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Performance Analysis of PV Systems in the Built Environment: a Case Study from a High Rise Building

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Affirmation

I hereby affirm that this Master thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text. This work has not been submitted for any other degree or professional qualification except as specified; nor has it been published.

Utrecht, September 2022

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Abstract

Worldwide energy consumption and the related GHG emissions have a significant environmental impact, and 33% come from the residential sector. Research is focusing on energy efficient buildings that produce renewable energy for their self-sufficiency using BIPV systems. The work investigates the performance of the case study, where PV modules have been installed on roof, walls and balconies, having different characteristics. In order to perform this analysis, a program has been coded using MS Access, a DBMS where code is written in Visual Basic and SQL and data are stored into relational DB. The program automatically recognizes data and, through a Graphical User Interface where data can be filtered or grouped, it creates a new Excel file with the results.
The analysis has been divided into sections, each considering an aspect of the PV system. As a result, the most performing modules are positioned on the left side façade of the building (looking from the front), which is facing South-West, followed by modules placed on the installed roof pergola, both vertical and tilted, that is facing South-East.

Keywords: BIPV performance, energy efficiency, PV system, residential retrofitting, Net Zero Energy Building

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List of Abbreviations

The most important abbreviations used in the report are listed below.

AC - *Alternating Current*

BAPV - *Building Applied Photovoltaics*

BIPV - *Building Integrated Photovoltaics*

BOS - *Balance of System*

CCS - *Carbon Capture and Storage*

CIGS - *Copper Indium Gallium Selenide*

c-Si - *Crystalline Silicon*

DB - *Database*

DC - *Direct Current*

DHW - *Domestic Hot Water*

EED - *Energy Efficiency Directive*

EIA - *Environmental Investigation Agency*

EPBD - *Energy Performance of Buildings Directive*

EU - *Europe*

GCHP - *Ground-Coupled Heat Pump*

GHG - *Greenhouse Gas*

GHI - *Global Horizontal Irradiance*

HVAC - *Heating, Ventilation and Air Conditioning*

KPI - *Key Performance Indicator*

MPPT - *Maximum Power Point Tracker*

POA - *Plane of Array*

PV - *Photovoltaics*

STC - *Standard Conditions*

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1 | Introduction

The fast growth of energy consumption worldwide is heightening the concern over several factors, among which the environmental impact. Primary energy consumption is increasing at a higher rate than worldwide population, CO_2 emissions are growing rapidly and electricity consumption is also rising significantly, and analytic predictions show how this trend will continue in the coming years [7].

A study ([8]) has confirmed global warming induced by human activity has reached in 2017 1°C above pre-industrial temperatures (where pre-industrial is considered to be the period around 1850-1900), with a 0.2°C increase per decade. The increase rate since 1970 has been around 1.7°C per century, while in the past millennia it was around 0.01°C per century. Global rates driven by human activity massively exceed the normal change caused by geophysical and biosphere forces that alter the Earth systems since millennia.

Around 20-40% of the global population in the last few years has already experienced a temperature over 1.5°C increase, which has led to major alterations of nature and human systems, which are extreme weather (e.g. droughts, floods, wildfires), sea level rise, biodiversity loss [9].

The European Commission with the Paris Agreement has set a target plan with the final goal of limiting this temperature rise to 1.5°C above pre-industrial levels (called 1.5°C scenario). One way to reach this goal is becoming climate neutral by 2050, with the midterm goal to reduce GHG (Greenhouse gas) emissions to 55% by 2030 [10] compared to 1990. Two among the key targets for 2030 are to obtain a share of at least 32% of renewable energy production and at least 32.5% improvement in energy efficiency. The EU has also adopted several rules to guarantee the monitoring of this process towards the achievement of the set energy targets.

One of the many directions of future climate policy-making concerns technological solutions that will play a role in fulfilling the agreed targets, among which electric vehicles, CCS (Carbon Capture and Storage), nuclear fusion or solar energy productions [11][12][13][14].

Energy consumed worldwide has a major impact on the 1.5°C scenario. Usually, energy consumption is split into the three end-use sectors, which are industry, transport and residential. Population growth, higher comfort levels and the increasing time spent in buildings have led the residential energy consumption level towards a dramatic raise.

Of all the global energy consumption, 33% comes from buildings [15]. Figure 1 shows the percentage of residential energy consumption per country and worldwide, which in 2008 was 31% [1]. In Europe, buildings energy consumption even accounts for 40% of total energy use and 36% of total CO_2 emissions [16]. In this sector, key factors for energy consumption are the location and size of the building (cold areas need less air conditioning during summer but more heating during winter, and vice versa for hot areas. However, small apartments need less energy, because of their minor area to be heated or cooled, as studied by Santamouris et al. [17]).

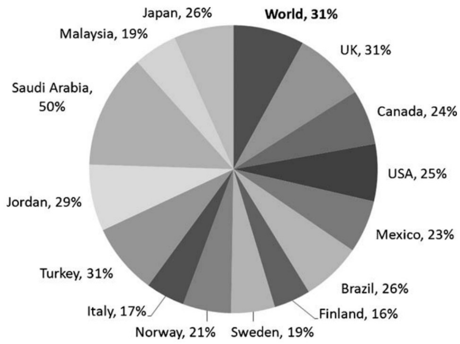


Figure 1: *Percentage of residential energy consumption of the most consuming countries and average worldwide percentage [1].*

The International Energy Outlook (part of the EIA, that is the Environmental Investigation Agency) every year publishes a forecast of future energy consumption trends in each sector, as shown in Figure 2, and it can be noticed how each one increases and especially how steep is the forecast for the residential sector.

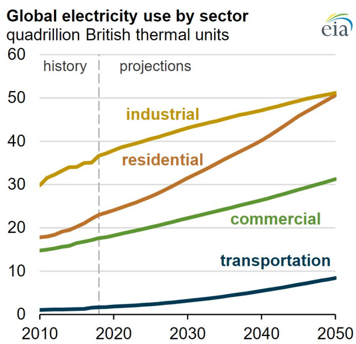


Figure 2: *EIA energy consumption outlook in building sector [2].*

It is therefore crucial to make the residential sector more energy efficient to be able to reduce the amount of final energy consumption and emissions emitted and take a great step towards achieving the European energy and environmental goals.

Research in the built environment is already addressing the study of energy efficient buildings, whose available energy for consumption comes from renewable sources and are well connected to the grid so to have the possibility to be fully independent and even sell excess energy to the grid. The energy system can also make use of batteries, which are not applicable yet for seasonal storage, but increase the self-consumption of a building for covering peak energy demand and keep the local grid operating.

The main renewable source to use for this type of buildings is solar PV, whose panels generate electrical power for the building. More specifically, two different systems exist depending on the installation and construction in the building: BIPV, the system where modules can be easily integrated in the building elements, mainly in the façade or in the roof, and BAPV, the system where modules are directly attached to the finished building.
BIPV replace the traditional construction elements used for the walls or the roof with PV, installed considering the building structure and therefore having some impact on the functionality. BAPV are just attached to the already existing surfaces, thus do not have a direct impact on the building functionality [18]. Even though they are both considered PV, there are some differences between them: BIPV can be either heavyweight or lightweight, while BAPV are only heavyweight; BIPV, being constructed directly into the structure, are more durable and have less chance of breaking or being moved by wind.

1.1. European regulations

Energy efficient buildings are key factors for enhancing people's quality of life, because they will lead to several benefits such as superior comfort levels and decreasing costs for the occupants.

Energy performance in buildings has to be encouraged with the correct legislation, that includes the EPBD (Energy Performance of Buildings Directive) and the EED (Energy Efficiency Directive). Established respectively in 2010 and 2012, these two directives are crucial for helping achieving a decarbonised and energy efficient environment by 2050 and creating a more stable condition for investing decisions.

The EPBD [19] promotes the improvement of energy performance in European buildings regarding climatic and local conditions, indoor climate requirements and cost-effectiveness. This is possible with the assess of a general methodology to calculate the integrated building's energy performance, the application of minimum energy efficiency requirements for new and upgraded buildings, plans at national level to increase the amount of nearly zero energy buildings, a certification on energy for each building, regular inspection regarding the HVAC (Heating, Ventilation and Air Conditioning) system and the independence of control systems for energy performance certificates.

The EED [20] tries to establish common measures to promote energy efficiency in Europe for the achievement of the energy efficiency target. It mainly gives rules for removing barriers in the energy market that can block supply and use efficiency.

The Netherlands agreed with these regulations and in 2012 created a Building Decree containing the guidelines for Almost Energy Neutral Buildings (called BENG in Dutch) [21].

1.2. Relevance of the research

This research is part of the Inside Out project [22], whose aim is to retrofit buildings to Net Energy Plus, that means to make them produce, over the course of the year, more electricity than their demand. As a matter of fact, the project main research question to answer is whether the refurbishment of the building has actually made it Net Energy Plus, also considering the comfort level of the tenants.
By optimizing the retrofitting and understanding what could affect the system in terms of performance, the final goal can be reached.

The project is focusing on a building from the 1960's to understand the optimal parameters and replicate the method in several other buildings of the same type from 1960's and 1970's.

These old buildings have a relative small roof area for PV systems, due to their height, and a limited budget for the renovation, thus the main challenge is to understand how to improve the renovation method and make the building as more energy efficient as possible. Applying this method to thousands of buildings in the Netherlands, especially antique ones, would help reduce the energy demand and related GHG emissions in the residential sector.

This research will be focusing primarily on the PV system performance, considering its components and external factors. A PV system is composed by the PV modules and the BOS (Balance of System), which is the equipment needed to power the conditioning and energy support, storage, safety and performance measurement (i.e. wiring, fuses, switches, inverters, optimisers). The external factors that affect the system output are mainly temperature, irradiance, installed capacity and shading effect.

Analysing the system power production is important for the Inside Out project as it is needed for the main research question ("Have the refurbishment measures led to a building that produces more energy than it consumes while maintaining comfort for the tenants?", as previously cited). This research will therefore support the Inside Out project by addressing the performance of the PV system and what can affect it.

1.3. Research boundaries

The main boundary on this research is represented by the dependency on the location of the collected data, that make the results case-specific and not directly generalised to all situations. The building composition (10 floors height, 58 apartments) is also quite specific. The results to be obtained in this research could then be applied with higher certainty in similar buildings, and probably some adjustments would have to be done for different type of buildings.
Moreover, since the building is located in the Netherlands, the irradiance is lower than the average European value [23].

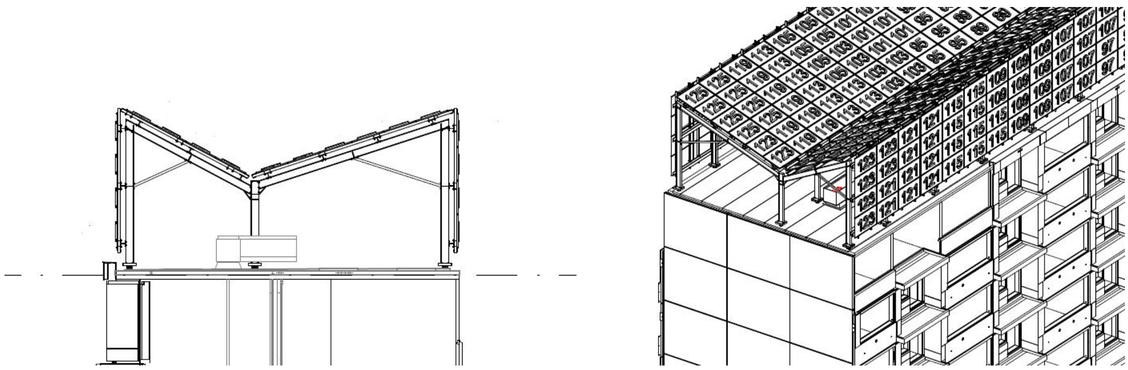
Another boundary is related to the tools used to compare the measured data: for this research the software MS Access [24] has been used for writing the code for the program that interacts with the DB (database) that will be constructed to store the collected data, together with MS Excel for creating the plots. Among MS Access' limits, the most relevant is certainly that it is not free and also not suitable for team use because it becomes slow. Also, each file can not contain more than 2 GB of data. The building has also been modelled in PVSites [3].

1.4. Case study description

In the Thesis "PV panels" will also be referred as "modules" interchangeably.
As previously mentioned, the studied building is 10 floors high and includes 58 apartments of 3 different sizes, as shown in Figure 3. They have different size and room disposition: the one highlighted in green is the biggest with its six rooms, the orange one has five rooms and the blue one only two. They all have a window facing the building façade.

Figure 3: *Apartments types floor plan (technical drawings from the building design).*

The roof has a fabricated pergola fully covered with BAPV, with an asymmetric structure resulted by a compromise among the PV modules surface area, shading and the maximum allowed building height. The internal side of the pergola positioned towards South-East has a larger area than the side towards North-West. The two sides of the pergola which are the continuation of the façades are also covered with BAPV. The structure of the pergola can be seen in Figure 4 with two different figure orientations.



(a) *Pergola shown at the front.* (b) *Pergola shown at 3/4.*

Figure 4: *Structure of the pergola positioned on the roof (technical drawings from BOS [25], the company that has installed the structure).*

The rest of the building, as the model in Figure 5 shows, is covered with BIPV. Specifically, the façade is composed by several balconies alternated to walls and the panels are located on both, also including the area below every window. The lateral walls on the building are also covered with BIPV.

The building PV system is composed by 1118 panels of different types connected to a battery with capacity of 75 kWh. Figure 5 shows an overview of the panels positioning, but it does not show their type differences. There are 3 types and they differ in colour, installed capacity and size. As for color, the majority of panels are black, with the exception of the façade: the modules on balconies are transparent and the others are coloured in grey like the building wall. The panels on the balcony and on the rest of the façade are BIPV with an installed capacity of 300 Wp, the modules on the pergola are BAPV and have an installed capacity of 355 Wp and the rest have an installed capacity of 340 Wp. Lastly, the grey modules on the façade have three different sizes (1.47 m^2, 1.62 m^2 and 1.88 m^2), modules on the balcony have a size of 1.7 m^2 and the rest of modules of 1.7129 m^2.

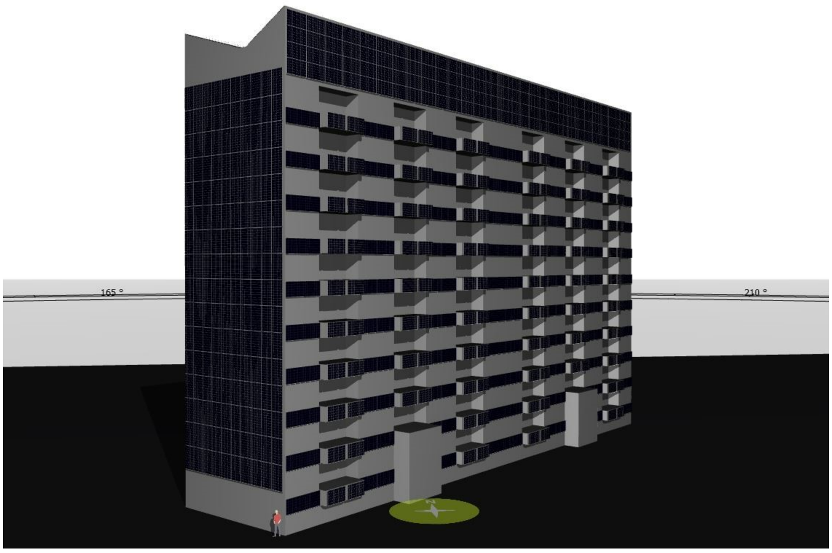


Figure 5: *Modelled representation of the studied building done with PVSites [3].*

The number of panels from the pergola assigned to each apartment is depending on its characteristics (mainly, size and location), but each of them has its own inverter with 3 kW capacity, 58 in total, connected behind the energy meter (the device used to measure the amount of energy consumed) and cover the household electricity demand.

Even more detailed, Figure 6 and 7 show how the modules on the pergola are positioned: each group of modules has a number that refers to a particular apartment, and their amount depends on the apartment size.

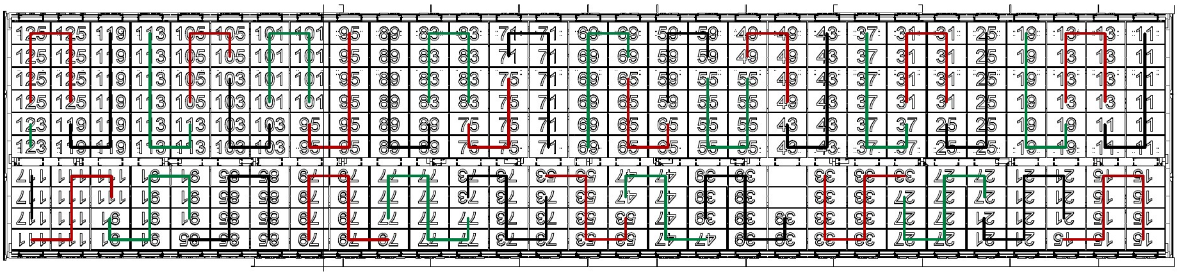


Figure 6: *PV modules disposition on the pergola, seen from above.*

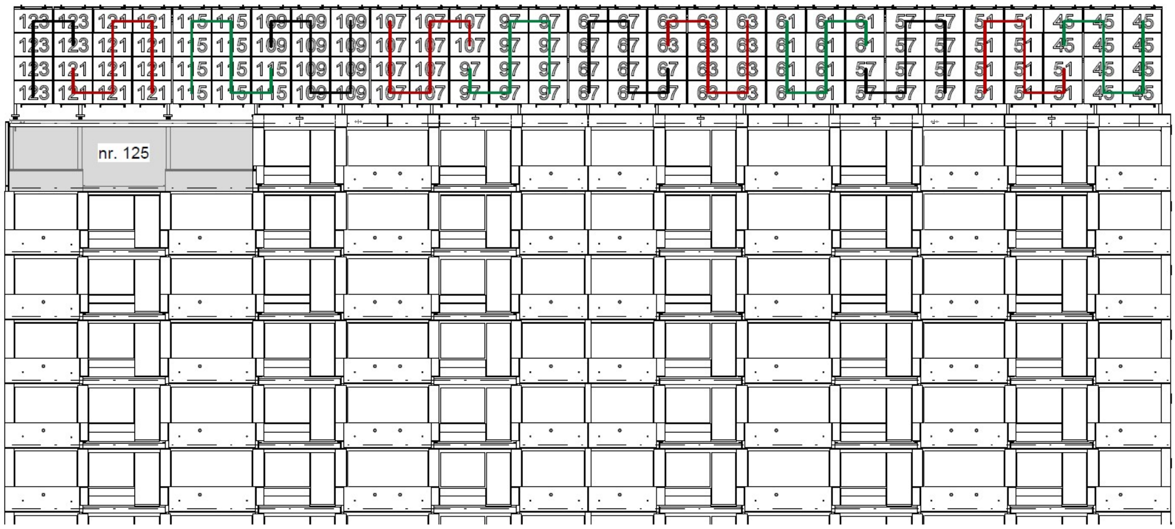
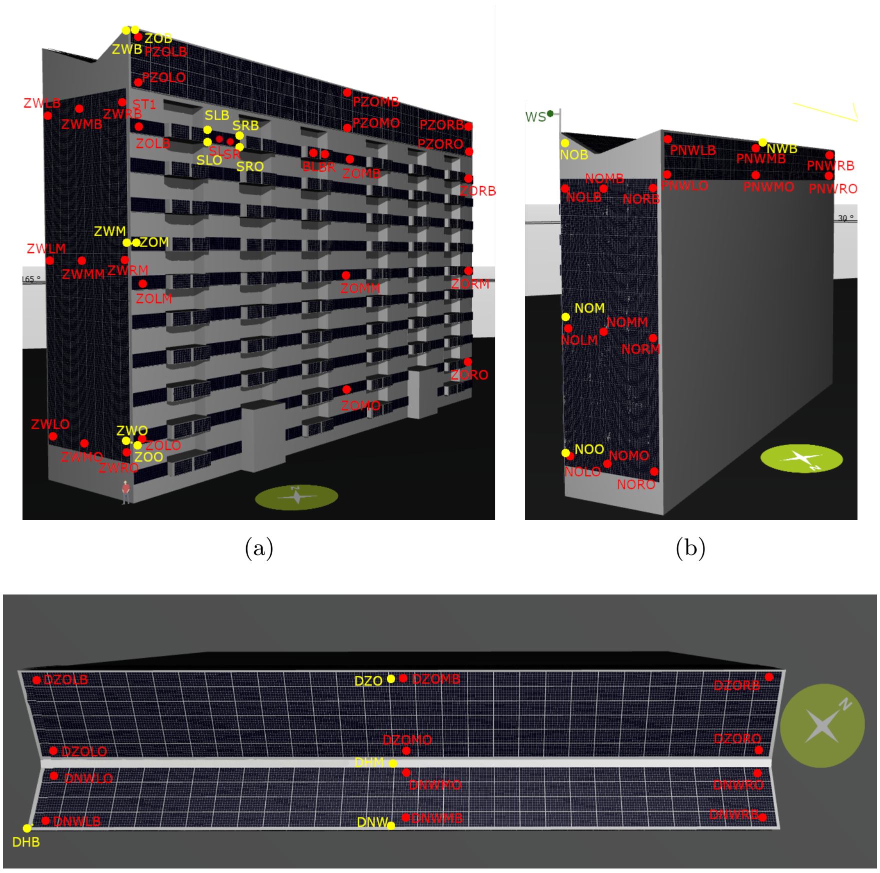


Figure 7: *PV modules disposition on the façade and back side of the pergola, seen from the front.*

The panels on balconies, façade and side of the building are linked to separate inverters, which are 7 and have a higher capacity, 7 kW or 17 kW, and they are responsible for the HVAC and DHW (Domestic Hot Water) demand of the building.

Several sensors have been positioned on the building in order to measure temperature and irradiance in each part of it, as shown in Figure 8. The sensor named WS measures the GHI (Global Horizontal Irradiance), which is not used for this analysis. Sensors coloured in red represent temperature sensors, while the yellow ones are for irradiance.

The roof area is relatively small compared to the rest of the building; its height highly contributes to this difference. This building is one of the highest buildings that has been studied for energy efficiency and, considering that in the Netherlands numerous similar buildings in terms of technical characteristics exist, the analysis that will be performed in this Thesis is likely to be valid as a potential analysis that could be made on these other buildings, contributing to the reduction of GHG emissions in the residential sector.



(a) (b)

(c)

Figure 8: *Sensors positioning on each side of the building (a. on façade and left side, b. on the right side and c. on the roof).*

Moreover, the building has become fully electric: it has been disconnected from natural gas supply and the district heating network, heat pumps for both heating and DHW have been installed and also electric stoves. Thus, it is thoroughly oriented to depend on the PV system.

1.5. Research Questions

As described in Section 1.2 the main research goal is to understand the performance of this PV system, thus the main research question is formulated as follows:

"*What factors must be considered during the performance assessment of a (BI)PV system, and what is their impact?*"

There are many parameters acting in different ways that also depend on other variables in the system, and they all have consequences on the system performance. This is the reason why, in order to answer the main research question, it will be made more specific by breaking it down into the following sub-questions:

1. Which parameters affect the performance of a (BI)PV system?

2. How can the performance of a (BI)PV system be assessed?
3. Considering the characteristics that can give shading in a building, how much do they impact a (BI)PV system performance?
4. Considering the modules' tilt, what impact does the difference between vertical and tilted modules have on the (BI)PV system performance?
5. How do different types of PV modules perform?
6. How do modules perform when installed in different parts of a building?

2 | Theoretical Background

The renewable energy source used in this case study is a PV system.

A PV system is an electric power system consisting of several components, divided into solar array and BOS, that absorb solar radiation and convert it to electricity.
The solar array is a module composed by solar cells, small electrical devices that convert photons into electricity. Conventional solar cells are made of c-Si (crystalline Silicon), that can be either polycrystalline or monocrystalline [26], wired in series, covered by tempered glass to be protected from the weather. The modules are usually connected in series to obtain a certain voltage and then these strings are connected in parallel to produce current. Figure 9 shows how the cells work.

