND CHALLENGES OF THE STUDY

This chapter presents a discussion about the results and challenges of the study. The goal of this thesis was to investigate the relationship between solar cells and pyranometers, and the primary factors emerging from this relationship. In addition, this study aimed to produce development proposals for the solar cell prototype.

### 5.1 Discussion

In this study, the correlation and regression results show that there is a strong relationship between a solar cell and pyranometers. In addition, this study investigated the impact of the seasonal variations on the measurement values. Similar results can be seen in the study of Azouzoute et al. (2019, 1209), which was made by using the monocrystalline cell and thermopile pyranometer to specify the accuracy of the monocrystalline cell in different climate conditions. The results between the solar cell and pyranometer had an agreement with an $R^2$

value of 99.97 %. In addition, the high-temperature periods showed that the relative deviation reached -4.8% and in the cold season (December) deviation reached -0.7%. (Azouzoute et al. 2019.) The results of Azouzoute et al. (2019) showed that the solar cell and pyranometer had a strong relationship and different climates impacted the accuracy of the equipment. The monocrystalline solar cell was not used in this thesis, but the nature between monocrystalline solar cell and polycrystalline solar cell was found to be the same at the beginning of this study. However, it should be noted that the monocrystalline solar cell is more efficient than polycrystalline solar cell which can be seen in the lower $R^2$ value in this study.

The correlation test was used to analyse the relationship between the equipment. The result showed that pyranometers CMP11 and SP Lite2 had a very strong correlation (99.9%) which supports the t-Test: Paired Two Sample for Means results. In addition, the correlation between the solar cell and pyranometers showed a strong correlation (77.5%). The second highest correlation was between the temperature sensors (95.6%). The correlation between high-cost sensors with pyranometer temperature was on average 48.5% and with air temperature 61.5%. The lowest correlation was between the solar cell and temperature sensors with an average of 54%. Even though there was a difference in correlation between pyranometers and different temperature sensors, the correlation showed that the temperature sensors have the same nature. These results answer the main aim of this thesis by showing that there is a strong correlation between the solar cell and pyranometers which means that the equipment has the same kind of nature and strong relationship.

Regression analysis was done to understand the relationships between different variables. In the first scenario, analysis was done between the solar cell and pyranometers, and in the second scenario between a solar cell and temperatures. The confidence level for both regression analyses was 95% and the p-value was tested under 0.05 level. Both regression analyses showed that the results are statistically significant at 95% confidence level based on p-values and the Significance f value. However, in the first scenario the accuracy of the

model was 61% and standard error 13%, but in the second scenario the accuracy decreased to 30% and the standard error to 17%. It should be noted that the amount of data was only three months. Regression results show that independent variables have an impact on the dependent variable. In addition, low p-values indicate that the probability that there is no relationship between the variables is small. It can be said that the correlation and regression test results support each other.

t-Test: Paired Two Sample for Means analysis was made to understand the variation on the seasons. In the winter, measured values were at their lowest and in the summer at their highest. In summer, the days are longer, and the location gets more sun. The assumption between the measuring devices was that CMP11 would measure higher values than SP Lite2. In 2020, CMP11 measured slightly more than SP Lite2 in three months from a total of eight months. The full year of measurement in 2021 and 2022 showed that SP Lite2 measured higher values than CMP11 every month, except in March 2021 when CMP11 had errors in the dataset. The study of Zeqiang et al. (2013) includes the silicon pyranometer performance test technique and sensitivity of the traceability system. The study states that the silicon pyranometer response time is generally less than thermopile pyranometers response time. In addition, silicon pyranometer has natural spectral selectivity determined by the semiconductor material. Thermopile pyranometer is a nearly neutral spectral broadband sensing equipment. The main solar spectrum showed that the silicon pyranometer had noticeably higher and a clear spectral response in long-wave range and shorter in short wave range. The thermopile pyranometer’s response curve was the opposite and showed a flat curve. (Zeqiang et al. 2013.) The minor differences in the measurement values between pyranometers can be explained by these differences in response time and spectral characteristics between pyranometers.