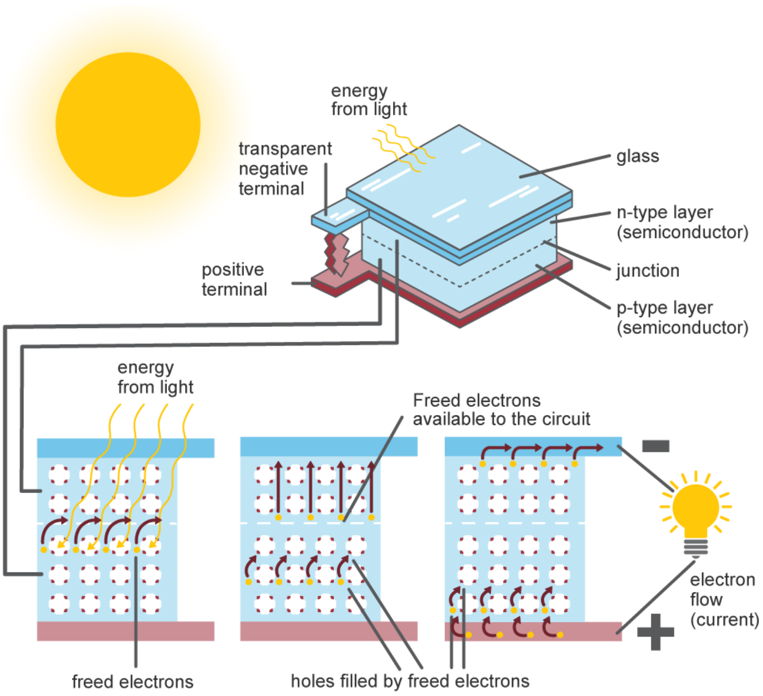


Figure 9: *Photovoltaic cell insight [4].*

In further detail, power is generated from photons separating into positive and negative charge carriers and being absorbed by a specific material. These charges produce current when an electric area is connected. These electric areas are permanent in cells at junctions and provide a voltage difference that produces power [5].
An equivalent circuit can show the most relevant characteristics of a solar cell, highlighted

in Figure 10. I_L represents the current induced by light, I_D the diode current, R_sh and I_sh respectively the shunt resistance and shunt current, R_s the series resistance and V the voltage that results from the cell. The positive and negative charges can be clearly seen in the figure.

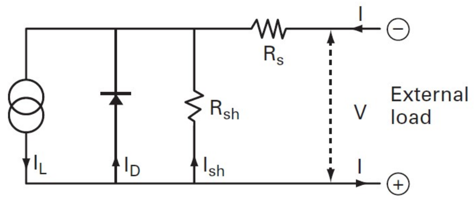


Figure 10: *Solar cell equivalent circuit [5].*

Maximum power production is a condition happening when the resistance external to the circuit equals the internal one, which depends on the whole system conditions. However, an electronic unit, called MPPT, connected to the external circuit and the array usually matches them [27].

The BOS is the ensemble of equipment and structures needed to make the system work, such as inverters (DC-AC power converters), electrical wiring and fuses, optimisers. The BOS components are also needed to ensure safety, storage or measure performance.
Inverters are used to convert DC power from the solar panels into AC power [28], needed to some grid-connected applications. A battery can be installed in the system to store surplus energy which is used later when the panels are not producing energy. To measure and monitor the system energy production and consumption, meters (or sensors) are usually used and they can have different characteristics.

PV systems can be either independent or connected to an electricity grid [5]. In the first situation usually the application is linked to small appliances, with or without an energy storage battery, since when the panels stop producing energy the work stops. The second situation, systems connected to an electricity grid, are the largest use of PV because this connection allows to export excess power and sell it [29], gaining a high advantage compared to independent systems.
Nonetheless, grid connected systems need to have control on the inverter, both on voltage and current. Control on current is generally made through active and reactive power control, which is based on eliminating double frequencies and thus make the system more stable [29].

Efficiency in solar cells is limited by several losses [30], some intrinsic but others determined by the structure. Reflection on the panel surface can cause around 3% loss (could be prevented playing with the thickness of the module top layer), photons with too long wavelength cause temperature rise on the module reducing power production by 23% (few studies are trying to overcome this issue using different solutions, e.g. using the produced heat in a combined solar heat and PV power system or removing long wavelength photons [30]), excess energy of active photons also cause heat and leads to a 33% loss, mismatch during the potential difference that produces voltage can cause a 20% loss, shading due to objects beside or on the building can also cause a loss, tilt of modules can be optimal or not depending on the sun inclination during the year.

2.1. Literature Review

Several study cases have also dealt with retrofitting existing building around the world, studying different building types and for different reasons.

In general, there are two ways of retrofit a building, and they are to build an envelope and to install a HVAC system [31]. The envelope includes wall and roof insulation, windows with enough glass layers for not losing energy and a good window-wall ratio, due to the fact that windows have a larger heat transfer than walls. The HVAC system mainly involves heat/cold sources and air conditioning units. Usually, both ways are executed on a building.

In Treviso, Northern Italy, an historic building that was originally a religious convent has been renovated and converted into a residential building in order to achieve a high energy class, improve its indoor thermal quality and include many comforts but maintaining the beauty of an old building [32]. During the refurbishment, a solar thermal and a photovoltaic system have also been installed.
The aim of achieving an A energy class included the installation of several structures, such as high insulated windows, a mechanical ventilation system with heat recovery, high wall insulation, heat pumps and solar thermal panels and a PV system. The two installed heat pumps installed are used respectively for heating and cooling and DHW. Thermal solar panels and the PV power plant have been installed at the end for covering DHW; the first one in vertical position and the latter on the roof.
A model has been used to calculate energy savings and CO_2 reduction and the results have been subsequently compared with the actual measures after the retrofit had finished. The energy saving is the most important benefit obtained, and it includes heating, DHW and ventilation. The new technologies installed have led to a reduction of losses, thus a more pleasant indoor climate and cost savings on energy.

In Tianjin, a cold region of China, an old factory that didn't reach the energy efficiency standards has been retrofitted in order for it to save energy and have a good indoor air quality [31].
The thickness of wall and roof thermal insulation and the glazing for windows have been chosen based on the window-wall ratio, taking into account both heat transfer coefficients and cost.
For both heat and cold sources a GCHP has been installed, a technology that became quite popular in China because of their high efficiency, which translates into cost and energy savings. Radiant floor heating has been installed after having done some analyses on the best way to provide heat, with fan coils for air conditioning. A water storage has also been installed for storing heat produced by the GCHP during the night.
A Building Management System controls the GCHP and HVAC operations, adjusting them

automatically according to predefined set points in order to optimize the energy consumption. After one operating year, the building had saved 58% of electricity from heating and 64% from cooling. The highest electricity consumption came from air conditioning, followed by sockets (products such as computers), the network computer room and lightning. Lastly, the environmental quality inside the building was satisfying.

In Stuttgart, Germany, the Center for Solar Energy and Hydrogen Research (ZSW) realized its new office with a PV-based façade [33]. The main goal was to maintain low costs while reaching a high efficiency, using CIGS film PV modules (Copper Indium Gallium Selenide, a specific thin-film solar cell) coloured black.
Four different sides of the building were analyzed, with different results obtained: the Southern façade has the highest efficiency, followed by the South-West one, while the South-Eastern one has an even lower efficiency; the North-West façade has the lowest efficiency and it is hardly acceptable.
The study case also showed how different power output there is between PV modules orientated with a 40° tilt and vertical ones on the façade.

3 | Program

3.1. Input Data Structure

The PV system production is measured in two different ways. First, at the sensor level - for each sensor linked to the BeNext system [34] - which does a complete monitoring of the building measuring irradiance and temperature using separate sensors, as previously stated in Section 1.4. Second, by monitoring the inverters connected with the platform SolarEdge [35], which gives the opportunity to have insight on the system details until the module level.

The data needed to run the program and analyse the results are distributed over the SolarEdge control website (obtained using a script written for Ubuntu that downloads everyday the previous day's data), the Hogeschool Utrecht cloud server and the design and installation company.

Available measured data are given every:

- 6-10 minutes: for every PV module with the recording of power readings
- 1 minute: irradiance (with GHI and POA at different locations for 18 measurements)
- 1 hour: for every PV module with the recording of produced energy, and temperature (for a representative set of 58 modules)

Each data type is collected daily in its own *.csv* file, thus there are 4 files for each day, respectively containing energy, power, irradiance and temperature data. The data set in formed by daily data starting from 31 June 2021, when the PV system started to function, until 31 August 2022.

Energy and power files have the same structure: 3 columns containing respectively *Timestamp* (time, in format dd/mm/yyyy HH:MM, e.g. 02/03/2022 08:00), *PO-id* (module name, e.g. "Module 53.0.8 (12A96309-27)") and *Energy* or *Power* (data, depending on the file type).

Irradiance files are structured with several columns: *Tijdstip* (time in format yyyy-mm-dd HH:MM:SS), *Username*, *ProductID* (meter ID), *Product* (meter name), *Datatype* (type of data), *Waarde* (value). For the analysis only Datatype and Waarde contain useful information. These files not only contain irradiance data but also others not used in this analysis.

Temperature files have 7 columns: *Year*, *Month*, *MonthNo* (month number, e.g. June is 6), *Day*, *Hour*, *Location* (the sensor name), *AverageTemperature.*

Data used for the analysis are: energy (Wh) produced by each module every hour, irradiance (Wh/m^2) received by each module every hour, temperature (°C) of each module every hour, installed capacity (Wh) of each module, size (m^2) of each module.

3.2. Data Linking

In Section 3.1 is described how each data file is structured and what contains. However, no file has information about where each module is positioned in the building and about which irradiance and temperature data are related to each sensor, which are needed for the analysis.

Because of a missing direct link between all these information, the data of each file can not be joined at this moment, therefore a model has been created with the scheme showed in Table 1, that also contains an example of a data instance.

Table 1: *Structure of the model created to link all information, with example.*

Modules	**Row**	**Column**	**Capacity (Wh)**	**Temperature sensor**	**Irradiance sensor**	**Size (m^2)**	**Category**	**Cells number**
Module 1.0.1 (12A96758-7A)	22	29	355	RSERT	RSE	1.7129	F	60

The column "Modules" contains the list of all modules installed in the building, named as their serial number and in the brackets the optimizer code they refer to.

Columns "Row" and "Column" refer to the position each module has in the building, referring to a matrix that has been constructed.
First of all, each side of the building has been considered on its own, and since modules have been installed with a matrix scheme, this has been exploited to create the model of a matrix that resembles the physical matrix structure, where the x,y correspond to a module position, that has been numbered accordingly. At the borders of Figures 11, 12, 13 and 14 there is a sequence of numbers corresponding to the x (columns) and y (rows) positions. Hence, as previously stated, an x,y position in the matrix identifies a single module.

Rows 11-14 in Figure 11 are the modules positioned on the front side of the pergola, while rows 1-10 represent each floor. Balconies are represented in blue and are placed on each row, on columns 3-4, 7-8, 11-12, 17-18, 21-22, 25-26. The positions on row 1 and 2, columns 7-8 and 21-22, are without modules due to the two entrances of the building.

Considering where the sensors are positioned, as seen in Section 1.4 in Figure 8, have been identified which modules are comprised in the area around each sensor. The temperature sensors areas are identified with a white rectangle in the figures, and the name of the correspondent sensor is written inside them. Same is for the irradiance sensors, which are less then the temperature ones thus have a bigger area, and have been identified with a green rectangle with the correspondent sensor name inside.

The decision of which modules are included in a certain area and not in another one was arbitrary. For example, in Figure 11 can be seen that rows 11-14 are split at y=10 and y=21, while rows 1-10 in y=10 and y=18. This decision would not have changed the final results as much, since in the end both temperature and irradiance measured with the sensors do not differ from each other very much.

All these gathered information have been inserted in the model of Table 1.

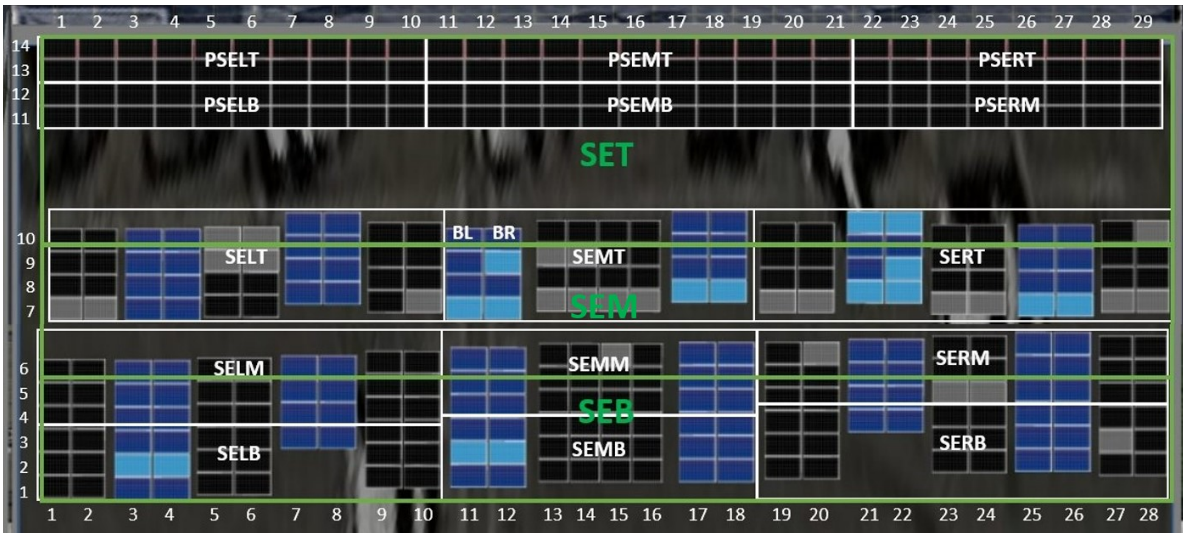


Figure 11: *Matrix showing position of each module and the area covered by temperature sensors (in white) and irradiance sensors (in green) on the façade and the front part of the pergola (modules on top).*

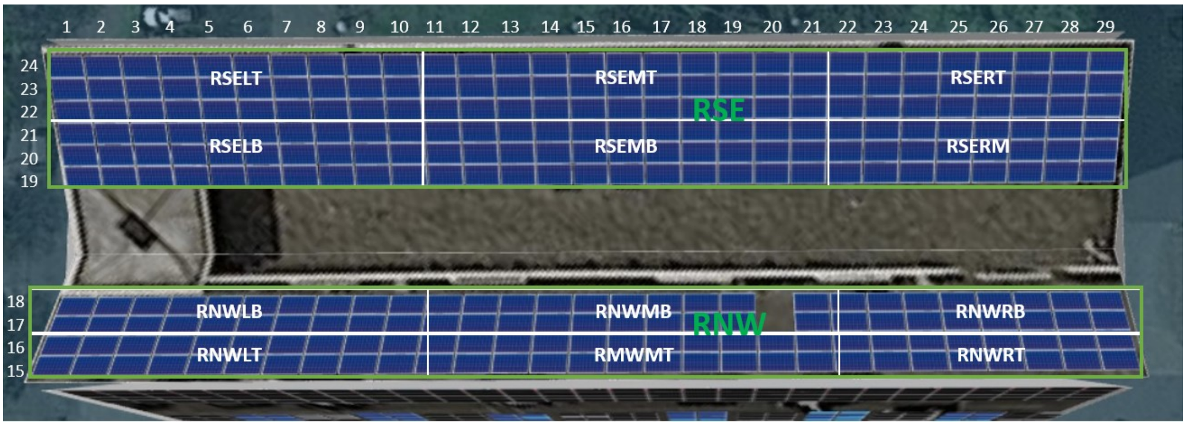


Figure 12: *Matrix showing position of each module and the area covered by temperature sensors (in white) and irradiance sensors (in green) on the upper part of the pergola.*

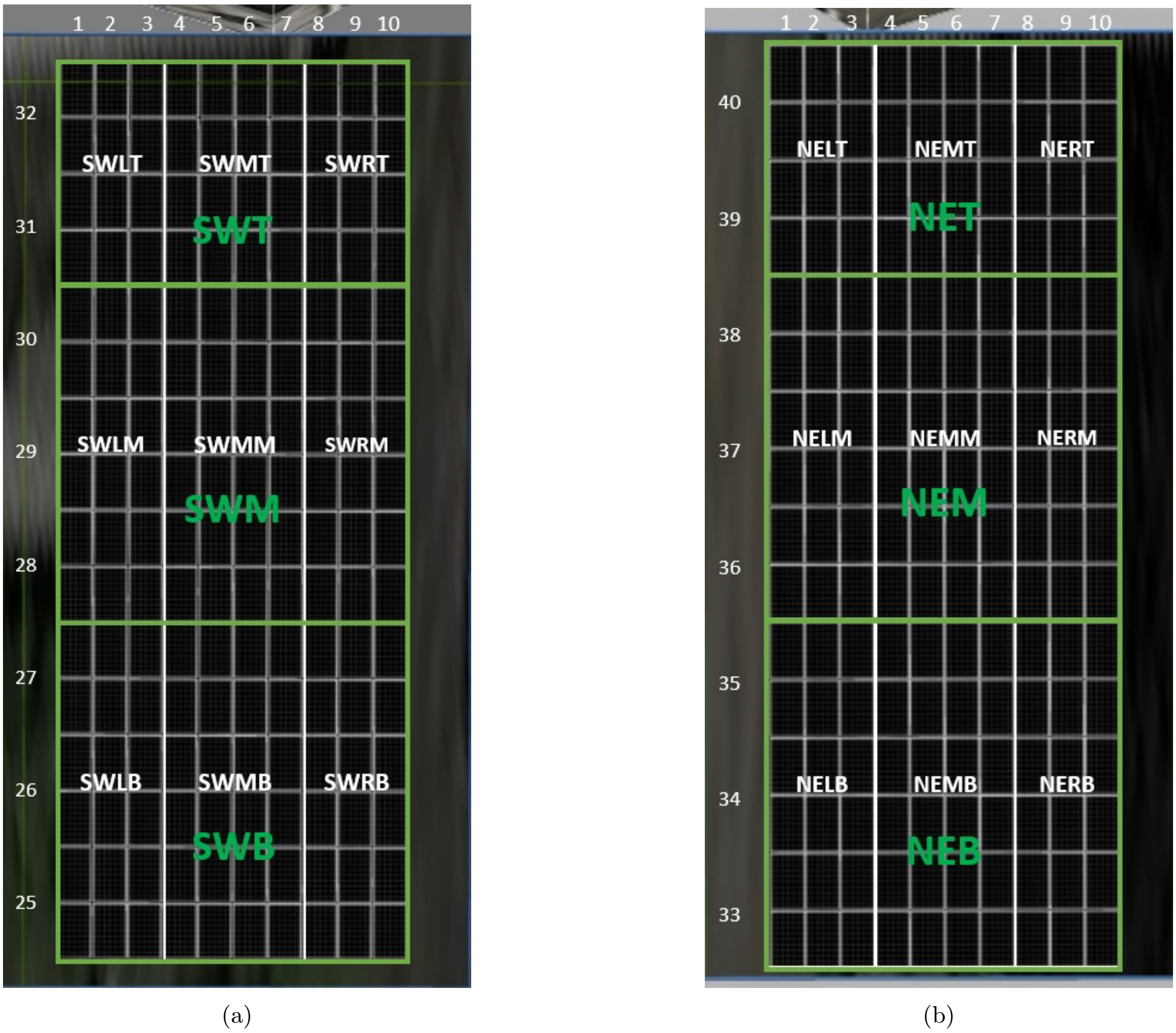


Figure 13: *Matrix showing position of each module and the area covered by temperature sensors (in white) and irradiance sensors (in green) on the two sides of the building, looking from the front: a) is the left side, b) is the right side.*

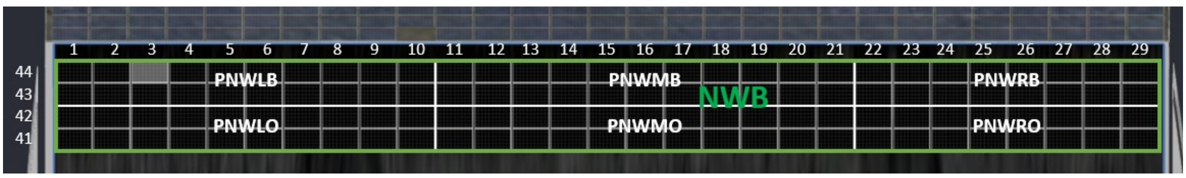


Figure 14: *Matrix showing position of each module and the area covered by temperature sensors (in white) and irradiance sensors (in green) on the back side of the pergola.*

Column 'Category' refers to the module position in the building that classifies them in different categories. There are 10 categories in total, which are:

- A: grey modules on the façade on the left of balconies (looking from the front)
- B: grey modules on the façade on the right of balconies (looking from the front)
- C: grey modules on the façade without any shading

- D: modules on balconies
- E: vertical modules on the pergola
- F: modules on the South-East side of the roof (the bigger area)
- G: modules on the North-West side of the roof (smaller area)
- H: modules on the left side of the building (looking from the front)
- I: modules on the right side of the building (looking from the front)
- J: modules on the back side of the pergola

These categories have been identified based on the difference in position and tilt of each module (e.g. grey modules on the left or right side of balconies can have shading, thus will have a different production than the same modules far from balconies or tilted modules on the roof). Figures 15, 16, 17 and 18 show the categories division.