The analysis of the relationship between the temperature and solar cell voltage supports the fact that solar cells are temperature dependent. Both values had the highest and lowest values at the same time, and both values decreased considerably between week one and week 13 when the season changes from

autumn to winter. The trend line $R^2$ value was higher for the solar cell voltage (0.76) than air temperature (0.55) which showed that the solar cell’s voltage trend line fits better to the data. Şamil Kalay et al. (2022, 55) state that the temperature change in PV modules has a major impact on the module performance. In addition, worth noting is that the thermal mass of the PV module causes delays in the response time to the temperature, even though the measuring conditions change. The average temperature is usually measured on the back of the PV module because the PV cells cannot physically determine the temperature. (Şamil Kalay et al. 2022, 55.) It should be noted that in this thesis, the solar cell mass was smaller than PV modules, and the temperature sensor was not next to the solar cell.

The analysis of solar noon using a 90th Percentile calculation showed that the average value has 54 minutes difference in summer and 33 minutes in winter in comparison to the real timings of Sun's location data from the Department of Environmental Protection and Urban Climatology Division of Stuttgart (n.d.). In winter all the peaks were in February when the season is turning from winter to spring. The differences in these timings could be caused by the comparison data coordinates which were not the exact study area coordinates and the 90th percentile calculation method was not a specific method. This result shows that the time of solar noon is different in summer and winter.

This study aimed to investigate the relationship between low-cost and high-cost sensors. In this study, the most expensive sensor was a thermopile pyranometer CMP11 (2664 €) and the second expensive was a silicon photodiode pyranometer SP Lite2 (457 €). The cost difference between pyranometers and solar cells was large because solar cells cost 2.55 €. Şamil Kalay et al. (2022, 59) state that using professional pyranometers significantly impacts the monitoring system's total cost. A profitable solution could be the installation of calibrated irradiance sensors together with a photodiode or reference PV cell (Şamil Kalay et al. 2022).

## 5.2 Challenges of the study and development proposals

One of the shortcomings of this study is that it does not consider the cloudiness of the sky. According to Michaelides (2012), local insolation is influenced by cloudiness, pollution, and other temporal variables at a particular location. In addition, Michaelides (2012) states that the geographic latitude of the location and a day of the year influences the total supply of solar energy collected. For this reason, the 90th Percentile results are not entirely accurate, as the coordinates used are not the exact study area coordinates. In addition, the initial plan for a solar cell comparison could not be implemented because the solar cells were not on the roof at the same time. Including satellite data or a cloud camera would have added more value to this study.

Another shortcoming of this study is that the spectral response of the solar cell is not considered even though it has an impact on the calibration of the solar cell. Chander et al. (2015) state that the spectral response is the sensitivity of a solar cell which is comparable to the light of different wavelengths during a measurement of short circuit current per unit light power. It is measured with spectrally clean light including a wide range of wavelengths corresponding to the solar radiation's spectrum (Chander et al. 2015). Concerning the spectral response on the calibrating process would increase the quality of the calibration. In addition, finding other studies that support the results was difficult because the equipment assembly differed from other studies. In addition, the choice of statistical tests was affected by the amount and nature of the data.

The amount of data for the solar cell was in total 13 weeks and it did not have comparison data. Michaelides (2012) states that solar installation that transforms the incident solar power to electrical energy works year-round and needs to be estimated based on the total energy. The best indicators of solar energy potential are the yearly averages of energy and power (Michaelides 2012). The longer data period for the solar cell would have added better reliability and quality to this study. The data quality for the pyranometers was higher because there were two years and eight months data in total, which allowed measurement values to be

reviewed and compared with each other. However, it should be noted that this thesis was conducted at the same time as the solar cell prototype.

From the view of prototype development, choosing a monocrystalline solar cell or using it together with a polycrystalline solar cell would have been a more interesting solution. However, the quality and quantity of data affected the decision of using the polycrystalline solar cell in this study. The actual calibration data is not part of this thesis. This thesis provided information, but it did not fully fulfil the original purpose.