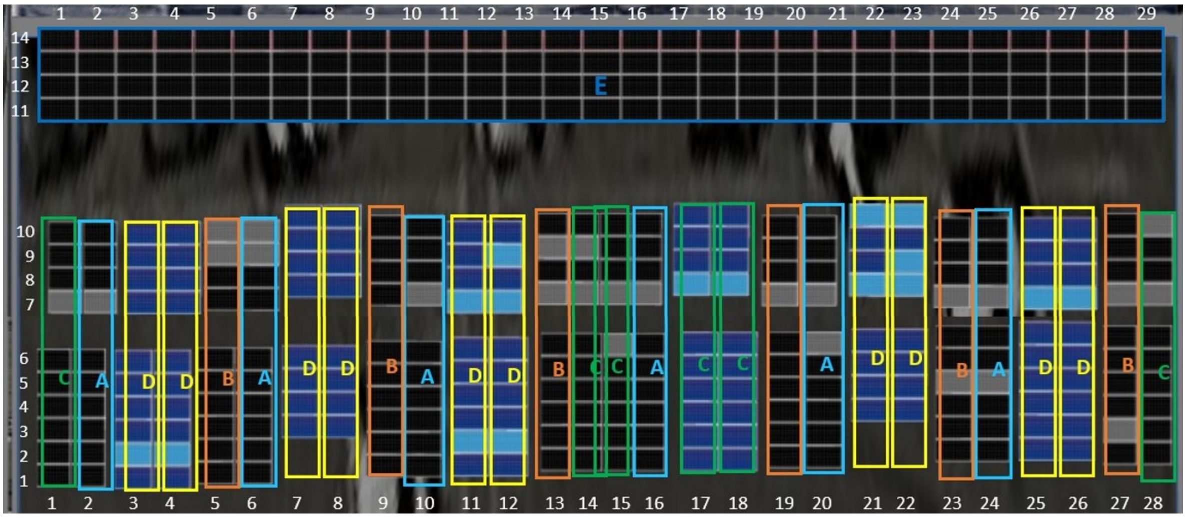


Figure 15: *Matrix showing position of each module and each category on the façade and the front part of the pergola (modules on top).*

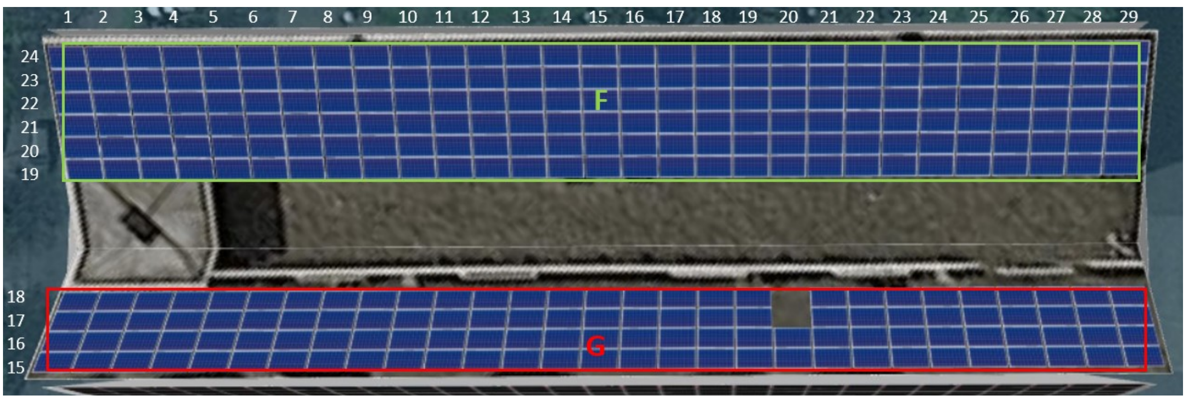
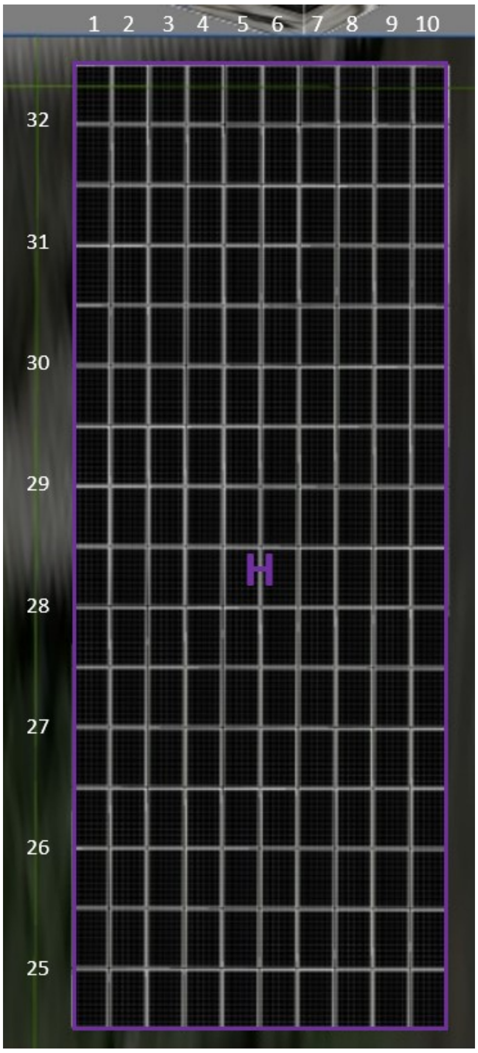
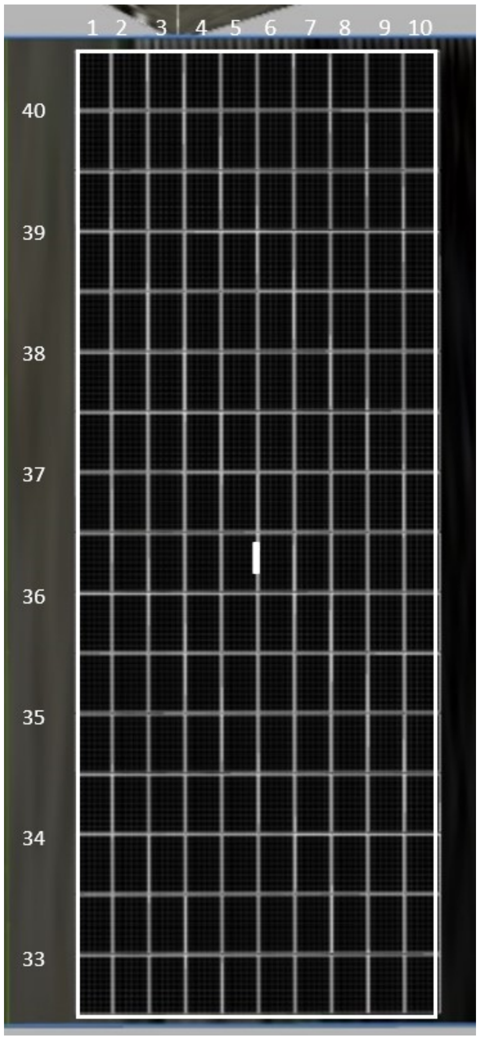


Figure 16: *Matrix showing position of each module and each category on the upper part of the pergola.*



(a)



(b)

Figure 17: *Matrix showing position of each module and each category on the two sides of the building, looking from the front: a) is the left side, b) is the right side.*

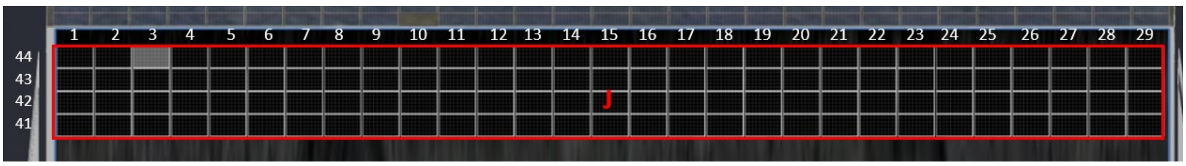


Figure 18: *Matrix showing position of each module and each category on the back side of the pergola.*

The "Capacity" column contains the capacity (in Wp) of each module, since they are of different type and have different characteristics. The same is for column 'Size', which contains the size (in m^2) of each module. These information are given by the constructor.

The columns "Temperature sensor" and "Irradiance sensor" show the sensors each module refers to. These sensors have been installed in particular positions on the building and their retrieved data are valid for the modules contained in their area, which means the modules closer to them. The names explanation is showed in Appendix B.

Lastly, the column "Cells number" contains the number of cells each module is structured with. Each type of module has a different number.

One issue that has been encountered while creating this model is that a few modules' names of the main façade had not been positioned on the building model (probably because of an error during the placement of modules on SolarEdge), thus the file has some empty rows next to these modules. They are in total 38, on a total of 949 modules of which the PV system is composed, and all reside in categories A, B, C and D. For this reason, since they are not part of any category, in the analysis they are not considered. However, considering categories ensures that this does not create any serious problem when analysing data.

3.3. Data transformations

Due to their different structures and units, each data file type needed certain transformations before being usable by the program.

The most complex transformation was needed by the irradiance files.
First of all, each file had a structure that was not readable neither by MS Access nor by MS Excel without requiring transformations during the loading. The first attempt has been to try uploading these `.csv` files and at the same time time fixing the conversion problems (mainly, a unusual format that Microsoft did not recognize, and also a problem with ''.'' and '','' regarding decimals). This procedure worked but was extremely slow so has been discarded.
Hence, the approach that proved to be the best one is, for each read `.csv` file, another `.csv` file is created having the correct format. The conversion procedure between the two files is as follows. After having written the first row containing headers, when the program reads the initial file, every time a ' ' (space) is encountered, in the new file the line is written, a new line is created and the following line is written, until the initial file is finished. In this way, the new created `.csv` file has the correct format and can be uploaded in the program. This procedure takes milliseconds, instead of minutes that were taken by other approaches.

Another issue with the irradiance files was that these files contain many other information than irradiance, thus they had to be divided. The division has been made through a difference in two columns: if the column "Datatype" contained the word "Irradiance", the value in column "Waarde" is irradiance.

Other than transformations on the file structure, transformations on data were also needed due to problems with the measured data, and they are listed as follows:

- because of the irradiance sensors issues, described in Appendix B, in the hourly DB was necessary to take outliers out of the analysis to not corrupt it. This has been done by deleting hourly irradiance values that were higher than 1200 Wh/m^2. This value has been calculated from the irradiance at STC (Standard conditions), that is 1000 Wh/m^2, increased by a 20% in order to cover particularly hot days.

For the same reason, also values that are "0" or lower have been excluded from the analysis.
Because energy starts getting produced when the irradiance is at least 25 Wh/m^2, values lower than this threshold have been excluded.

- because of the same sensors issues, the irradiance in particular hours and days did not go hand in hand with the energy production levels, because it had low values when the actual energy production was in fact high, or viceversa. This problem lead to having efficiency values not conform with the reality of the system and not real (higher than 50% or even higher than 100%). For this reason, after analyzing the exact reason why this was happening, efficiencies higher than 30% have been left out of the analysis. This threshold has been put higher than the efficiency of modules described in their technical information, because its only scope was to remove outliers. This efficiency issue was given by the equation, that has been discussed later in Section 4.2: by considering the ratio between produced energy and received irradiance, every time the irradiance sensors have a problem, this value does not reflect the reality.

- because of energy production data not being always measured perfectly, outliers were taken out by deleting hourly data with values higher than 450 Wh. This threshold has been set higher than the installed capacity of modules (which is the maximum energy they can produce in one hour) only to not consider outliers, which were way higher than this value.

- exactly as irradiance sensors, temperature sensors also had some issues, described in depth in Appendix B. Due to these issues, some temperature sensors did not give any data, and these cells have been temporarily transformed into the value "99999", and then into "0". Since temperature data will be analysed on their own, and they are not part of any equation, rows containing temperature "0" will not be deleted from the data set. Also, because temperature sensors with issues are all placed on the main façade, removing rows with "0" would mean not have any data for categories A, B, C and D, energy and irradiance included, and the analysis would not make sense.

- during the day, irradiance sensors only gave values during certain hours and, in the data set, had "0" values when energy was still producing something, thus to avoid having only "0" irradiance values in the analysis, a range of hours per day has been selected, using the longest days in summer to analyse which they could be. It has been selected to only consider hours from 6:00 to 18:00. During shorter days, in winter, modules stop producing energy earlier than 18:00, thus these days do not have the same problem of having "0".

To conclude, in general the data files were not ready to be used and needed a few changes, which happens when dealing with real-life systems.

3.4. Program Setup

The program coded to be able to analyse the system has the structure showed in Figure 19.

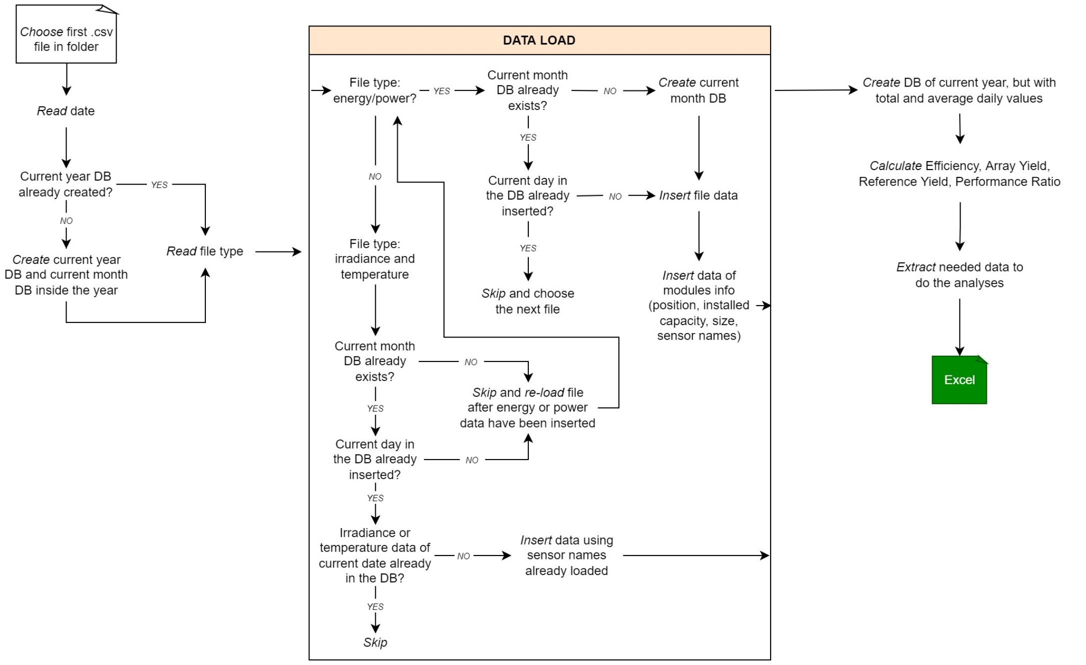


Figure 19: *Program flowchart showing each passage the program does to load and extract data.*

The program has been coded in Visual Basic, using the environment that the MS Access program provides. Access is a DBMS (Database Management System) that easily allows management and interaction between databases (DB). Moreover, Access also provides the possibility of writing queries in SQL, which is useful for certain tasks. The DBs are relational, made of rows and columns, meaning that data are stored in tables. Each table can have as many fields (or attributes) as needed, which indeed can be thought of as columns.
Data can be inserted into tables via data forms or queries, through the data relationships that have been created.

The program structure is divided into different DBs in order to clearly use the data: one DB contains data divided into monthly tables, where each one contains a list per each module and each hour of the day of all energy and power productions, irradiance and temperature values. Each year of data corresponds to a DB on its own. Similarly, another group of DB still has data for each module, but tables are structured at daily level.
Both the hourly and daily DBs, other than energy, power, irradiance and temperature data, also contain all the other modules information (i.e. all data on modules information described in Section 3.2).

As Figure 19 shows, the program automatically recognizes the date inside each file, checks whether the DB with the file's year exists and, if not, it creates it.

Then it reads the file type, and depending if it is energy or power, temperature or irradiance it has different procedures: when the file is energy or power, it checks whether the DB with the file's month exists and, if not, it creates it inside the current year DB. Then, it checks whether the data of the current day has already been inserted and, if not, it insert them. After inserting energy and power data, the program completes the monthly DB with data on modules information described in Section 3.2.
Otherwise, when the file type is irradiance or temperature, it follows the same procedure just described but with a substantial difference, which is that if the month or day has not been inserted yet in the DB, it does not insert them. This is because irradiance and temperature are linked to each module through their sensors name, and they are inserted in the DB only after inserting modules with energy and power. Thus, when dealing with this file type, the program only inserts new data if the DB already contains the current day.
Each passage skips the file if it has already been inserted. The already inserted files will be deleted from the main folder, one more way to be sure the program does not insert the same data twice. This makes the entire process faster during this phase.

After loading all data, the program creates the daily DB that, as previously mentioned, has the same tables composition of the current hourly DB, but with daily data inside. In this DB, the KPIs, that will be discussed in Section 4.2, are calculated (efficiency, array yield, reference yield, performance ratio).

Lastly, as showed in Section 3.5, the program offers the possibility to group data by time constraints and parameters, more specifically by day, week, month or year and by category, irradiance or temperature sensor and module name, and they can also work as filters. These extracted data will be inserted in a new Excel document.

The program is automatically linked to the all above mentioned DBs. The code written in order to created all the DBs, link tables, transform and group data and do the data extraction is structured in different forms inside the program.

In order to link all the needed data mentioned in Section 3.2 and setup the analysis, the table structure in the DB is the same for each month: module name, date, energy (Wh), power (Wh), irradiance (Wh/m^2), name of correspondent irradiance sensor, temperature, name of correspondent temperature sensor, the different efficiencies (eq. 4.1 - 4.4), the module information described in Section 3.2 and some intermediate results that are needed for the analysis.

As previously mentioned, the irradiance and temperature values that correspond to a particular module can be assigned through the sensor names, thus in order to assign the correct values the irradiance and temperature data must always be uploaded in the database *after* the energy or power data, which contain the information on sensors.

While uploading all the cited data, the trasformations described in Section 3.3 are made.

3.5. Program User Interface

The program offers a user-friendly Graphical Interface that makes it immediately understandable. The homepage in Figure 20 has a simple structure made of three buttons, which are “Loading Data”, “Extracting Data” and “Close”. The last button closes the program.
The entire program is divided into buttons, each one running a specific part.

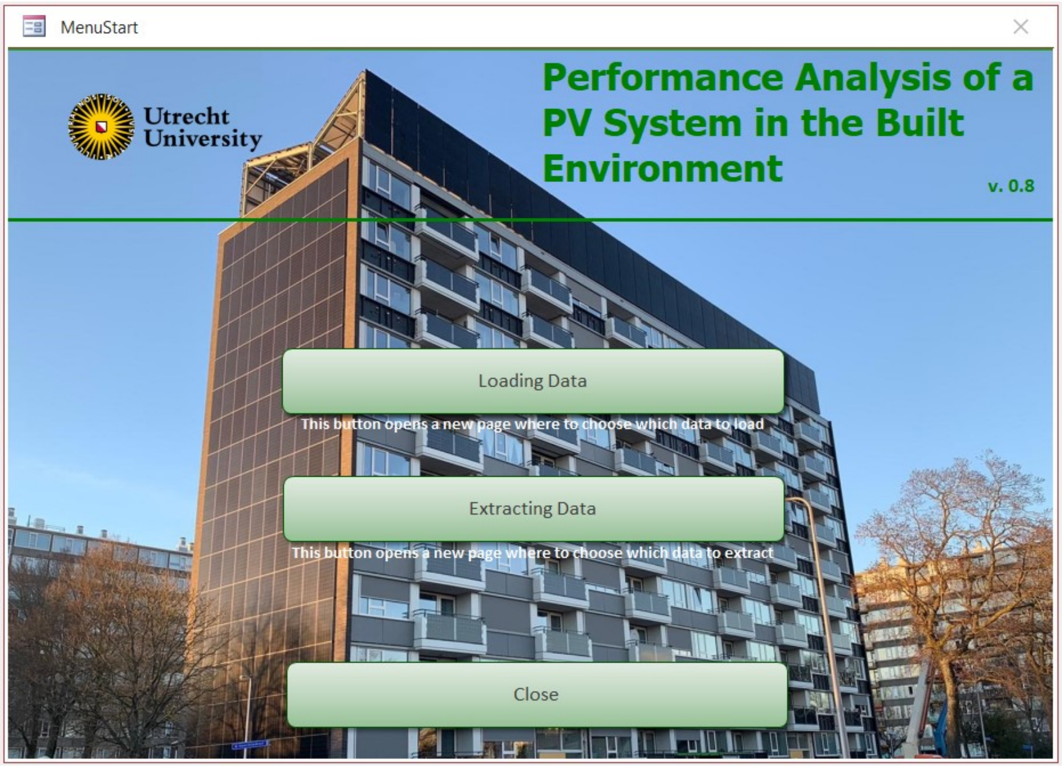


Figure 20: *Homepage of the program.*

The first button, “Loading Data”, opens the page showed in Figure 21, where it is possible to choose what to load: energy and power data, irradiance data, temperature data. Energy and power data loading are included in the same form because of their similar procedure. As it has been explained in Section 3.4, the correct order for importing data is to first load Energy and Power, then Irradiance and Temperature. This is very important, because a wrong order in loading data will lead to an error in the DB. It takes a few seconds for data to load, somewhat longer if many days are being loaded. The last button is needed to return to the homepage.

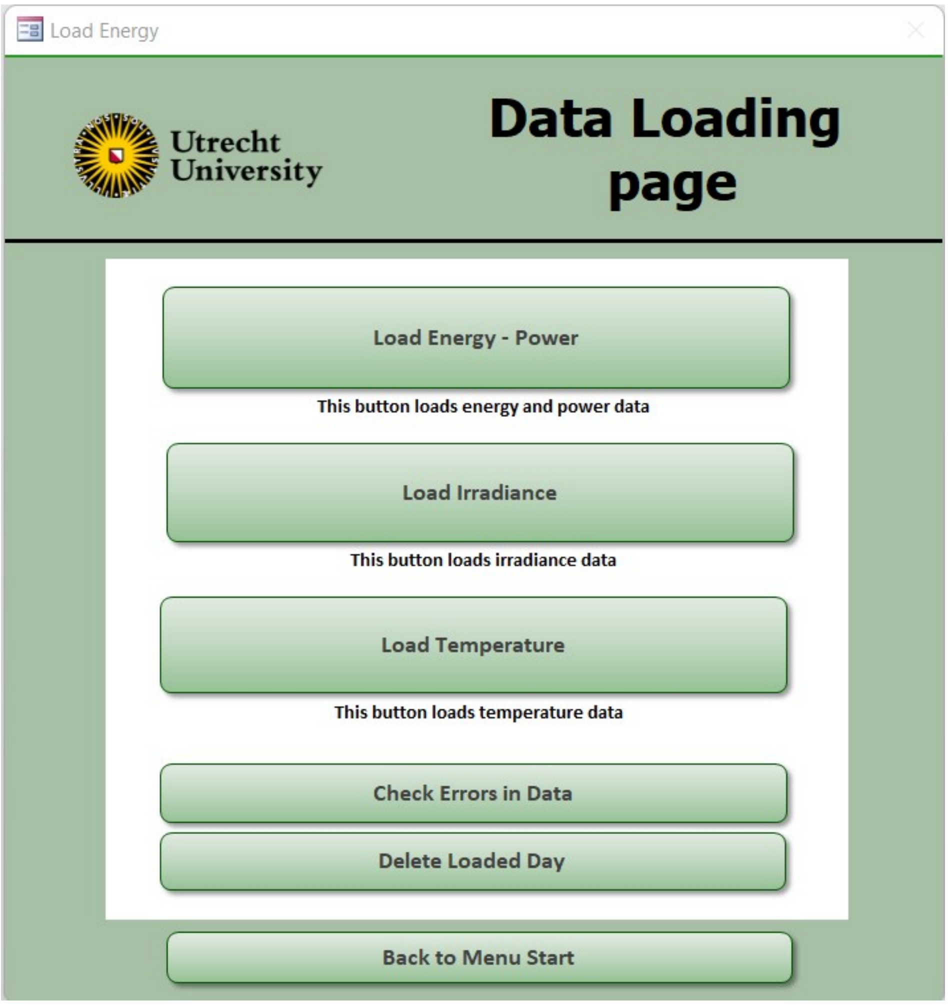


Figure 21: *Program page with loading buttons.*

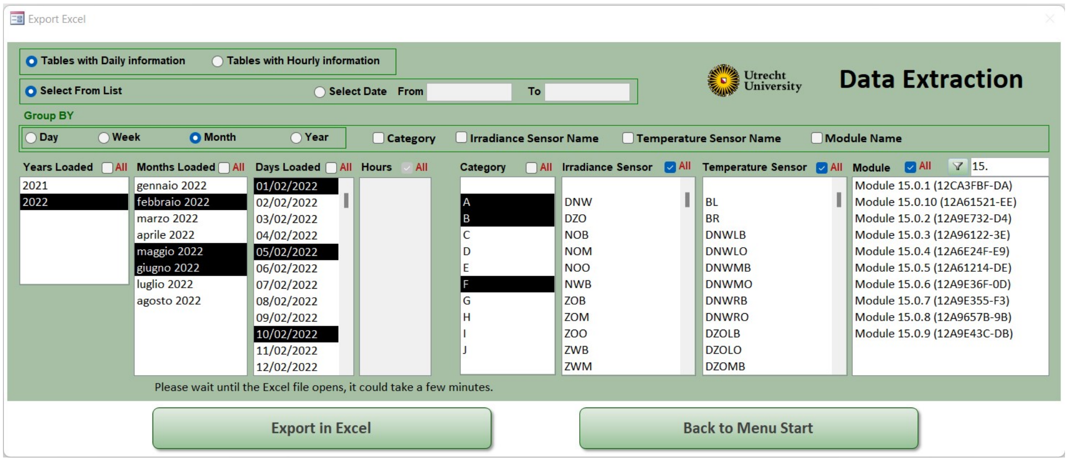
Back to the home page (Figure 20), the second button, "Extracting Data", opens the page in Figure 22, where the extraction parameters can be selected. This section has a distinct form.

The first choice on top refers to the two different DB mentioned at the beginning of Section 3.4, which are with daily and hourly data. By default, the program has been set to always choose daily information if not specified. This choice, thus, determines the correct underlying DB to use.

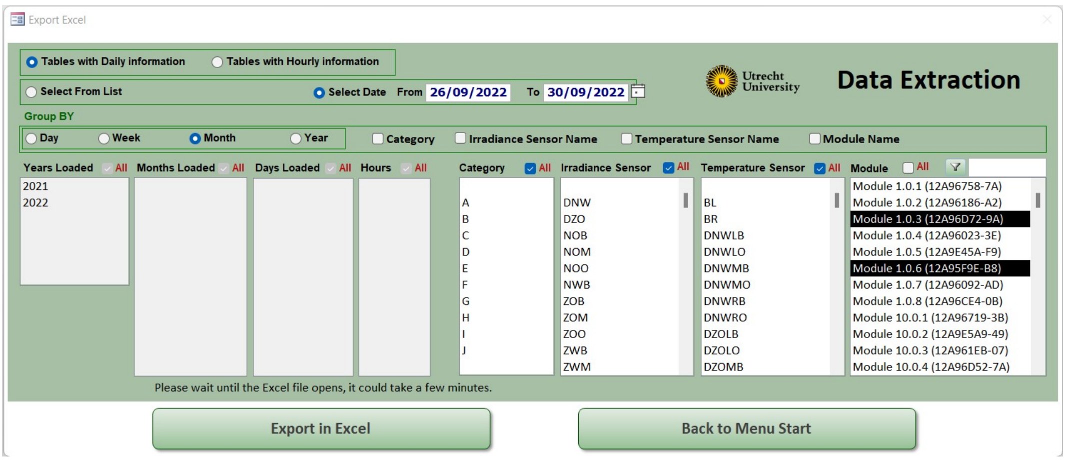
The second choice regards choosing the date. By default, the program has been set to choose from the list below, in order to choose the days of interest, but the "Select Date" choice allows to select from the calendar a range of days, as showed in Figure 22 (b).

The third choice is about grouping data. The first 4 choices regard time grouping and can be chosen either day, week, month or year, and they are mutually exclusive, meaning that only one can be chosen. The second 4 choices regard data grouping and can be chosen to group by category, irradiance or temperature sensor name and module name, and in this case they could all be chosen at the same time. As an example, in Figure 22 has been chosen to group by month and category.

The last choice is not about grouping data, but about filtering them. In the first 4 blocks can be chosen to filter on a specific year, month, day and hour. Hour can be chosen only when selecting "Tables with Hourly Information" on the first choice. The filter can be done by choosing one or more values on the list, as the example showed in Figure 22 (a), where have been chosen: year 2022, months february, may and june, days 01/02/2022, 05/02/2022 and 10/02/2022. The second 4 blocks are filters on data, thus category, irradiance and temperature sensor name and module name. The procedure of selecting one or more values on the list works as the time blocks, except that the filter for module name also has the possibility to write a number or a code to find in the list, so to reduce the choice, considering that modules are hundreds. For each filter can also be selected all values, by clicking on the flag "All".
The two buttons on the bottom are respectively for exporting data, that automatically creates a new Excel file with them, or to go back to the homepage.



(a)



(b)

Figure 22: *Program page with extraction setup.*

4 | Analysis

The data analysis' biggest aim is to assess the performance of a BIPV system and understand which factors can impact it, and this can be seen by comparing modules placed in different positions and look at their performance. Fundamental for this aim has been the division of modules in categories, described in Section 3.2.

In this chapter have been plotted graphs with the necessary information for giving an answer to the Research Questions. An analysis has been performed confronting different set of categories and will be determined the performance of the system in each situation.

4.1. Parameters that affect the performance of a (BI)PV system

The parameters that usually affect the system performance are irradiance, temperature, modules position on the building, technological construction and the module type. More specifically, the incoming *irradiance* is the solar radiation that each category or set of categories receive on average every hour, *temperature* is the temperature in °C that each category or set of categories have on average every hour and is considered only to be module temperature. The *position in the building* is the POA (Plane of Array, in terms of tilt) and shading depends from it (given by surroundings and the building itself). The *technological construction* is given by the constructor and for the following analyses is taken the important value of installed capacity. The *module type* refers to colour of modules, size and number of cells contained in each one.

As a result of these parameters, each module produces a certain amount of energy, defined as the energy (measured in *Wh*) that each category or set of categories produce on average every hour.

4.2. Assessing the performance of a (BI)PV system

The parameters described in Section 4.1 can affect the energy production of a module and thus of the entire PV system. In order to assess the performance of the system, the involvement of these parameters needs to be measured using three different KPI (Key Performance Indicators): system efficiency, energy yield and performance ratio.
The first value, system efficiency, represents the ability of converting the incoming solar energy from the panels into electricity and is expressed as a value between 0 and 1, conveying the

information of how much input energy the system is able to convert into output energy. For the purpose of determining the overall system efficiency, the efficiency of every single module has to be calculated and in most cases for each category. This value strongly depends on the panel efficiency, thus its design characteristics, and for this reason it is not an absolute comparison between different systems [36] [37]. The resulting equation for the system efficiency η is as follows:

$$\eta = \frac{Produced\ energy\ by\ the\ system\ [kWh]}{Solar\ energy\ input\ on\ the\ PV\ module\ area\ [kWh/m^2]\text{x}Modules\ size\ [m^2]\text{x}Time[h]} \tag{4.1}$$

Where *Solar energy input on the PV module area [kWh/m^2]* is the irradiance the modules receive.

The system efficiency, however, can sometimes lead to an incorrect conclusion on the system, because of its equation that considers the ratio between produced energy and received irradiance and thus strongly depends on the difference between these two parameters. Thus, it needs to be compared with other parameters.

The energy yield can be divided into two different values, both expressing the time that the system works at its best conditions: array yield (Eq. 4.2) focuses on the array performance, which represents the time that the PV array (the module in this case) produces energy at its installed capacity. In this Thesis, the values obtained for the array yield are the average amount of time that each category, or set of categories, produce at the installed capacity in a day. Values will be mostly considered weekly and monthly averages, but the array yield meaning does not change and still represents the hours in a day. Array yield is a good parameter to compare modules, or even systems, because the higher it is, the better the performance, since it is measured in h/day that the module is able to produce at its installed capacity (which is also called maximum capacity).
Reference yield (Eq. 4.3) indicates the ideal case, that is if the system had no energy losses, thus measures the number of hours producing at the reference irradiance [38]. It also has some restrictions, as it strongly depends on the solar irradiation, so by itself it does not give an absolute evaluation either [39]. Both array and reference yield unit is h.
The equations are respectively:

$$Y_A = \frac{Energy\ generated\ by\ the\ module\ [kWh]}{Module\ installed\ capacity\ [kWp]} \tag{4.2}$$

$$Y_R = \frac{Irradiance\ on\ the\ module\ [kWh/m^2]}{Reference\ irradiance\ at\ STC\ [kWh/m^2]} \tag{4.3}$$

Where irradiance at STC is set at 1 kW/m^2.

The performance ratio compares the actual yield achieved by the system (eq. 4.2) with the ideal case of the reference yield (eq. 4.3); this means that it gives an insight on the amount of losses, which determines the quality of the system. This performance indicator allows different systems to be compared and also monitors the performance over time. However, as previously mentioned for the efficiency, The equation is defined as:

$$P_R = \frac{Y_A}{Y_R} \tag{4.4}$$

All these performance indicators should be calculated for having an insight into the system performance. The P_R is the most useful parameter for long-term performance determination, hence it will only be calculated on a yearly basis and for each category.

The overall performance of a module, a category, a set of categories or a system has to be determined by analysing each KPI, together with its produced energy and received irradiance. The next sections will indeed deepen into these parameters' analysis.

4.3. The impact of shading on a (BI)PV system performance

Some particular characteristics in a building can create shading during the day. These could be for example a very prominent roof, a balcony, large curtains outside the windows, a chimney. If they typically are not causing any issue to the building, when analysing a BIPV they can. Modules on the façade that have shading for some time every day can produce less energy, thus decreasing the total system performance. The magnitude of this impact on the case study system performance will be discussed in this section.

The impact of shading will be analysed in two passages. Because in the case study the characteristic that can bring shading are balconies, will be first analysed the difference in shading of modules that are positioned on the main façade, respectively on the left and on the right of balconies. Then, the difference in performance of modules positioned next to balconies (left and right combined) versus the modules on the main façade that are not next to the balconies will be considered.

Performance of modules positioned on the left versus on the right of balconies. This paragraph analyses the differences between grey modules on the main façade, situated on the left and on the right of balconies, which have been defined as category A and B. As already said, both categories have grey modules, but being placed on one side of a balcony or the other, considering that both sides have shading during the day in different moments, can result in different performance. They are both composed by modules with installed capacity of 160 Wp, 180 Wp and 220 Wp, in similar proportions.

Figures 23 to 26 show a division in summer and winter weeks, where summer is comparing 2021 and 2022 on weeks 23-40 and winter is a combination of 2021 and 2022 and covers weeks 45-10. This division helps understanding what is different during each time of the year.

For the sake of clarity, it needs to be noticed that weeks 30-33 of 2021 and week 36 of 2022 do not have weekly values. This is due to a problem in the irradiance sensors, which resulted in having wrong values for the sensors related to the modules of which these categories are composed by. Moreover, temperature sensors on the main façade are also problematic. In Appendix B has been reported an analysis on the reliability of each sensor.

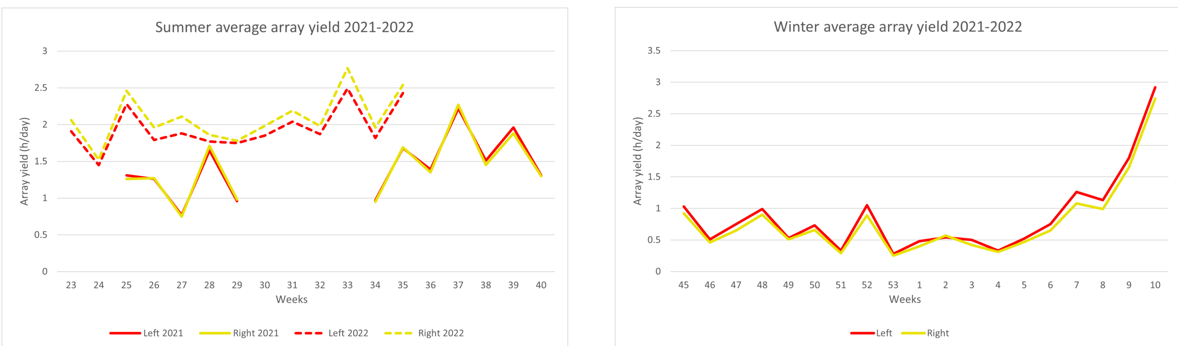
(a) (b)

Figure 23: *Average efficiency comparison of modules positioned on the left and right of balconies, divided into summer (a) and winter (b).*

Figure 23 compares the efficiency of the two categories during summer and winter.

It can be seen that during summer, in 2021 the categories have the same values except for week 28 where modules on the right are higher and week 37 where left is higher. Altogether, their efficiency on average is the same, 9.3%.
In 2022, modules on the right in general have higher values than those on the left, except for some weeks where they have the same. On average, modules on the left have an efficiency of 8.5%, while those on the right have 9.1%.
Modules positioned on the right of balconies have a higher efficiency during summer.

During winter, the opposite happens and modules on the left of balconies have a higher efficiency than those on the right (respectively 8.1% and 7.1%, on average).



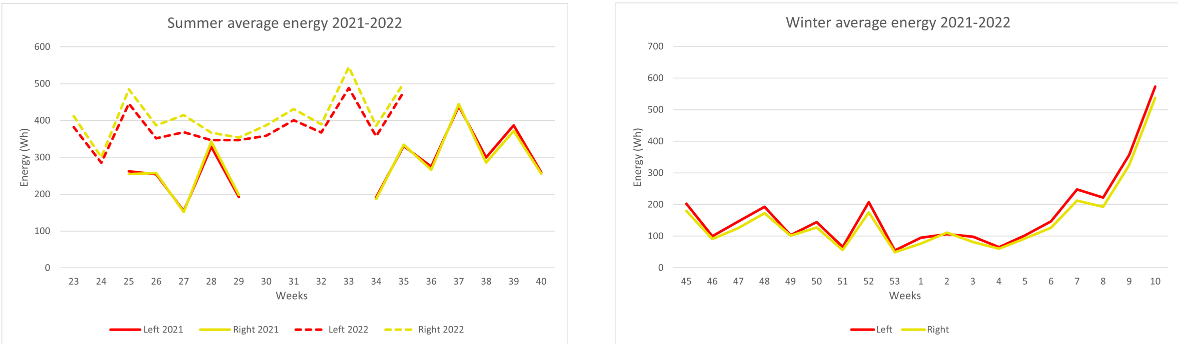
(a) (b)

Figure 24: *Average array yield (h/day) comparison of modules positioned on the left and right of balconies, divided into summer (a) and winter (b).*

Figure 24 compares the array yield of the two categories during summer and winter.

During summer 2021, the array yield is slightly higher for modules on the left of balconies, on average 1.41 h/day versus 1.4 h/day of modules on the right of balconies. During summer 2022, modules on the right of balconies have a higher array yield than modules on the left, respectively 2.1 h/day and 1.95 h/day. This means that in summer modules on the right of balconies in one day produce at their installed capacity more time than those on the left.

During winter, the array yield is on average higher for modules on the left of balconies, 0.86 h/day against 0.78 h/day of those on the right.



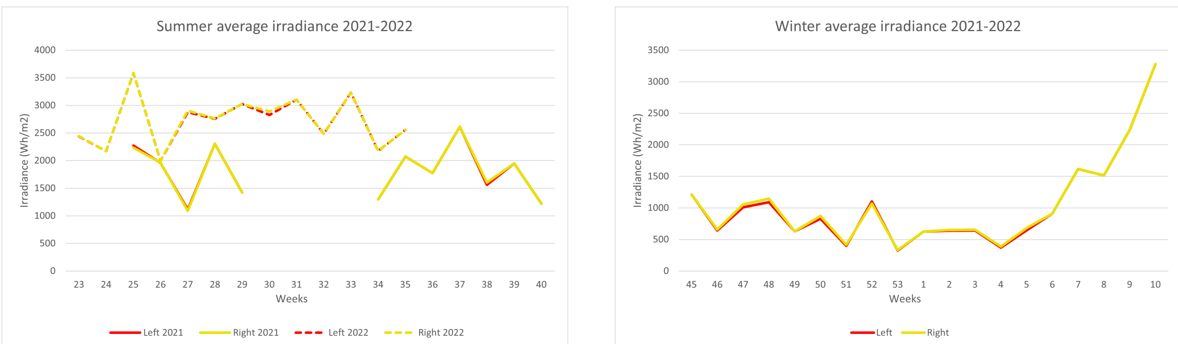
(a) (b)

Figure 25: *Average energy production (Wh) comparison of modules positioned on the left and right of balconies, divided into summer (a) and winter (b).*

Figure 25 compares the energy production of the two categories during summer and winter.

During summer 2021, the categories have on average the same produced energy, while in 2022 is higher what modules on the right of balconies produce, on average 412 Wh against 383 Wh for those on the left.

During winter, modules on the left of balconies produce always somewhat more energy on average than those on the right, respectively 170 Wh and 152 Wh.



(a) (b)

Figure 26: *Average irradiance (Wh/m^2) comparison of modules positioned on the left and right of balconies, divided into summer (a) and winter (b).*

Figure 26 compares the received irradiance of the two categories during summer and winter.

Both during summer and winter, irradiance is exactly the same for the two categories, because they have the same irradiance sensors and thus receive the same values.
Also, both categories do not have temperature values registered due to a sensors issue, as stated in the beginning of this section.

In Figure 27 is showed the change, in percentage, from summer 2021 to summer 2022 of modules on the left and on the right of balconies in four parameters. Energy production in modules on the left of balconies, on average, has increased less than for modules on the right. This was already visible in Figure 25, where the energy in summer 2022 was higher on modules on the right of balconies. A lower increase in energy production has lead to a lower increase in array yield, as visible in Figure 24.

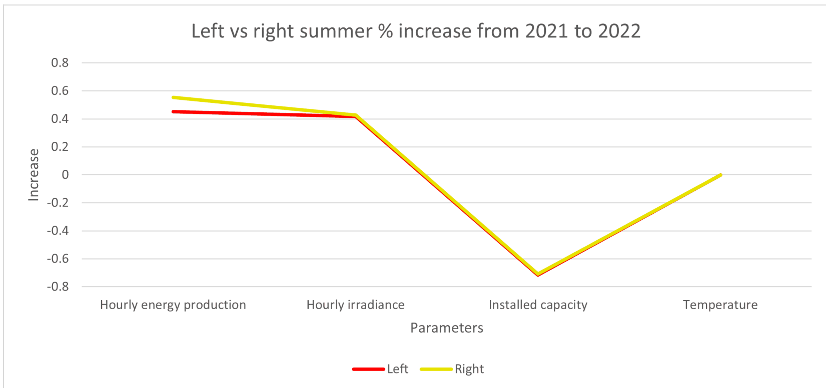
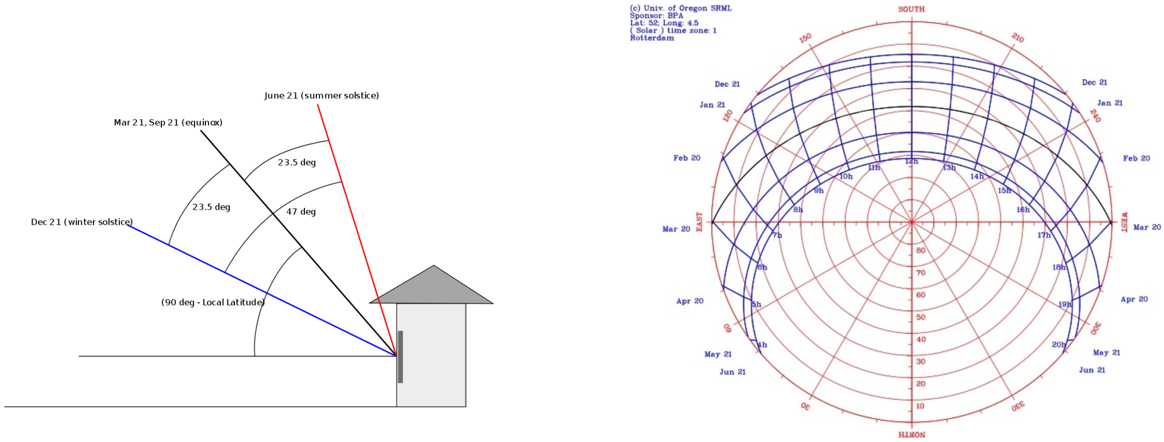


Figure 27: *Percentage of increase during summer from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of modules on the left and on the right of balconies.*

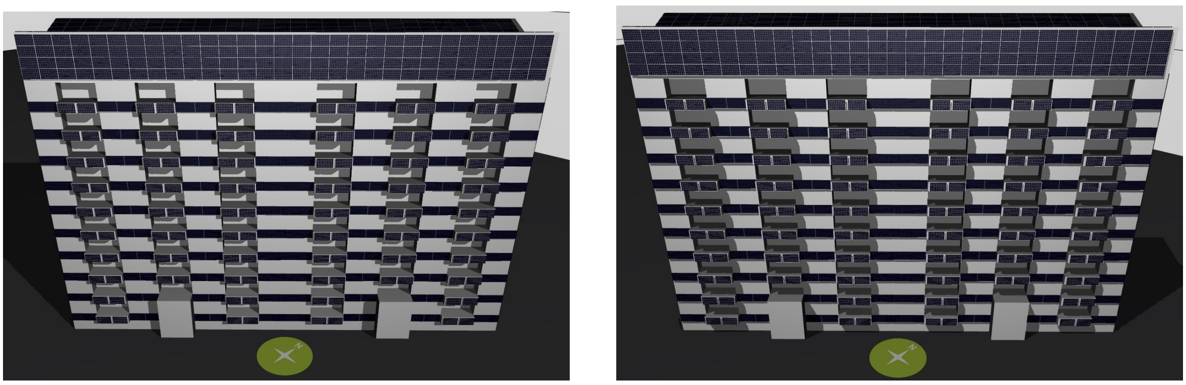
Overall, looking at the entire data set, the modules on the two sides of balconies perform alike. As analysed above, during summer modules on the right are more performing, while during winter modules on the left are more performing.
Indeed, looking at the sun path in Figure 28 and considering the building orientation towards South-East, during winter modules on the right of balconies get more shading already from early afternoon. The sun rises from South-East, thus during early morning modules on the left of balconies do not have shading because the sun is facing the main façade, while moving towards South-West, where it goes down, the rays face more and more the side façade on the left, resulting in bringing shadow to modules on the right of balconies.



(a) (b)

Figure 28: *Images showing the sun inclination and position during the year, respectively the difference in solar inclination (a) and the difference in the sun path (b) [6].*

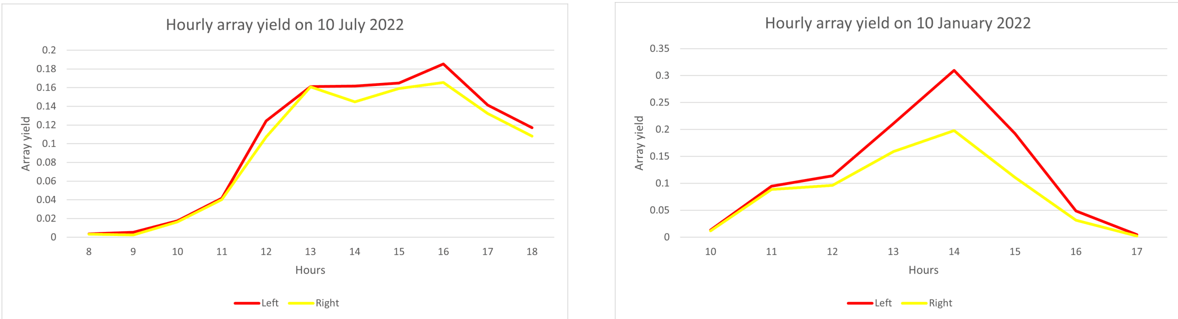
Figure 29 clearly shows that, during summer, since sun rises from North-East and in the morning it slowly moves towards South increasing its inclination, it gives shadow to modules on the left of balconies, for about 5-6 hours. Since 12:00, the sun is very high in the sky, its rays are almost vertically tilted, and it moves faster towards North-West, where it goes down. This results in modules on the right of balconies having shadow only for about 2-3 hours a day. In Figure 29, part (b), is represented the shading at 13:00, and already at 14:00 it was covering almost the entire main façade. Pictures on the model of winter days have not been showed because, as previously mentioned, modules on the left of balconies never get shading and modules on the right get it as in Figure 29. Because of these differences in sun positioning, the modules on the right have more hours without shading, thus more hours where they can produce energy.



(a) (b)

Figure 29: *Images taken from the case study building model, created a few years ago, showing the shading respectively at 8:00 (a) and 13:00 (b) of 10 July 2022.*

Also looking at some hourly data, it becomes clearer how shading impacts energy production and how different it is from modules on the left and on the right of balconies in each moment of the day, on the same days. In this situation, the chosen modules are column 16 (on the left of balconies) and column 13 (on the right of balconies) All the chosen modules are of the same type and all have a total of 48 cells, which means 32.65 $cells/m^2$. Entire columns have been chosen in order to cover each floor, and close to each other in order to have the same external conditions (temperature and irradiance). For summer, the chosen day has been 10 July 2022, while for winter 10 January 2022.