For practical reasons, it could be suggested that the data logger could save research data monthly so that the new file always starts at the beginning of each month. This would make it easier to process and separate the data when needed. In addition, data handling would be easier if new equipment data would always be added after the old equipment's data. In this data set, the solar cell data was added between old equipment's data rows which needed to be considered when these datasets were combined with the data files without the solar cell.

# 6 CONCLUSION

This study showed that the relationship between low-cost and high-cost sensors is strong. Seasonal variations and temperature changes should be considered because of the impact on the measurement values. The low-cost sensor prototype calibration process could be upgraded by concerning the cloudiness of the sky by using a cloud camera and including the spectral response of the solar cell to the calibration process. Longer measurement periods would increase the reliability of the process.

The price between high-cost and low-cost sensors is large. Pyranometers are high quality measuring equipment with the disadvantage of the expensive price. Solar cells are more price competitive. The cost of professional pyranometers significantly impacts the monitoring system's total cost. A profitable solution could be the installation of calibrated irradiance sensors together with a reference solar cell so that the cost could be reduced.

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# REGRESSION ANALYSIS RESULTS

SUMMARY OUTPUT

| Regression Statistics | |
|---|---|
| Multiple R | 0,78119449 |
| R Square | 0,61026483 |
| Adjusted R Square | 0,6102626 |
| Standard Error | 0,12660011 |
| Observations | 350373 |

ANOVA

| | df | SS | MS | F | Significance F |
|---|---|---|---|---|---|
| Regression | 2 | 8793,13643 | 4396,568 | 274312,5 | 0 |
| Residual | 350370 | 5615,585873 | 0,016028 | | |
| Total | 350372 | 14408,7223 | | | |

| | Coefficients | Standard Error | t Stat | P-value | Lower 95% | Upper 95% | Lower 95,0% | Upper 95,0% |
|---|---|---|---|---|---|---|---|---|
| Intercept | -0,02714705 | 0,000335107 | -81,01 | 0 | -0,027803851 | -0,0264903 | -0,02780385 | -0,02649025 |
| 1.CMP11 | 0,00299755 | 2,76698E-05 | 108,3331 | 0 | 0,002943319 | 0,0030518 | 0,002943319 | 0,003051782 |
| 4.SPLite2 | -0,00214692 | 2,74528E-05 | -78,2042 | 0 | -0,002200729 | -0,0020931 | -0,00220073 | -0,002093116 |

Figure 10 Excel screenshot. Regression analysis result between solar cell (dependent variable) and pyranometers (independent variables).

SUMMARY OUTPUT

| Regression Statistics | |
|---|---|
| Multiple R | 0,551816663 |
| R Square | 0,30450163 |
| Adjusted R Square | 0,304497659 |
| Standard Error | 0,169120922 |
| Observations | 350373 |

ANOVA

| | df | SS | MS | F | Significance F |
|---|---|---|---|---|---|
| Regression | 2 | 4387,479422 | 2193,74 | 76699,13 | 0 |
| Residual | 350370 | 10021,24288 | 0,028602 | | |
| Total | 350372 | 14408,7223 | | | |

| | Coefficients | Standard Error | t Stat | P-value | Lower 95% | Upper 95% | Lower 95,0% | Upper 95,0% |
|---|---|---|---|---|---|---|---|---|
| Intercept | -0,16663746 | 0,000845711 | -197,038 | 0 | -0,168295 | -0,1649799 | -0,168295029 | -0,164979892 |
| 7. Pyr Temp | 0,000640802 | 0,00017331 | 3,697439 | 0,000218 | 0,00030112 | 0,0009805 | 0,00030112 | 0,000980484 |
| 8. Air temperature | 0,017749312 | 0,000160042 | 110,9039 | 0 | 0,01743563 | 0,018063 | 0,017435633 | 0,01806299 |

Figure 11 Excel screenshot. Regression analysis result between solar cell (dependent variable) and temperature sensors (independent variables).