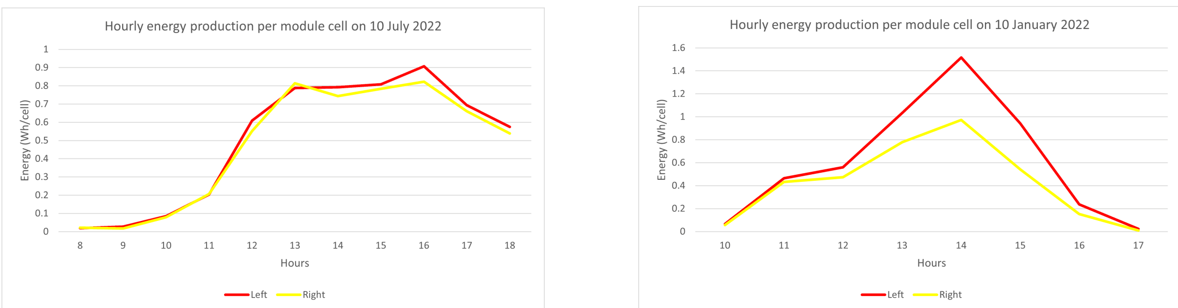


(a) (b)

Figure 30: *Hourly array yield (h/day) for two modules positioned on the left and on the right of a balcony, during summer (a) and winter (b).*

In Figure 30 the array yield calculated in each hour of the summer and winter day for the two columns of modules is showed. During the summer day, the column on the right of balconies always has lower values than the one on the left, especially since 11:00 where, as previously commented, sun is moving towards North-West and it brings shadow to the modules on the right. On average, modules on the column on the left of balconies have an array yield of 0.1 h/day and those on the right of 0.09 h/day.

During the winter day, in the morning, sun faces South-East and thus the column on the right of balconies has full sun, while since 12:00 it starts getting shaded and its array yield drops. On average, modules on the column on the left of balconies have an array yield of 0.12 h/day and those on the right of 0.08 h/day.



(a) (b)

Figure 31: *Hourly energy production per module cell, for two modules positioned on the left and on the right of a balcony, during summer (a) and winter (b).*

Figure 31 shows the energy that every hour is produced by each cell on the chosen modules. This allows to better analyse the shading effect, compared to the produced energy by the entire module. Indeed, the trend for both the summer and winter day is very similar to the array yield one and, during winter, the modules positioned on the right of balconies have more shading and thus each cell produces less energy.

Figure 32, 33 and 34 show the entire data set, from which it is easier to summarize the analysis also deepening into what happens during an entire year of data.

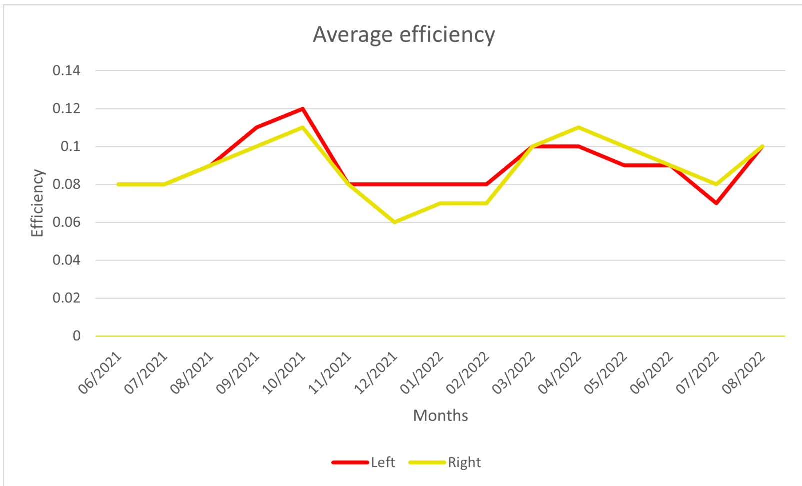
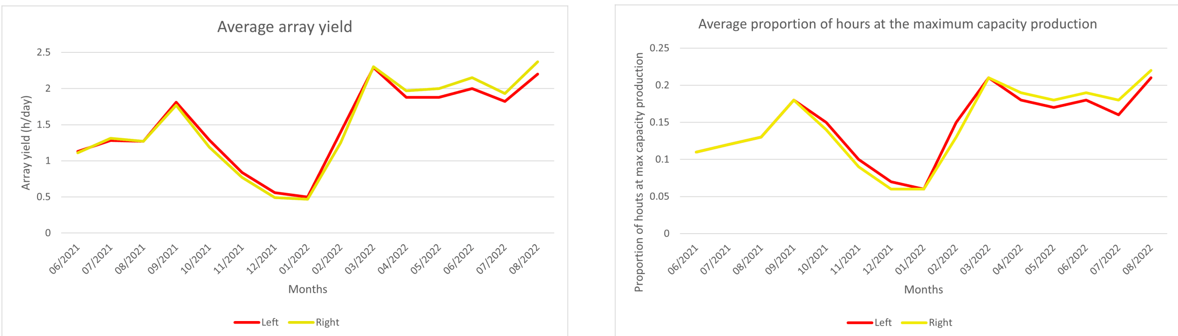


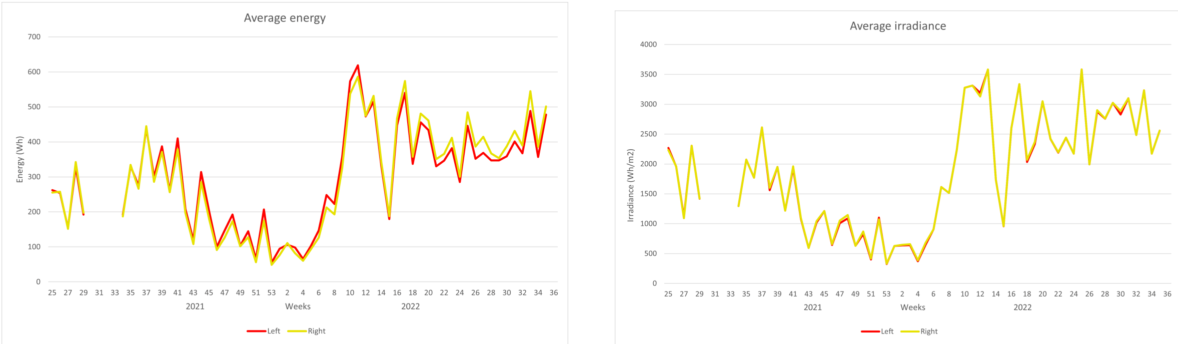
Figure 32: *Average efficiency comparison of modules positioned on the left and right of balconies.*

When considering one year of data, from September 2021 to August 2022 (week 36 of 2021 to week 36 of 2022), modules positioned on the right of balconies are marginally more performing than those on the left. Throughout the year, on average, modules positioned on the left of balconies have an efficiency of 9.1% while those on the right have 8.9%; respectively, they have an array yield of 1.48 h/day and 1.49 h/day, an average proportion of hours producing energy at the maximum capacity of 15.16% and 15.25%, they produce on average an energy of 300 Wh and 302 Wh, they receive an irradiance of 1875 Wh/m^2 and 1884 Wh/m^2.



(a) (b)

Figure 33: *Average array yield (h/day) (a) and proportion of hours in which energy is produced at installed capacity over the total hours of energy production (b) comparison of modules positioned on the left and right of balconies.*



(a) (b)

Figure 34: *Average energy production (Wh) (a) and irradiance (Wh/m^2) (b) comparison of modules positioned on the left and right of balconies.*

In Figure 35 is showed the change, in percentage, from 2021 to 2022 of modules on the left and on the right of balconies in four parameters. Energy production in modules on the left of balconies, on average, has increased less than for modules on the right. This was already visible in Figure 34, where the energy in 2022 was higher on modules on the right.

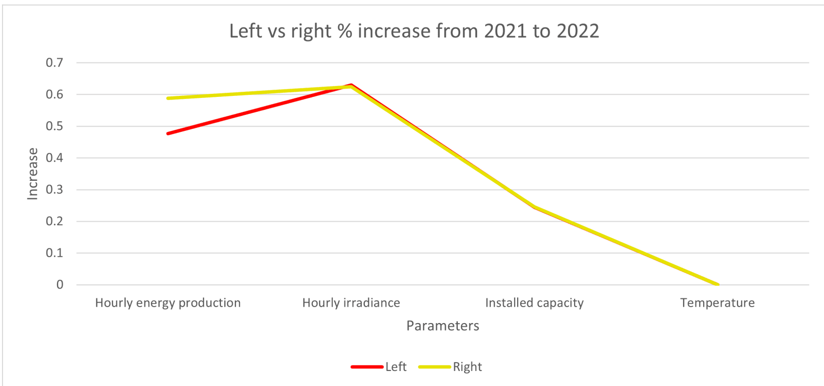


Figure 35: *Percentage of increase from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of modules on the left and on the right of balconies.*

To conclude, it is difficult to understand which category is more performing.
During summer 2021, they have the same efficiency, array yield is higher in modules on the left of balconies by 0.01 h/day, energy production is the same, irradiance is the same.
During summer 2022, efficiency is higher in modules on the right of balconies by +0.6%, array yield is higher in modules on the left of balconies by 0.15 h/day, energy production is higher in modules on the left of balconies by 29 Wh, irradiance is the same.
During winter, efficiency is higher in modules on the left of balconies by +1%, array yield is higher in modules on the left of balconies by 0.08 h/day, energy production is higher in modules on the left of balconies by 18 Wh, irradiance is the same.
Looking at the entire year, efficiency is higher in modules on the left of balconies by +0.3%, array yield is higher in modules on the right of balconies by 0.01 h/day, the proportion of hours producing energy at the maximum capacity is higher in modules on the right of balconies by

+0.09%, energy production is higher in modules on the right of balconies by 2 Wh, irradiance is the same.

Looking at summer and winter data, modules on the left of balconies are slightly more performing almost in every parameter, but looking at the entire year modules on the right are. This difference could derive from the few weeks (41-44 of 2021 and 11-22 of 2022) that have not been considered in the seasonal analysis, choice that has been made in order to only compare very cold and very hot weeks, thus spring and early autumn are not included. These differences could also come from some imprecision in collecting data and, considering how small they are, a minimum error could change the result.

Overall, the difference between these two categories is not enough to state that there is evidence of one category being more performing.

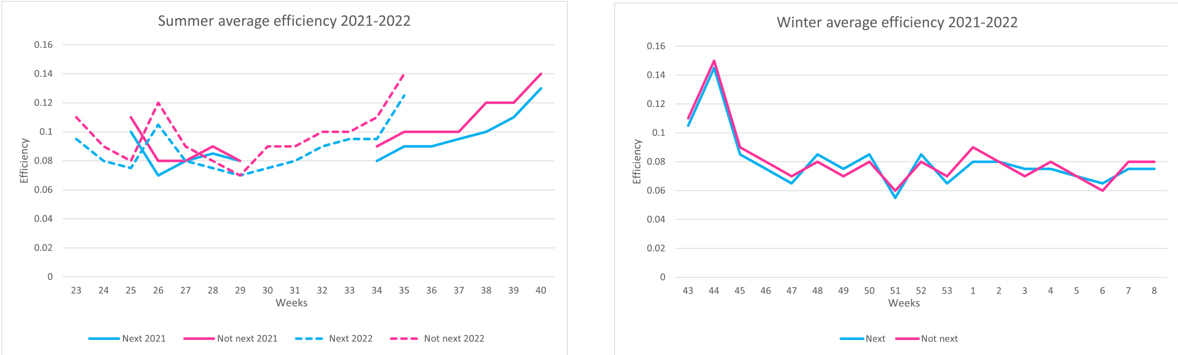
Performance of modules positioned next (on the left and on the right) versus not next to balconies.

Modules positioned next to a balcony have shading during the day, thus is important to understand how much this shading can impact the system performance. This is done by comparing these modules with others that are not positioned next to balconies.

This paragraph analyses the differences between grey modules situated on the façade that are next to balconies or not, which have been defined respectively as the set of categories A and B, and category C. Each category is a mix of different types of modules; more specifically, categories A and B are a mix of modules with an installed capacity of 160 Wp, 180 Wp and 220 Wp, while category C is only composed by the first two types. The number of modules in each category is also different, because category A and B each have 51 modules, while category C only has 33. Moreover, in category A and B, modules with installed capacity of 220 Wp are the most numerous. This means that category A and B have a total installed capacity that is higher than category C (more modules and a higher installed capacity), respectively 10300 Wp, 10400 Wp and 5600 Wp.

Figure 36 to 39 show a division in summer and winter weeks, where summer is comparing 2021 and 2022 on weeks 23 - 40 and winter is a combination of 2021 and 2022 and covers weeks 45 - 10. This division helps understanding what is different during each time of the year.

For the sake of clarity, it needs to be noticed that weeks 30-33 of 2021 and week 36 of 2022 do not have weekly values. This is due to a problem in the irradiance sensors, which resulted in showing wrong values for the sensors related to the modules of which these categories are composed by. Moreover, temperature sensors on the main façade are also problematic. In Appendix B has been reported an analysis on the reliability of each sensor.



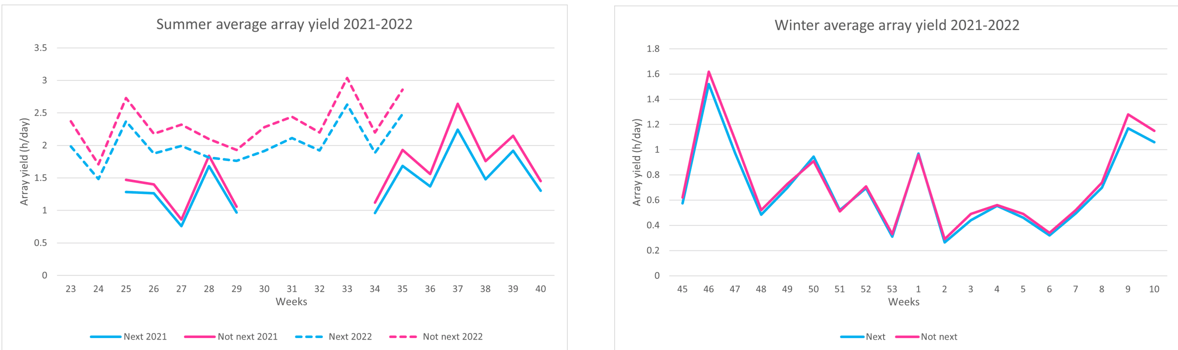
(a) (b)

Figure 36: *Average efficiency comparison of modules positioned on the façade next to balconies and not, divided into summer (a) and winter (b).*

Figure 36 compares the efficiency of the two set of categories during summer and winter.

During summer, efficiency in both years is higher for modules distant from balconies. On average, in 2021 modules next to balconies and not respectively have an efficiency of 9.18% and 9.81%, while in 2022 they have 8.77% and 9.78%.

During winter, the two set of categories have on average a very similar efficiency, respectively 7.63% for modules next to balconies and 7.78% for modules not next to balconies.



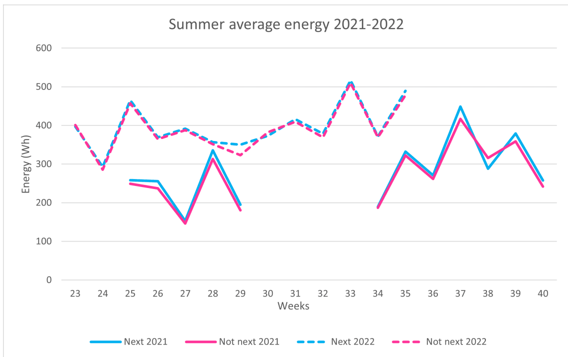
(a) (b)

Figure 37: *Average array yield (h/day) comparison of modules positioned on the façade next to balconies and not, divided into summer (a) and winter (b).*

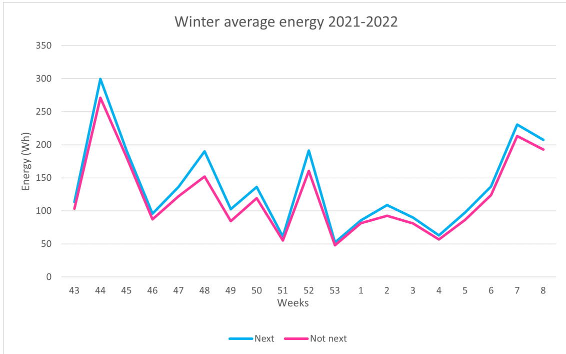
Figure 37 compares the array yield of the two set of categories during summer and winter.

During summer, in both years, modules not next to balconies have a higher value for array yield. On average, in summer 2021 modules next to balconies have an array yield of 1.41 h/day and those distant from balconies of 1.6 h/day, while in summer 2022 they respectively have 2.02 h/day and 2.3 h/day.

During winter, modules distant from balconies have a higher array yield, on average 0.82 h/day against the 0.95 h/day of modules next to.



(a)



(b)

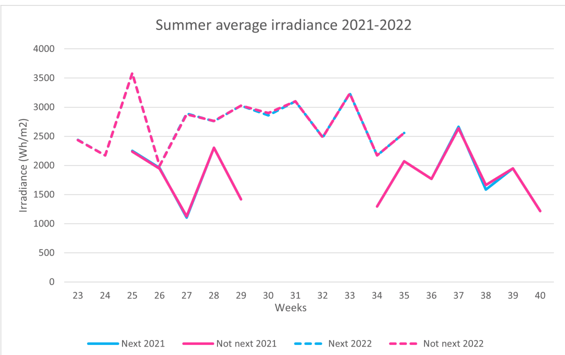
Figure 38: *Average energy production (Wh) comparison of modules positioned on the façade next to balconies and not, divided into summer (a) and winter (b).*

Figure 38 compares the energy production of the two set of categories during summer and winter.

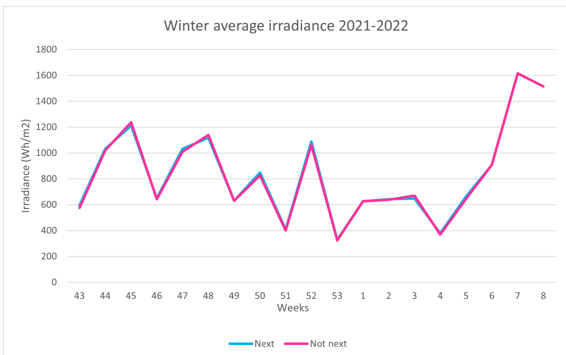
During summer, in general, modules next to balconies have on average a higher produced energy value (280 Wh against 269 Wh of modules not next to balconies, in 2021, and respectively 397 Wh and 391 Wh in 2022).

During winter, modules next to balconies on average produce more than modules not, respectively 161 Wh and 145 Wh.

The result that modules next to balconies produce on average more energy than modules not next to balconies may seem strange, but considering which modules compose each category, as explained at the beginning of this paragraph, if the hourly energy production of category C (modules not next to balconies) is lower than the production of modules that are next to balconies, this does not mean that they are less efficient. On the contrary, considering that category C has half of the installed capacity of the other two categories, and that it produces an amount of energy just smaller than them, it is in fact more performing.



(a)



(b)

Figure 39: *Average irradiance (Wh/m^2) comparison of modules positioned on the façade next to balconies and not, divided into summer (a) and winter (b).*

Figure 39 compares the irradiance of the two set of categories during summer and winter.

As in the situation of modules on the left and on the right of balconies, also in this case the two set of categories have the same irradiance since they have the same irradiance sensors. And temperature can also not be analysed because of the issues stated at the beginning of this section.

In Figure 40 is showed the change, in percentage, from summer 2021 to summer 2022 of modules next and not to balconies in four parameters. Energy production in modules next to balconies, on average, has increased less than for modules not next. In Figure 38 has been noticed that energy in 2021 was higher for modules next to balconies, therefore since the two set of categories have almost a similar energy production in 2022, overall the increase of modules on the next is lower. Installed capacity is the opposite, it has increased less in modules distant from balconies. This change in energy production and installed capacity has lead to an higher array yield in modules not next to balconies, as showed in Figure 37.

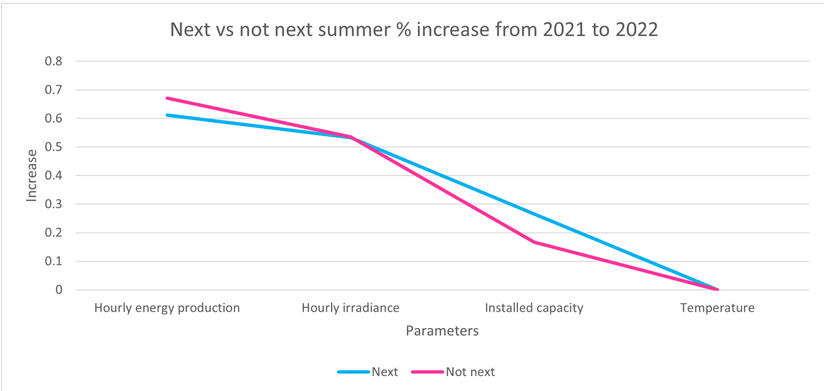
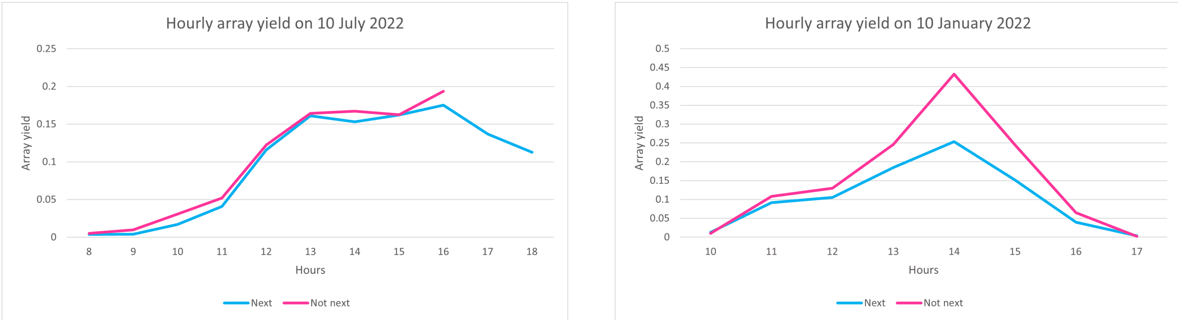


Figure 40: *Percentage of increase during summer from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of modules next and not to balconies.*

Looking at some hourly data, it becomes clearer how shading impacts energy production and how different it is from three categories, of which two are positioned next to a balcony and the third one distant from it, in each moment of the day, on the same days. In this situation, the chosen modules are the same used for the analysis of Figure 30 and 31, thus column 13 on the main façade for modules in category A, column 16 for category B and column 15 for category C. Modules all have an installed capacity of 160 W, 48 cells and 35.65 $cells/m^2$. Categories A and B in this analysis are combined by using the average of their values, as previously said, and again, columns are close to each other in order to have similar conditions. For summer, the chosen day has been 10 July 2022, while for winter 10 January 2022.

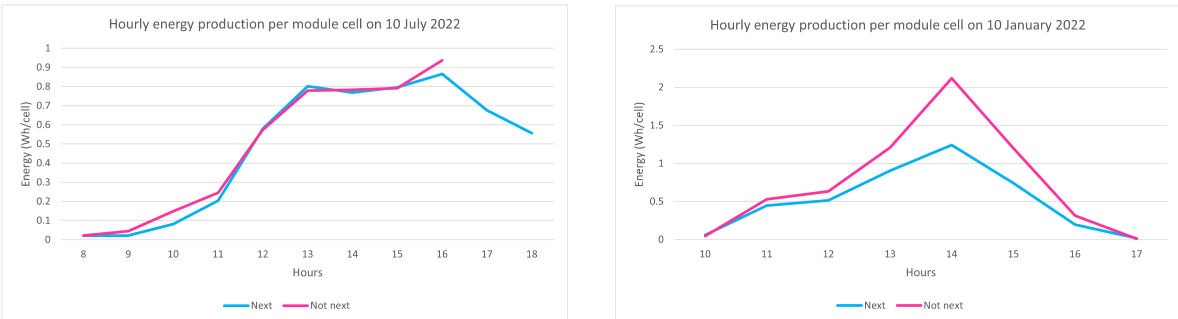


(a) (b)

Figure 41: *Hourly energy production per module cell, for three modules of which two are positioned next to a balcony and the third one distant from it, during summer (a) and winter (b).*

In Figure 30 the array yield calculated in each hour of the summer and winter day for the two modules is showed. In the summer day, the column distant from the balcony has a higher array yield, as previously analysed, and it has to be considered that since 15:00 the sun faces already the back side of the building, thus none of the modules on the façade has irradiance. Modules, however, continue their energy production and those next to the balcony have a higher array yield. On average, modules next to balconies have an array yield of 0.09 h/day and those not next to balconies of 0.1 h/day.

In the winter day, the column distant from the balcony has a higher array yield in general. In this period, the sun rises towards South-East and goes down towards South-West, thus the main façade always has sunlight. On average, the column next to balconies have an array yield of 0.1 h/day and the one distant from balconies of 0.15 h/day.



(a) (b)

Figure 42: *Hourly energy production per module cell, for three modules of which two are positioned next to a balcony and the third one distant from it, during summer (a) and winter (b).*

Figure 42 shows the energy that every hour is produced by each cell on the modules. This allows to better analyse the shading effect, compared to the produced energy by the entire module. The trend is the same of the array yield for both periods, thus the analysis described for Figure 41 is still valid. On average, the two categories produce the same energy per cell, 0.48 $Wh/cell$ during summer, while modules next to balconies 0.51 $Wh/cell$ and those not next to balconies of 0.75 $Wh/cell$ during winter.

Figure 43, 44 and 45 show the entire data set, from which it is easier to summarize the analysis also for deepening into what happened during an entire year.

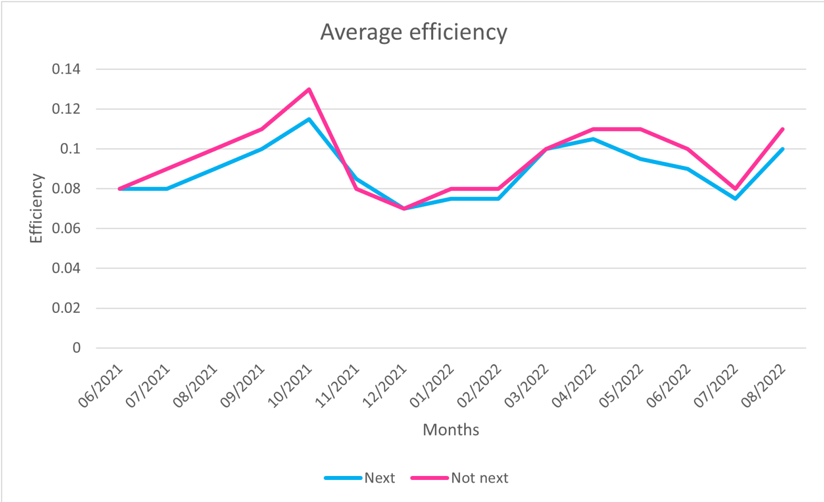
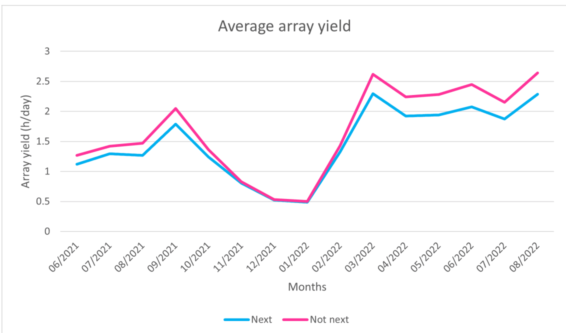
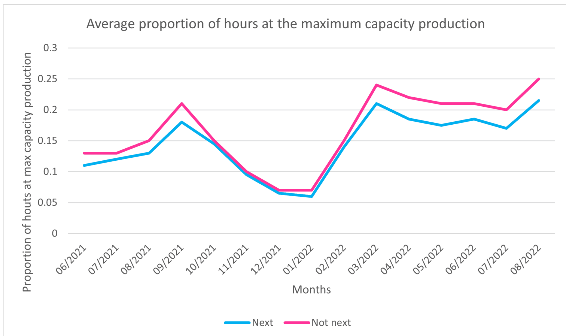


Figure 43: *Average efficiency comparison for modules next to balconies and not next to balconies.*

When considering one year of data, from September 2021 to August 2022 (week 36 of 2021 to week 36 or 2022), grey modules not positioned next to balconies are more performing than those on next to. Throughout the year, modules positioned next to balconies have an efficiency of 9.04%, while modules positioned distant from balconies have 9.5%; respectively, they have an array yield of 1.54 h/day and 1.75 h/day, an average proportion of hours producing energy at the maximum capacity of 15.2% and 17.3%, they produce on average an energy of 301 Wh and 289 Wh, they receive an irradiance of 1880 Wh/m^2 and 1884 Wh/m^2.



(a)



(b)

Figure 44: *Average array yield (h/day) (a) and proportion of hours in which energy is produced at installed capacity over the total hours of energy production (b) comparison for modules next to balconies and not next to balconies.*

(a) (b)

Figure 45: *Average energy production (Wh) (a) and irradiance (Wh/m^2) (b) comparison of modules positioned on the façade next to balconies and not.*

In Figure 46 is showed the change, in percentage, from 2021 to 2022 of modules next and not to balconies in four parameters. Energy production in modules next to balconies, on average, has increased somewhat less than for modules distant. The total capacity, however, has increased somewhat less in modules distant to balconies. A lower increase in energy production and a higher increase in installed capacity has lead to a lower increase in array yield for modules next to balconies.

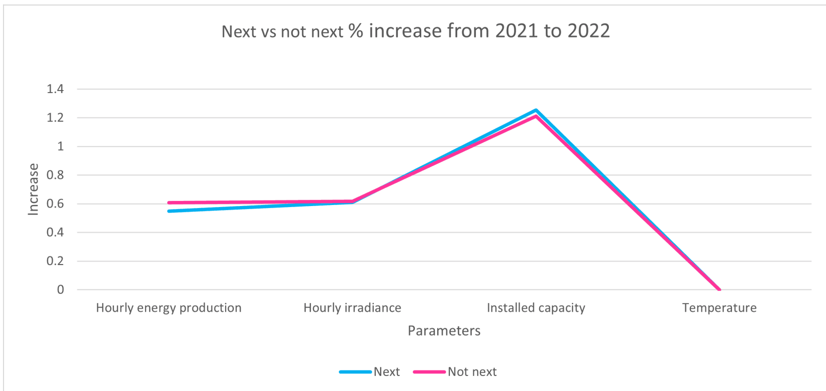


Figure 46: *Percentage of increase from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of modules on the left and on the right of balconies.*

To conclude, from the seasonal analysis resulted that modules not next to balconies perform better in both summer and winter, but when comparing the differences of each value it will result more clear.
During summer 2021, efficiency is higher in modules distant from balconies by +0.63%, array yield is higher in modules distant from balconies by 0.19 h/day, energy production is higher in modules next to balconies by 11 Wh, irradiance is the same.
During summer 2022, efficiency is higher in modules distant from balconies by +1.01%, array yield is higher in modules distant from balconies by 0.28 h/day, energy production is higher in modules next to balconies by 6 Wh, irradiance is the same.
During winter, efficiency is higher in modules distant from balconies by +0.15%, array yield

is higher in modules distant from balconies by 0.13 h/day, energy production is higher in modules next to balconies by 16 Wh, irradiance is the same.
Looking at the entire year, efficiency is higher in modules distant from balconies by +0.46%, array yield is higher in modules distant from balconies by 0.21 h/day, average proportion of hours producing energy at the maximum capacity is higher in modules distant from balconies by +2.1%, energy production is higher in modules next to balconies by 12 Wh, irradiance is higher in modules distant from balconies.

Overall, the difference, in each analysis, is sufficient to say that modules distant from balconies are more performing.

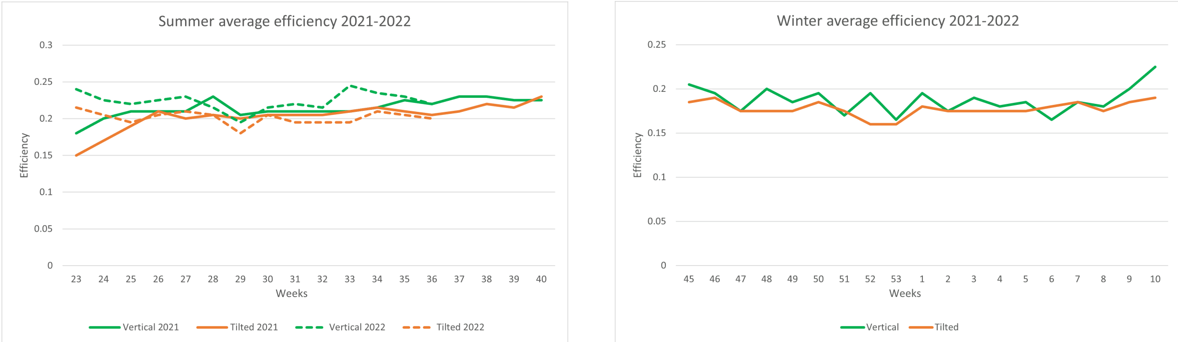
4.4. (BI)PV system performance difference from modules with different tilt

Commonly, when PV systems are installed on a building, it is a residential building with a tilted roof, where modules are installed. The optimal tilt to install a module is generally defined as the latitude where it is built increased by 15°. The optimal tilt also varies from summer to winter, because the angle of sun also varies during seasons [40]. When installing a BIPV, however, modules are also installed on other areas of the building, such as walls, where they are installed vertical. The difference in performance between installing tilted and vertical modules will be discussed in this section.

The analysis will be performed by confronting modules installed on the case study pergola, which are both vertical and tilted. The case study optimal tilt should be around 67°, since it is located in Utrecht, Netherlands, that has a latitude of 52°. However, in the case study the two tilted surfaces have an angle approximately of 20° (the area towards North-West) and 15° (the area towards South-East), because of the small available area where to build the pergola, and in this analysis the optimal tilt would not be considered.

Vertical modules on the pergola are categories E and J, while tilted modules on the pergola are categories F and G. These categories are composed by a mix of modules with installed capacity of 180 Wp, 300 Wp, 340 Wp and 355 Wp. Categories E and F are facing South-East, while categories G and J face North-West.

Figure 47 to 51 show a division in summer and winter weeks, where summer is comparing 2021 and 2022 on weeks 23 - 40 and winter is a combination of 2021 and 2022 and covers weeks 45 - 10. This division helps understanding what is different during each time of the year.



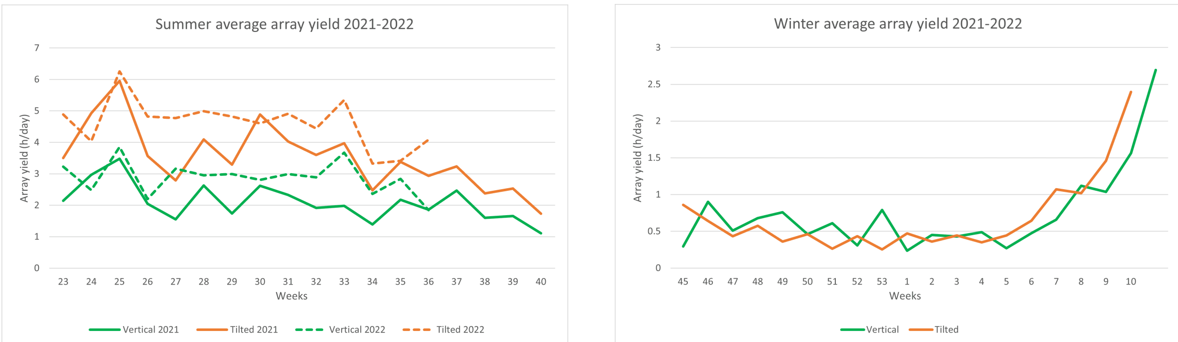
(a) (b)

Figure 47: *Average efficiency comparison of modules positioned on pergola vertical and tilted, divided into summer (a) and winter (b).*

Figure 47 compares the efficiency of the two set of categories during summer and winter.

During summer, vertical modules have a higher efficiency than tilted ones, respectively 21.4% and 20.3% in 2021, 22.2% and 20.1% in 2022. Vertical modules have increased their efficiency from 2021 to 2022, while tilted ones still have a similar value.

During winter, efficiency is higher for vertical modules compared to tilted ones. On average, they respectively have 18.7% and 17.7%.



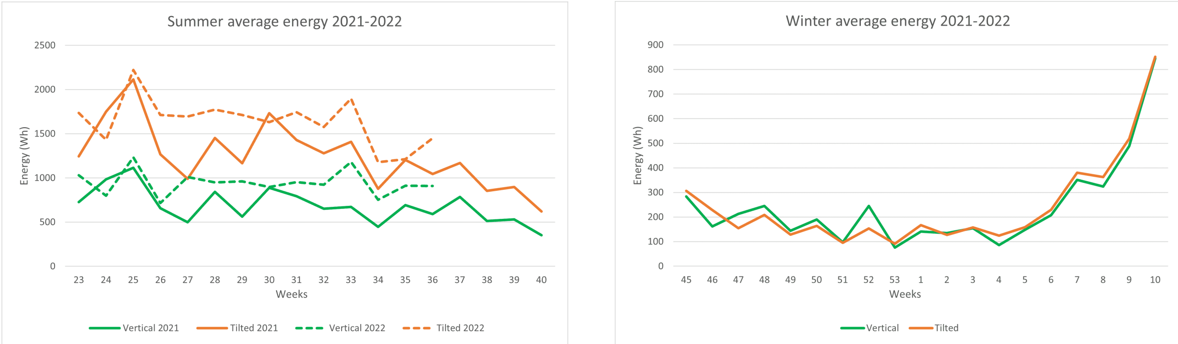
(a) (b)

Figure 48: *Average array yield (h/day) comparison of modules positioned on pergola vertical and tilted, divided into summer (a) and winter (b).*

Figure 48 compares the array yield of the two set of categories during summer and winter.

During summer, vertical modules have an average array yield of 2.1 h/day in 2021, while tilted ones have 3.5 h/day. In 2022, they respectively have 2.9 h/day and 4.6 h/day. Both set of categories have increased their array yield between summer 2021 and 2022, but tilted modules always have a higher value.

During winter, array yield is higher for vertical modules than tilted ones, respectively 0.76 h/day and 0.68 h/day, on average.



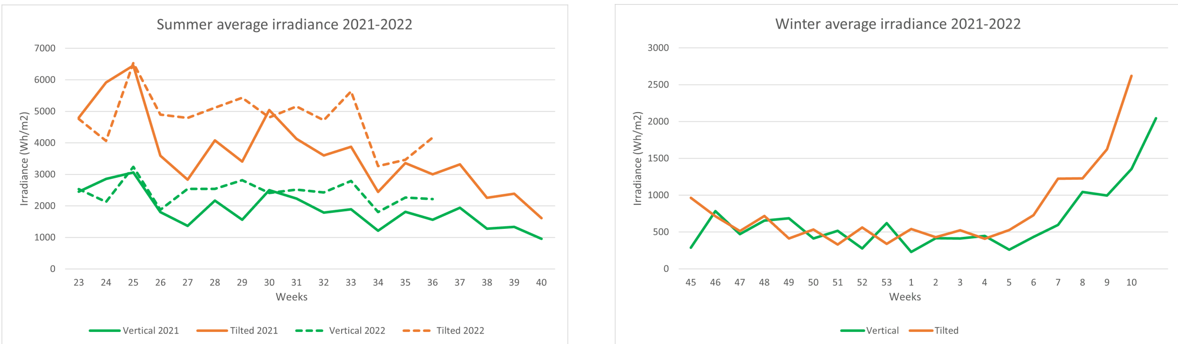
(a) (b)

Figure 49: *Average energy production (Wh) comparison of modules positioned on pergola vertical and tilted, divided into summer (a) and winter (b).*

Figure 49 compares the energy production of the two set of categories during summer and winter.

During summer, energy production is higher in tilted modules, in both years. The difference between vertical and tilted modules is substantial. They respectively produce on average 683 Wh and 1248 Wh in 2021, while 925 Wh and 1641 Wh in 2022.

During winter, vertical modules produce on average more energy than tilted ones, but their values are not very different. Respectively, 238 Wh and 242 Wh.



(a) (b)

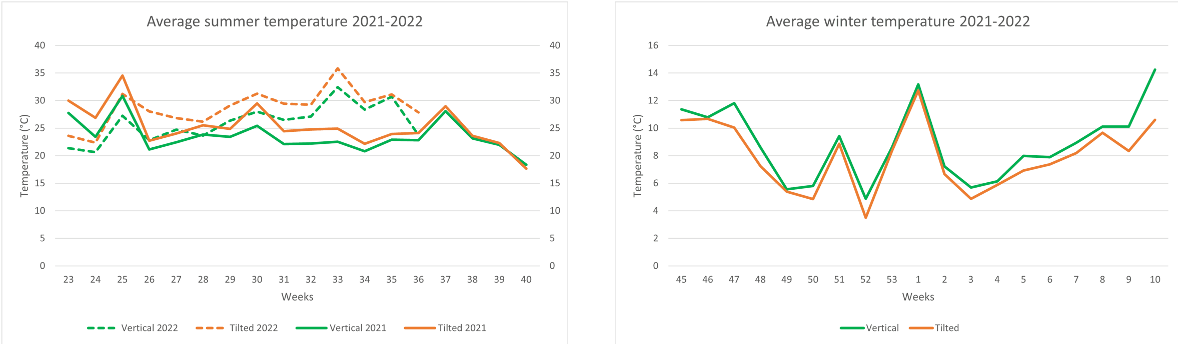
Figure 50: *Average irradiance (Wh/m^2) comparison of modules positioned on pergola vertical and tilted, divided into summer (a) and winter (b).*

Figure 50 compares the irradiance of the two set of categories during summer and winter.

During summer, like it is for energy production, also for irradiance tilted modules have substantially higher values, they receive on average 1878 Wh/m^2 and 3672 Wh/m^2 in 2021, 2409 Wh/m^2 and 4772 Wh/m^2 in 2022.

During winter, irradiance values are higher for tilted modules, but the two set of categories alternate in having higher irradiance every week. On average, they receive 666 Wh/m^2 and

786 Wh/m^2. This difference is mainly given by the fact that tilted modules receive higher irradiance from week 4 on.



(a) (b)

Figure 51: *Average temperature comparison of modules positioned on pergola vertical and tilted, divided into summer (a) and winter (b).*

Figure 51 compares the temperature of the two set of categories during summer and winter.

During summer, the average temperature on tilted modules is considerably higher than vertical ones. Respectively, in 2021 vertical modules have 23.6°C and tilted have 25.3°C, in 2022 25.9°C and 28.7°C.

During winter, vertical modules have higher temperature than tilted ones. On average, 8.9°C and 7.9°C.

In Figure 52 is showed the change, in percentage, from summer 2021 to summer 2022 of vertical and tilted modules on the pergola in four parameters. Energy production in tilted modules, on average, has increased less than for vertical modules. The total capacity has increased less in vertical modules. A lower increase in energy production and installed capacity has lead to a lower increase in array yield in tilted modules.

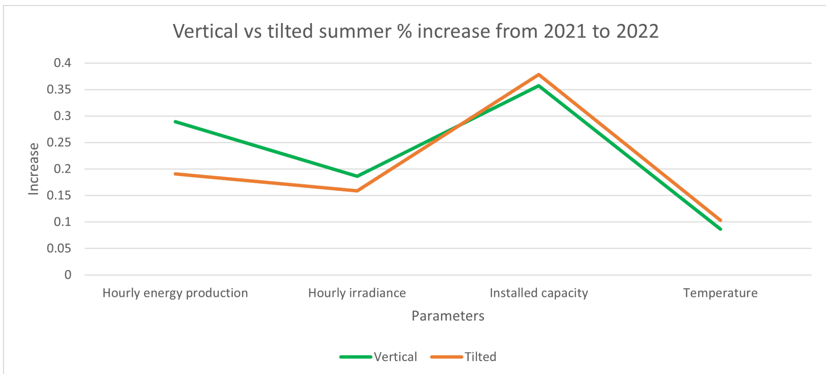


Figure 52: *Percentage of increase during summer from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of vertical and tilted modules on the pergola.*

Overall, even though looking at the efficiency vertical modules on the pergola seem to be more performing than tilted ones during summer, this is just an illusion. The reason is that efficiency is calculated as the ratio between average energy production and average received irradiance, thus a small difference in the proportion of these two elements can lead to different values in efficiency, as explained in Section 4.2. The real result of this analysis is given by all the other results, especially the array yield, which reflects the modules amount of time they are producing energy at the installed capacity. The higher array yield, the better the performance.
During winter the situation is the opposite and vertical modules perform better. This comparison between vertical and tilted modules clearly shows the difference given by the slope that sun rays have during each time of the year, previously seen in Figure 28 and discussed in Section 4.3: during summer they are very much inclined and indeed tilted modules are more performing, while during winter the are more horizontal and thus vertical modules gain advantage from this.

Figure 53, 54, 55 and 56 show the entire data set, from which it is easier to summarize the analysis also deepening into what happens during an entire year of data.

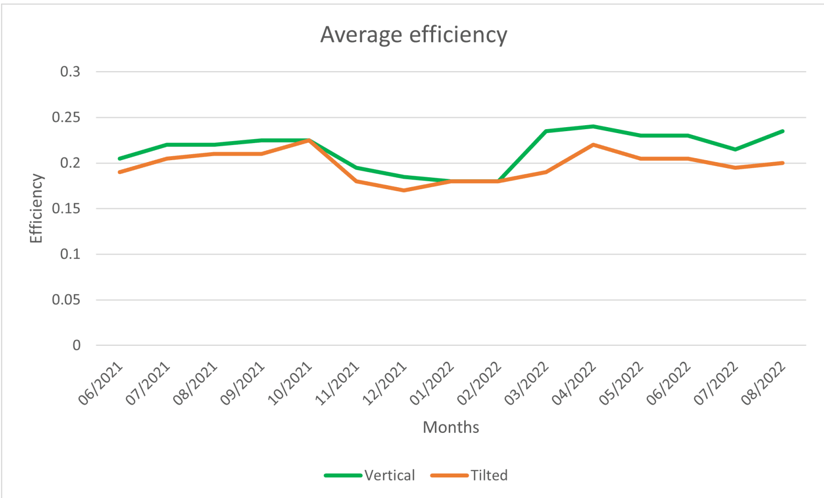
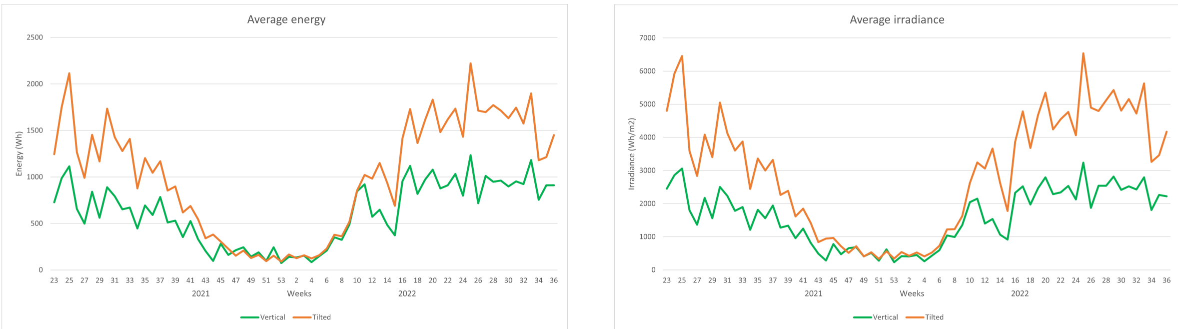


Figure 53: *Average efficiency comparison of vertical and tilted modules positioned on pergola.*

When considering one year of data, from September 2021 to August 2022 (week 36 of 2021 to week 36 or 2022), the scale of values moves towards modules positioned tilted on the pergola. Throughout the year, modules positioned vertical have an efficiency of 21.4%, while modules positioned tilted have 19.6%; respectively, they have an array yield of 1.8 h/day and 2.6 h/day, they have an average proportion of hours producing energy at the maximum capacity of 17.9% and 24.3%, they produce on average an energy of 576 Wh and 924 Wh, they receive an irradiance of 1483 Wh/m^2 and 2683 Wh/m^2, they have an average temperature of 17.1°C and 17.8°C.

(a) (b)

Figure 54: *Average array yield (h/day) (a) and proportion of hours in which energy is produced at installed capacity over the total hours of energy production (b) comparison for vertical and tilted modules on the pergola.*



(a) (b)

Figure 55: *Average energy production (Wh) (a) and irradiance (Wh/m^2) (b) comparison of modules positioned on pergola vertical and tilted.*

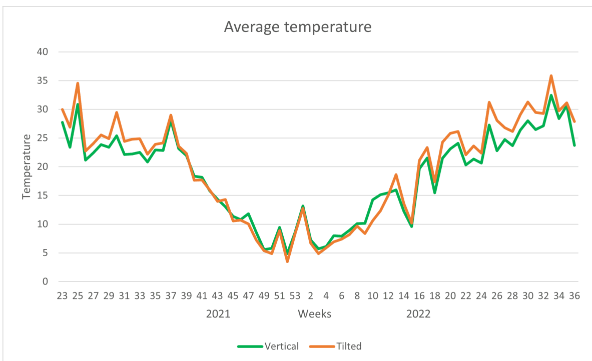


Figure 56: *Average temperature of modules positioned on the pergola vertical and tilted.*

In Figure 57 is showed the change, in percentage, from 2021 to 2022 of vertical and tilted modules on the pergola in four parameters. Energy production in tilted modules, on average, has increased less than for vertical modules. The installed capacity has increased less in vertical modules.

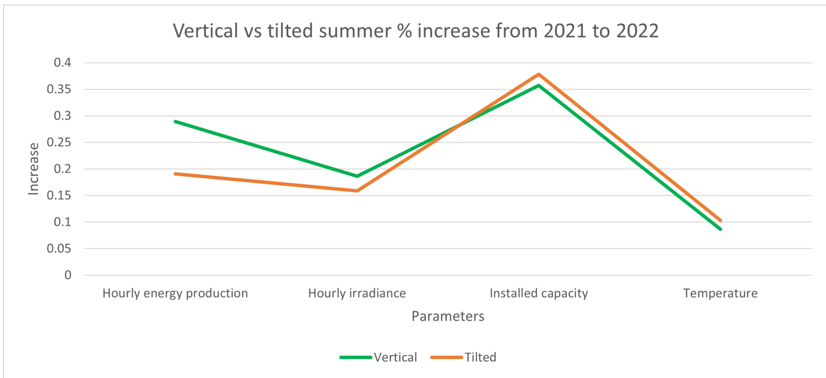


Figure 57: *Percentage of increase from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of vertical and tilted modules on the pergola.*

To conclude, tilted modules are most performing during summer, while vertical modules are slightly more performing during winter. This is due to the sun inclination, that during summer favors tilted modules and during winter favors vertical ones. When comparing the differences of each value it will be easier to see the most performing tilt.
During summer 2021, efficiency is higher in vertical modules by +1.1%, array yield is higher in tilted modules by 1.4 h/day, energy production is higher in tilted modules by 565 Wh, irradiance is higher in tilted modules by 1794 Wh/m^2, temperature is higher in tilted modules by 1.7°C.
During summer 2022, efficiency is higher in vertical modules by +2.1%, array yield is higher in tilted modules by 1.7 h/day, energy production is higher in tilted modules by 716 Wh, irradiance is higher in tilted modules by 2363 Wh/m^2, temperature is higher in tilted modules by 2.8 °C.
During winter, efficiency is higher in vertical modules by +1%, array yield is higher in vertical modules by 0.08 h/day, energy production is higher in tilted modules by 4 Wh, irradiance is higher in tilted modules by 120 Wh/m^2, temperature is higher in vertical modules by 1°C.
Looking at the entire year, efficiency is higher in vertical modules by +1.8%, array yield is higher in tilted modules by 0.8 h/day, the average proportion of hours producing energy at the maximum capacity is higher in tilted modules by +6.4%, energy production is higher in tilted modules by 348 Wh, irradiance is higher in tilted modules by 1200 Wh/m^2, temperature is higher in tilted modules by 0.7°C.

Overall, the difference of the parameters is sufficient to say that tilted modules are more performing than vertical ones.

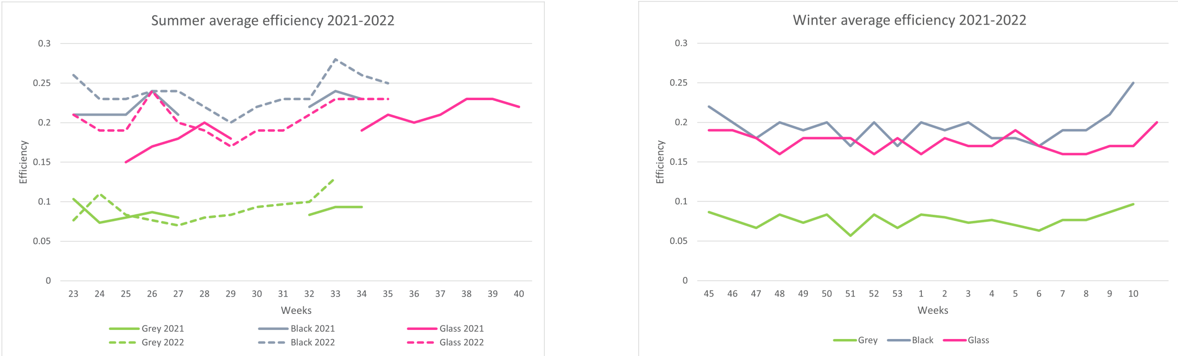
4.5. Impact of the type of PV on their performance

Many different types of PV modules exist on the market. They can differ in material composition, already discussed in Section 2 (mono- and poly- crystalline, thin film), in installed capacity (related to the number of cells and the modules area), in costs, in layer colour. Each

type of PV module has a certain performance that, as previously mentioned, also depends on the outdoor conditions.
Recently, thanks to an increasing interest and study on BIPV, when integrating a PV system in a building a compromise between technical and aesthetic requirements has to be found [41]. Therefore, more and more modules installed on walls are equipped with an aesthetic layer, which makes them more pleasant to see and thus people could be more willing to install them on their houses.
The difference in performance of different types of modules, especially considering the coloured layer, will be discussed in this section.

This section analyses the differences between modules situated on the main façade, that are of different types. These are here described as grey modules, black modules and glass modules. More specifically, they do not only differ in colour but also in composition, size, installed capacity and position. Grey modules are composed by glass-glass, have an average size of 1.77 m^2, an average installed capacity of 195 Wh (that derives from being composed mostly by modules with 220 Wp capacity) and are positioned on each part of the main façade except for balconies. Black modules are composed by glass-plastic, have an average size of 1.7 m^2, an average installed capacity of 318 Wh (that derives from being composed mostly by modules with 340 Wp capacity) and are positioned on the pergola and on the lateral façades; during this comparison, only those positioned on the vertical front side of the pergola are considered, so that they have the same irradiance, temperature and tilt conditions of the other two types. Glass modules are composed by glass-glass, have a size of 1.7 m^2, an installed capacity of 300 Wp and are positioned on the balconies, on the main façade. Grey modules are composed by modules referred to as categories A, B and C, black modules are category E and glass modules are category D.

Figure 58 to 61 show a division in summer and winter weeks, where summer is comparing 2021 and 2022 on weeks 23 - 40 and winter is a combination of 2021 and 2022 and covers weeks 45 - 10. This division helps understanding what is different during each time of the year.
For the sake of clarity, it needs to be noticed that weeks 30-33 of 2021 and week 36 of 2022 do not have weekly values. This is due to a problem in the irradiance sensors, which resulted in showing wrong values for the sensors related to the modules of which these categories are composed by. Moreover, temperature sensors on the main façade are also problematic. In Appendix B has been reported an analysis on the reliability of each sensor.



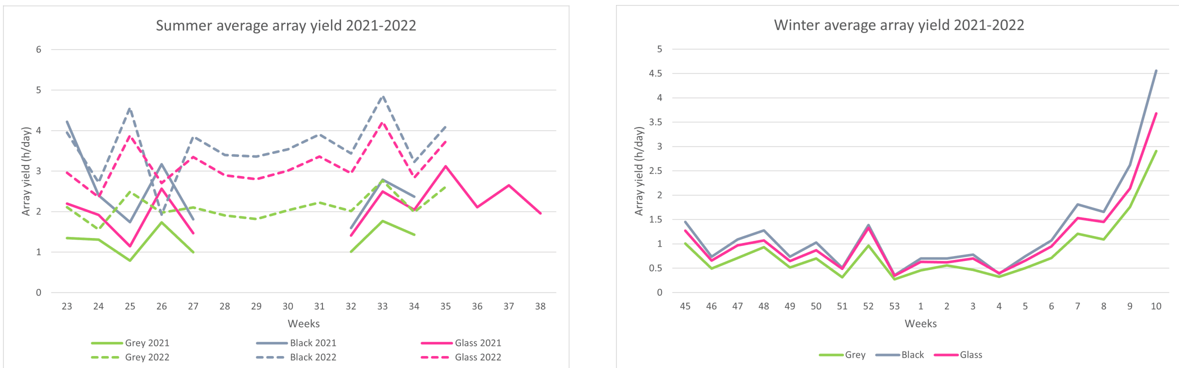
(a) (b)

Figure 58: *Average efficiency comparison of grey, black and glass modules, divided into summer (a) and winter (b).*

Figure 58 compares the efficiency of the three set of categories during summer and winter.

During summer, black modules on the façade have the highest efficiency, followed by glass modules and lastly, with a significant lower value, grey modules. In 2021, grey modules have an average efficiency of 9.6%, black modules of 22.3% and glass modules of 19.7%, while in 2022 they respectively have 9.11%, 23.8% and 20.5%.

During winter, efficiency is higher for black modules, but glass modules are just behind and in some weeks they have the same values. Grey modules have rather a very lower efficiency. Indeed, grey modules have 7.7%, black modules have 19.4% and glass modules 17.4%.



(a) (b)

Figure 59: *Average array yield (h/day) comparison of grey, black and glass modules, divided into summer (a) and winter (b).*

Figure 59 compares the array yield (h/day) of the three set of categories during summer and winter.

During summer, the array yield reflects the order given by efficiency, since black modules have the higher value. In 2021 grey modules have an average array yield of 1.5 h/day, black modules of 2.5 h/day and glass modules of 2.1 h/day, while in 2022 they respectively receive

2.1 h/day, 3.6 h/day and 3.1 h/day.

During winter, array yield is not that different for the three types of modules, even though black modules still have the higher one and grey modules the lower. Grey modules have on average 0.84 h/day, black modules 1.2 h/day and glass modules 1.1 h/day.

(a) (b)

Figure 60: *Average energy production (Wh) comparison of grey, black and glass modules, divided into summer (a) and winter (b).*

Figure 60 compares the energy production of the three set of categories during summer and winter.

During summer, black modules produce the highest amount of energy, on average. Grey modules produce in 2021, on average, 276 Wh, black modules 785 Wh and glass modules 628 Wh, while in 2022 they produce respectively 395Wh, 1113Wh and 948Wh.

During winter, black and glass modules produce similar amounts of energy on average, even though black modules still produce somewhat more. Grey modules produce on average 156Wh, black modules 383Wh and glass ones 322Wh.

(a) (b)

Figure 61: *Average irradiance (Wh/m^2) comparison of grey, black and glass modules, divided into summer (a) and winter (b).*

Figure 61 compares the irradiance of the three set of categories during summer and winter.

During summer, the received irradiance in 2021 is 1797 Wh/m^2 for grey modules, 2060 Wh/m^2 for black modules and 1872 Wh/m^2 for glass modules. In 2022 they respectively receive 2714 Wh/m^2, 2747 Wh/m^2 and 2738 Wh/m^2.

During winter, all modules have the same irradiance values, with a very small difference that could also come from imprecise irradiance values. This could be given by the fact that during winter the sun rays are more horizontal and all vertical modules are hit the same way. Grey modules on average receive 1041 Wh/m^2, black modules receive 1035 Wh/m^2 and glass modules 1046 Wh/m^2.

Because of issues in the temperature sensors on the main façade, the temperatures can not be compared, as previously mentioned.

In Figure 62 is showed the change, in percentage, from summer 2021 to summer 2022 of grey, black and glass modules in four parameters. Energy production in glass modules has increased the most, and their installed capacity has decreased the most. This is the reason why, in Figure 59, the difference in glass modules array yield from 2021 to 2022 is not that high compared to the other two types.

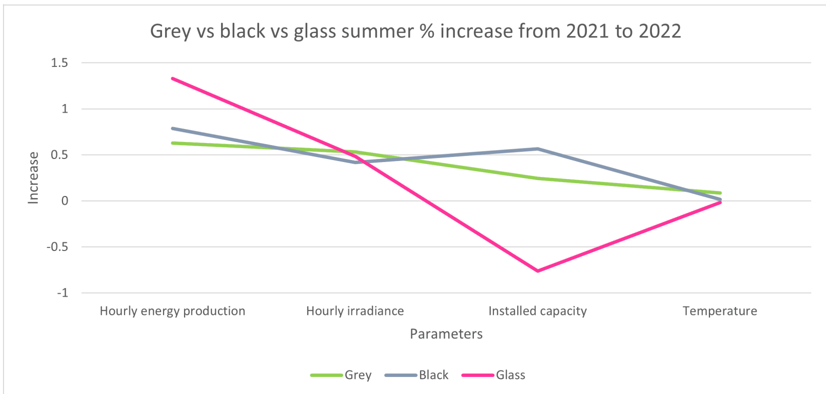


Figure 62: *Percentage of increase during summer from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of grey, black and glass modules pergola.*

Overall, looking at the entire data set, among grey, black and glass modules, the most performing seem to be the black ones, both during summer and winter. During summer, the difference between module type is greater than winter, and this is also due to the shadow that most grey modules have considering that the majority of them are positioned next to balconies (refer to the analysis in Section 4.3).

Figure 63, 64 and 65 show the entire data set, from which it is easier to summarize the analysis also deepening into what happens during an entire year of data.

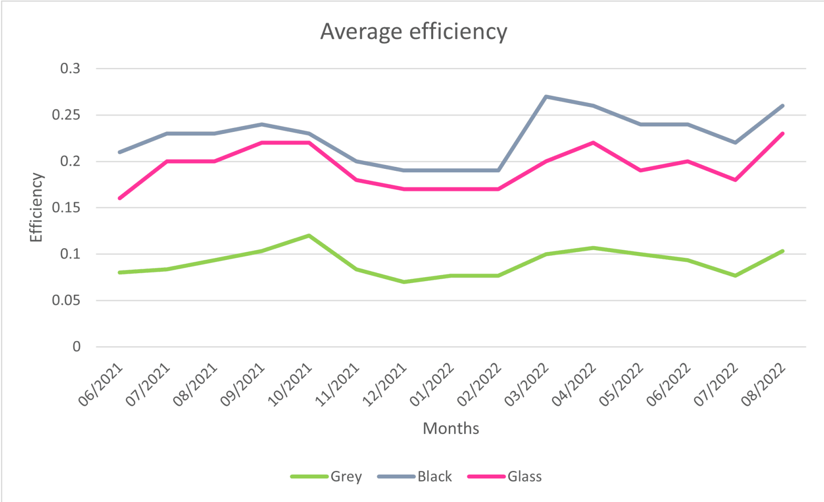


Figure 63: *Average efficiency comparison of grey, black and glass modules.*

When considering one year of data, from September 2021 to August 2022 (week 36 of 2021 to week 36 or 2022), black modules are more performing than grey and glass ones. Throughout the year, grey modules have an efficiency of 9.2%, black modules of 22.7% and glass modules have 19.6%; respectively, they have an array yield of 1.6 h/day, 2.6 h/day and 2.2 h/day, an average proportion of hours producing energy at the maximum capacity of 15.9%, 24.5% and 21.2%, they produce on average an energy of 297Wh, 749Wh and 653Wh, they receive an irradiance of 1881 Wh/m^2, 1830 Wh/m^2 and 1912 Wh/m^2.

(a) (b)

Figure 64: *Average array yield (h/day) (a) and proportion of hours in which energy is produced at installed capacity over the total hours of energy production (b) comparison of grey, black and glass modules.*

(a) (b)

Figure 65: *Average energy production (Wh) (a) and irradiance (Wh/m^2) (b) comparison of grey, black and glass modules.*

In Figure 66 is showed the change, in percentage, from 2021 to 2022 of grey, black and glass modules in four parameters. Glass modules have the highest increase in energy production, irradiance and installed capacity.

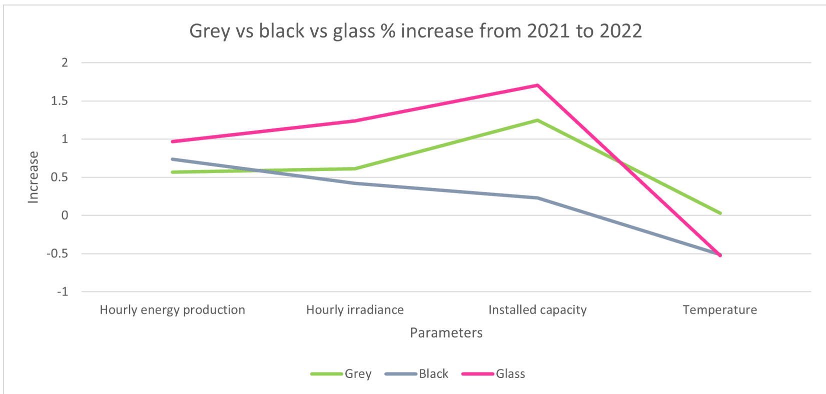


Figure 66: *Percentage of increase from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of grey, black and glass modules pergola.*

To conclude, it seems that black modules are more performing than the other two types, but a data comparison on each period will give a better prospect.
During summer 2021, efficiency is higher in black modules by +12.7% from grey modules and +2.6% from glass modules, array yield is higher in black modules by 1 h/day from grey modules and 0.4 h/day from glass modules, energy production is higher in black modules by 509Wh from grey modules and 157Wh from glass modules, irradiance is higher in black modules by 263 Wh/m^2 from grey modules and 188 Wh/m^2 from glass modules.
During summer 2022, efficiency is higher in black modules by +14.7% from grey modules and +3.3% from glass modules, array yield is higher in black modules by 1.5 h/day from grey modules and 0.5 h/day from glass modules, energy production is higher in black modules by 718Wh from grey modules and 165Wh from glass modules, irradiance is higher in black modules by 33 Wh/m^2 from grey modules and 9 Wh/m^2 from glass modules.
During winter, efficiency is higher in black modules by +11.7% from grey modules and +2%

from glass modules, array yield is higher in black modules by 0.36 h/day from grey modules and 0.1 h/day from glass modules, energy production is higher in black modules by $227Wh$ from grey modules and $61Wh$ from glass modules, irradiance is higher in glass modules by 5 Wh/m^2 from grey modules and 11 Wh/m^2 from black modules.
Looking at the entire year, efficiency is higher in black modules by +13.5% from grey modules and +3.1% from glass modules, array yield is higher in black modules by 1 h/day from grey modules and 0.4 h/day from glass modules, average proportion of hours producing energy at the maximum capacity is higher in black modules by +8.6% from grey modules and +3.3% from glass modules, energy production is higher in black modules by $452Wh$ from grey modules and $96Wh$ from glass modules, irradiance is higher in glass modules by 31 Wh/m^2 from grey modules and 82 Wh/m^2 from black modules.

Overall, even though irradiance is higher in glass modules it is a very small difference compared to the other parameters, whose difference is sufficient to state that black modules are the most performing over the three types, followed by glass modules.

4.6. Impact on the performance of modules installed on different parts of a building

In the northern hemisphere, the best direction that PV modules should face in order to better exploit their production is South. This direction allows to produce energy during most of the day, because of the sun movement, which moves from East to West during the day, as explained in Section 4.3. However, the possibility to install modules facing East and West is also interesting. Furthermore, as previously mentioned, modules can be installed both on the roof and the walls, and this can also lead to a difference in performance.
The difference in performance of each side and location of the building will be discussed in this section.

This paragraph analyses the differences between modules situated on the main façade (facing South-East), on the pergola (facing both South-East and North-West), on the left side façade from the front (facing South-West) and on the right side façade from the front (facing North-East). They have been defined respectively as the set of categories A, B, C, D, categories E, F, G, J, category H and category I.
This analysis comprehends all the modules on the building, thus each category, or set of categories, is composed by different types of modules, each of them already explained in the previous analyses on Section 4.3, 4.4 and 4.5. Shortly, the main façade is composed by grey and glass modules with mainly 220 Wp and 300 Wp installed capacity (on average, 238 Wp), the pergola is composed by vertical and tilted modules with mainly 340 Wp and 355 Wp installed capacity (on average, 343 Wp), the left side façade is composed by modules with 340 Wp installed capacity and the right side façade is also composed by modules with 340 Wp installed capacity.

Figure 67 to 70 show a division in summer and winter weeks, where summer is comparing 2021 and 2022 on weeks 23 - 40 and winter is a combination of 2021 and 2022 and covers weeks 45 - 10. This division helps understanding what is different during each time of the year.
For the sake of clarity, it needs to be noticed that weeks 30-33 of 2021 and week 36 of 2022 do not have weekly values. This is due to a problem in the irradiance sensors, which resulted in showing wrong values for the sensors related to the modules on the main façade. The same problem has happened on the left side façade, but also in weeks 26, 29-36, 40 and 45 of 2021 and weeks 1, 3 and 7 of 2022. Moreover, temperature sensors on the main façade are also problematic. In Appendix B has been reported an analysis on the reliability of each sensor.

(a) (b)

Figure 67: *Average efficiency comparison of modules positioned on the façade and pergola, divided into summer (a) and winter (b).*

Figure 67 compares the efficiency of the four set of categories during summer and winter.

During summer, the main façade has an efficiency significantly lower than modules on the pergola and on lateral façades. Respectively 12.1% for the main façade, 20.8% for the pergola, 25% for the left façade and 21.5% for the right façade in 2021, 11.9%, 21.2%, 25.5% and 22% in 2022. Modules on the left façade have the highest efficiency followed by those on the right façade, pergola and lastly the main façade.

During winter, modules on the left façade have a higher efficiency than the other set of categories, followed by modules on the right façade. On average, modules on the main façade have 10.1%, modules on the pergola 18.3%, modules on the left façade 23.9% and on the right façade 21.5%.

(a) (b)

Figure 68: *Average array yield (h/day) comparison of modules positioned on the façade and pergola, divided into summer (a) and winter (b).*

Figure 68 compares the array yield of the four set of categories during summer and winter.

During summer, array yield is higher for modules on the left façade. On average, in 2021 modules on the main façade have an array yield of 1.6 h/day, modules on the pergola of 2.9 h/day, modules on the left façade of 3.8 h/day and on the right façade 1.2 h/day, while in 2022 2.4 h/day, 3.8 h/day, 4.5 h/day and 1.5 h/day.

During winter, array yield is higher in the left façade modules, followed by modules in the main façade. Respectively, the main façade has 0.9 h/day, the pergola has 0.7 h/day, the left façade 1.1 h/day and right façade 0.3 h/day.

(a) (b)

Figure 69: *Average energy production (Wh) comparison of modules positioned on the façade and pergola, divided into summer (a) and winter (b).*

Figure 69 compares the energy production of the four set of categories during summer and winter.

During summer, on average, modules on the main façade produced in 2021 $365Wh$, modules on the pergola produce $992Wh$, modules on the left façade produced $1287Wh$ and modules on the right façade $408Wh$, while in 2022 they respectively produced $534Wh$, $1293Wh$, $1526Wh$ and $507Wh$. All set of categories have increased their energy production from 2021 to 2022, but is clear how modules on the left side façade always produce three times more than the main façade energy.

During winter, modules on the left façade have higher energy production. Modules on the main façade produce on average 197Wh, those on the pergola produce 240Wh, on the left façade 367Wh and on the right façade 92Wh.

(a) (b)

Figure 70: *Average irradiance (Wh/m^2) comparison of modules positioned on the façade and pergola, divided into summer (a) and winter (b).*

Figure 70 compares the irradiance of the four set of categories during summer and winter.

During summer, the set of categories on the main façade and the pergola receive an amount that is not that different between each other. Respectively, modules on the main façade receive 1816 Wh/m^2, those on the pergola receive 2852 Wh/m^2, modules on the left façade receive 2953 Wh/m^2 and those on the right façade receive 1085 Wh/m^2 in 2021, and in 2022 they received 2720 Wh/m^2, 3619 Wh/m^2, 3447 Wh/m^2 and 1331 Wh/m^2. Modules on the pergola receive more irradiance on average, which depends on the sun rays slope, that in summer is very much inclined and especially tilted modules on the pergola benefit from it, as explained in Figure 28.

During winter, modules on the main façade receive a higher amount of irradiance compared to the others. On average, respectively 1043 Wh/m^2 for the main façade, 726 Wh/m^2 for the pergola, 947 Wh/m^2 for left façade and 253 Wh/m^2 for the right façade. This is also because of the sun inclination during winter, where sun rays are almost horizontal (Figure 28) and thus they benefit vertical modules; since modules on the main façade are all vertical they have an advantage, while modules on the pergola are both vertical and tilted, in general they are not exploiting the bets out of winter irradiance. Modules on the left façade also receive quite a high amount of irradiance, while the right façade not, because during winter they barely receive some sunlight.

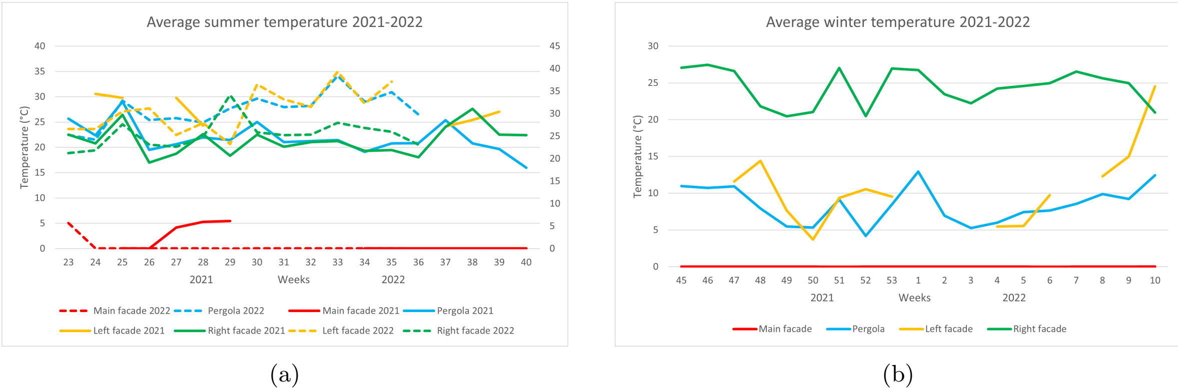


Figure 71: *Average temperature (°C) comparison of modules positioned on the façade and pergola, divided into summer (a) and winter (b).*

Figure 71 compares the temperature of the four set of categories during summer and winter.

Since temperature sensors on the main façade have some problems, they don't have values thus it is not possible to compare all the temperatures. However, it is possible to compare the other three set of categories.

During summer, for all of them, temperature in 2022 is higher than 2021, respectively of 24.5°C for pergola, 30.7°C for left façade and 24°C for right façade in 2021 and 27.4°C, 30.8°C and 25.4°C in 2022.

During winter, the left façade clearly has the highest temperature. The average temperature is 8.4°C for pergola, 10.2°C for left façade and 2.4°C for right façade.

In Figure 72 is showed the change, in percentage, from summer 2021 to summer 2022 of modules on façade, pergola, left side façade and right side façade in four parameters. Modules on the main façade have the highest increase in energy production, while modules on the left façade the highest increase in used installed capacity.

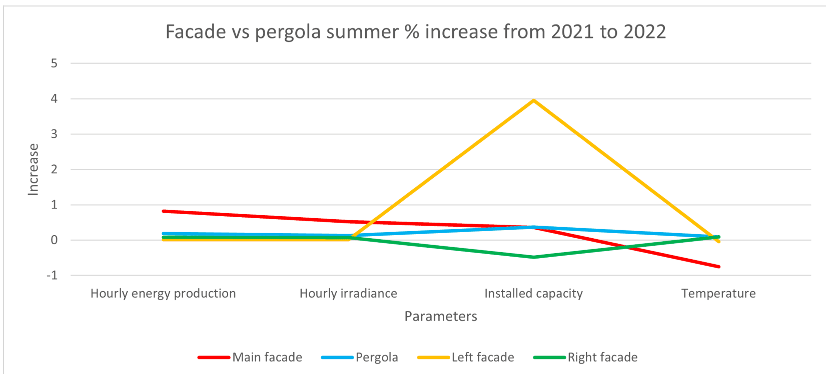


Figure 72: *Percentage of increase during summer from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of modules on the façade, the pergola, left side façade and right side façade.*

Figure 73, 74, 75 and 76 show the entire data set, from which it is easier to summarize the analysis also deepening into what happens during an entire year of data.

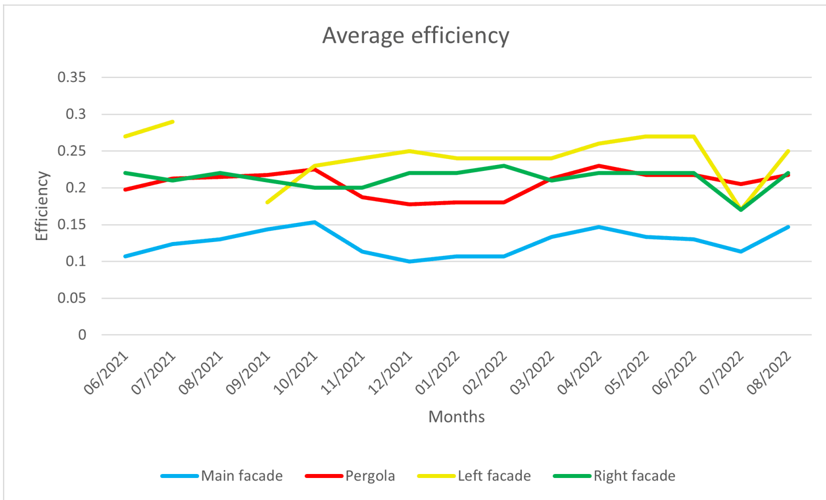
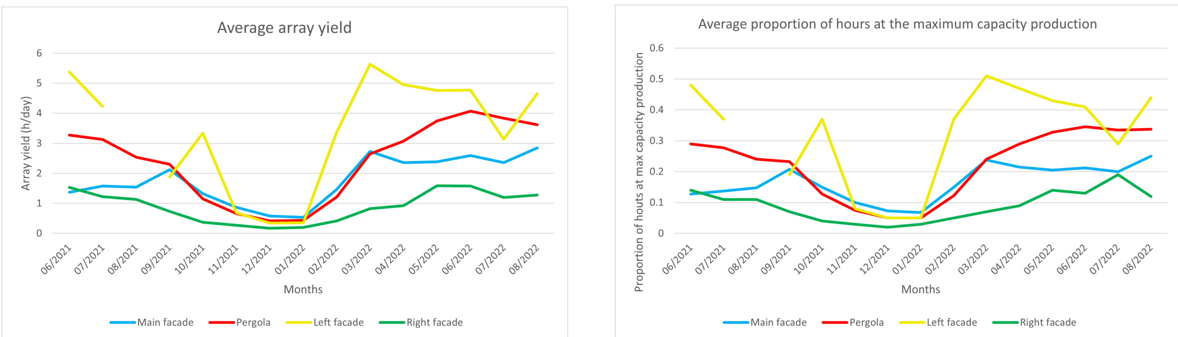


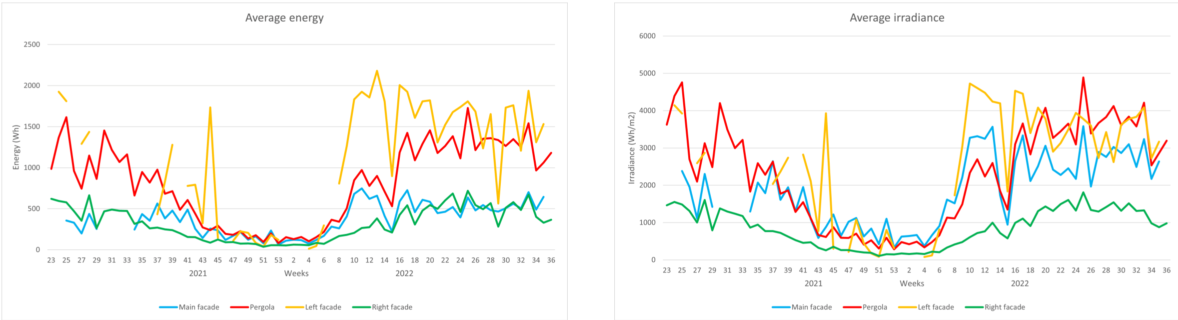
Figure 73: *Average efficiency comparison of modules positioned on the façade and pergola.*

When considering one year of data, from September 2021 to August 2022 (week 36 of 2021 to week 36 or 2022), the scale of values moves towards modules on the left façade. Throughout the whole year, modules on the main façade have an efficiency of 12.7%, modules on the pergola of 20.5%, modules on the left façade of 23.6% and on the right façade 21.3%; respectively, they have an array yield of 1.8 h/day, 2.3 h/day, 3.1 h/day and 0.8 h/day, an average proportion of hours producing energy at the maximum capacity of 17.2%, 21.1%, 30.5% and 8.1%, their average produced energy is 386Wh, 753Wh, 1121Wh and 293Wh, their received irradiance 1890 Wh/m^2, 2091 Wh/m^2, 2596 Wh/m^2 and 754 Wh/m^2, their temperature 17.4 °C, 22.7 °C and 23.5 °C.



(a) (b)

Figure 74: *Average array yield (h/day) (a) and proportion of hours in which energy is produced at installed capacity over the total hours of energy production (b) comparison for modules positioned on the façade and pergola.*



(a) (b)

Figure 75: *Average energy production (Wh) (a) and irradiance (Wh/m^2) (b) comparison of modules positioned on the façade and pergola.*

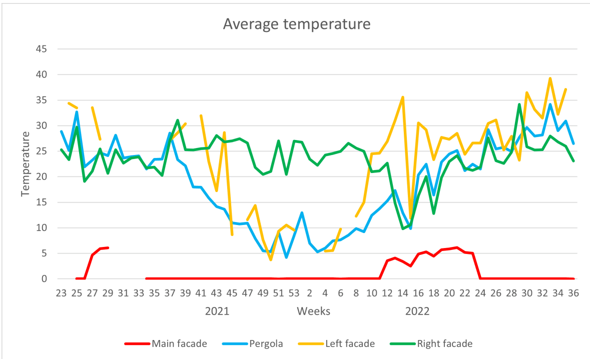


Figure 76: *Average temperature (°C) of modules positioned on the façade and pergola.*

In Figure 77 is showed the change, in percentage, from 2021 to 2022 of modules on façade, pergola, left side façade and right side façade in four parameters. Modules on the left façade have again the highest increase in installed capacity used, while modules on the main façade the highest increase in temperature.

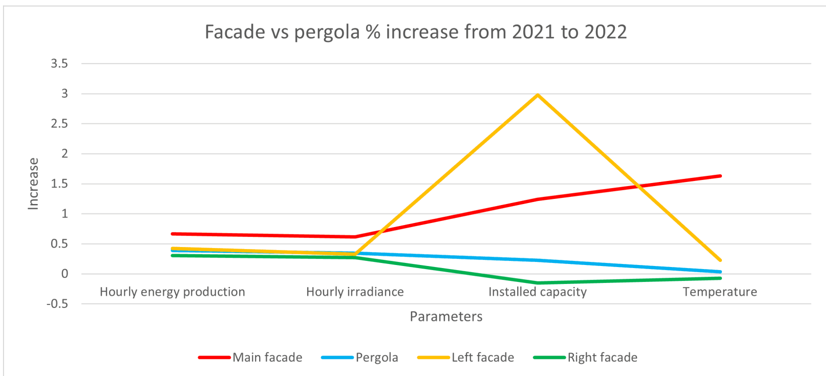


Figure 77: *Percentage of increase from 2021 to 2022 of average energy production, average irradiance reception, total installed capacity and average temperature of modules on the façade, the pergola, left side façade and right side façade.*

To conclude, the left side façade seems to be the most performing, but an insight in the

difference of each parameter in each period will show it better.
During summer 2021, efficiency is higher in modules on the left side façade by +12.9% from the main façade, +4.2% from the pergola and +3.5% from the right side façade, array yield is higher in modules on the left side façade by 2.2 h/day from the main façade, 0.9 h/day from the pergola and 2.6 h/day from the right side façade, energy production is higher in modules on the left side façade by 922Wh from the main façade, 295Wh from the pergola and 879Wh from the right side façade, irradiance is higher in modules on the left side façade by 1137 Wh/m^2 from the main façade, 101 Wh/m^2 from the pergola and 1868 Wh/m^2 from the right side façade, temperature is higher in modules on the left side façade by 6.2 °C from the pergola and 6.7 °C from the right side façade.
During summer 2022, efficiency is higher in modules on the left side façade by +13.6% from the main façade, +4.3% from the pergola and +3.5% from the right side façade, array yield is higher in modules on the left side façade by 2.1 h/day from the main façade, 0.7 h/day from the pergola and 3 h/day from the right side façade, energy production is higher in modules on the left side façade by 992Wh from the main façade, 233Wh from the pergola and 1019Wh from the right side façade, irradiance is higher in modules on the pergola by 899 Wh/m^2 from the main façade, 172 Wh/m^2 from the left side façade and 2288 Wh/m^2 from the right side façade, temperature is higher in modules on the left side façade by 3.4 °C from the pergola and 5.4 °C from the right side façade.
During winter, is higher in modules on the left side façade by +13.8% from the main façade, +5.6% from the pergola and +2.4% from the right side façade, array yield is higher in modules on the left side façade by 0.2 h/day from the main façade, 0.4 h/day from the pergola and 0.8 h/day from the right side façade, energy production is higher in modules on the left side façade by 170Wh from the main façade, 127Wh from the pergola and 275Wh from the right side façade, irradiance is higher in modules on the main façade by 317 Wh/m^2 from the pergola, 96 Wh/m^2 from the left side façade and 790 Wh/m^2 from the right side façade, temperature is higher in modules on the left side façade by 1.8 °C from the pergola and 7.7 °C from the right side façade.
Looking at the entire year, efficiency is higher in modules on the left side façade by +10.9% from the main façade, +3.1% from the pergola and +2.3% from the right side façade, array yield is higher in modules on the left side façade by 1.3 h/day from the main façade, 0.8 h/day from the pergola and 2.3 h/day from the right side façade, the average proportion of hours producing energy at the maximum capacity is higher in modules on the left side façade by +13.3% from the main façade, +9.4% from the pergola and +22.4% from the right side façade, energy production is higher in modules on the left side façade by 735Wh from the main façade, 368Wh from the pergola and 828Wh from the right side façade, irradiance is higher in modules on the left side façade by 706 Wh/m^2 from the main façade, 505 Wh/m^2 from the pergola and 1842 Wh/m^2 from the right side façade, temperature is higher in modules on the right side façade by 6.1 °C from the pergola and 0.8 °C from the left side façade.

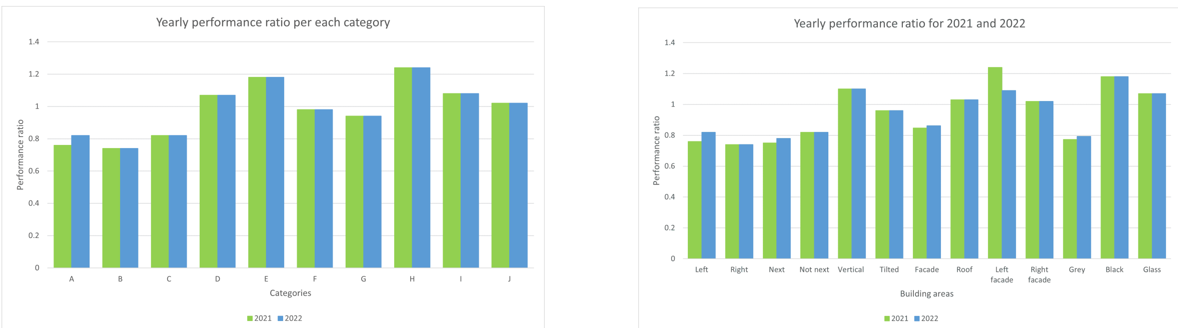
Overall, modules on the left side of the façade, facing South-West and positioned vertically, are the most performing.

4.7. General observations

To conclude the analysis, a few last observations will be done considering the building entirely. Among these, the performance ratio, that has been calculated on a yearly basis for each category. The analysis has been done both for category division and set of categories, to complete the comparison analyses earlier analysed. Figure 78 shows the annual values, both divided by category and building area (or set of categories, the ones studied in the analysis).

All categories have the same performance ratio value in both 2021 and 2022, except for category A, where 2021 has a higher value. As already stated in Section 4.2, this value gives an idea of how important losses are, thus the higher is it the lower are losses, because it is closer to the ideal case without losses. The best performing category is H, modules positioned on the on the left side façade of the building looking from the front. This short façade is facing South-West thus has light many hours during the day and has no shadow given by any object, except for a small cabin at the bottom, which only covers the first row of modules.
After H, the most performing categories in terms of performance ratio are E and I, respectively the vertical modules positioned on the pergola in the front part and the modules on the right side façade looking from the front.
Category I does not receive that much sunlight during the day, since it is situated towards South-East, but it also does only have a small cabin at the bottom covering the first row of modules, thus having no shading it performs well. The only problem it has is not receiving much sunlight during the day.
Category E has been analysed when comparing grey, black and glass modules (it is the black one) in Section 4.5, and it was already clear how well performing it is.

The worst performing categories are A and B, modules positioned next to balconies. As already analysed during the comparison of these two categories, they have the disadvantage of receiving shadow during some hours of the day, and this makes them less performing than other categories. In support of the analysis in Section 4.3, which concluded that modules positioned on the right of balconies (category B) are slightly more performance than modules on the left (category A), in 2022 category B is indeed more performing.

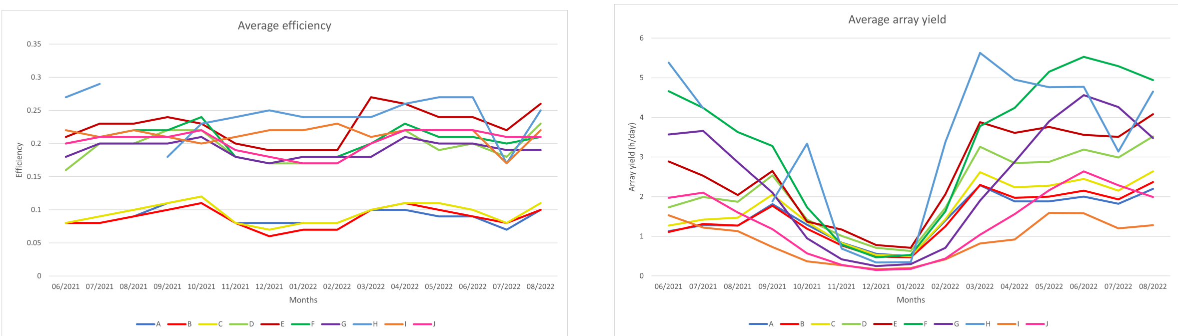


(a) (b)

Figure 78: *Yearly performance ratio calculated for each category (a) and building area (or set of categories) (b).*

When looking at the yearly performance ratio calculated per each building area, some areas have the same value for 2021 and 2022, but some don't. The most performing are modules on the left façade for 2021, while overall are black modules positioned on the front vertical side of the pergola (category E), followed by vertical modules on the pergola, which is the set of categories composed by E and J. Because of this, is reasonable to conclude that in terms of performance ratio modules on the front of the pergola have the highest performance.
The worst performing modules are grey ones (categories A, B and C), which here are in the building areas "Left", "Right", "Next" and "Grey", all the lowest.

Figure 79 and 80 show the monthly efficiency and array yield of each category. Category H, because of the issues on the irradiance sensors previously cited, does not have available data during August 2021.



(a) (b)

Figure 79: *Average monthly efficiency calculated (a) and array yield (h/day) (b) for each category.*

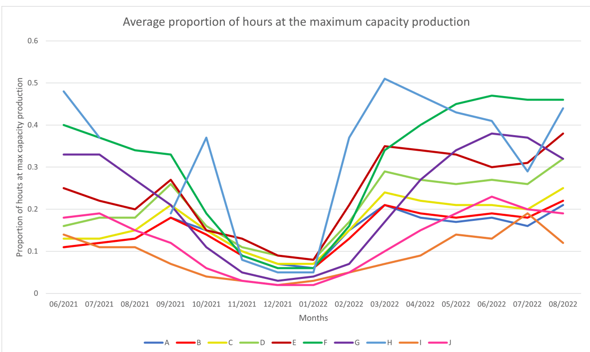


Figure 80: *Proportion of hours in which energy is produced at installed capacity over the total hours of energy production, for each category.*

In terms of efficiency, category H is indeed the most performing (on average, 24.3%), followed by category E and I (with respectively 22.7% and 21.3%, on average). The least performing are categories A, B and C, as previously said (with an average of 9%).

In terms of array yield, the most performing is again category H (on average, 3.4 h/day), followed by category F. The least performing is category I (with an average of 0.9 h/day).

In terms of average proportion of hours in which energy is produced at the installed capacity, category H is the most performing with an average value of 32.2%, and the worst performing is category I with 8.9%.

Overall, category H results to be the most performing under many points of view, even though is in a position where it doesn't always receives sunlight, even during summer. The 3 most performing categories are E (black vertical modules on the front pergola), F (tilted modules on pergola towards South-East) and H (modules on the left side façade towards South-West).

5 | Discussion and conclusions

The environmental impact of worldwide energy consumption and the related GHG emissions are of significant concern, and 33% of it comes from the residential sector. Researchers in the built environment are studying energy efficient buildings, of which the major part produce renewable energy by installing PV systems, having both modules attached to the finished building (BAPV) and modules integrated in the building during construction (BIPV).

This Thesis focused on the performance analysis of one particular building that has been refurbished by covering its roof, walls and balconies with PV modules, each with different characteristics that needed to be investigated for understanding their distinctions.

For the purpose of loading, linking and comparing the data obtained for each module and perform the analysis, a program has been coded in MS Access, a DBMS where code is written in Visual Basic and SQL. This program automatically reads the files containing data, understands which type they are and whether they have already been stored and, if not, it stores them in a relational DB composed by tables that communicate through queries. When all data have been stored, the program calculates the performance indicators needed to perform the analysis, and in the end it creates a new Excel file containing the needed data, grouped by and filtered on what the user has chosen using the Graphical User Interface that has been created expressly for this necessity.

During the analysis, it has been found that the parameters that affect the system performance are mainly irradiance, temperature, the position of a module on the building, the technological construction and the module type. These factors affect the energy production of each module and thus the entire system performance. The importance of these parameters can be assessed using different KPI, which are *efficiency*, that provides the information of how much input energy the system is able to convert into output energy, *array yield*, that indicates the time that the system can produce energy at its installed capacity *reference yield*, that indicates the time that the system works at the reference irradiance, and finally, *performance ratio*, that indicates the quality of the system by giving an insight of its losses.

The system performance analysis has been divided into four sections, each one analysing a different aspect of the considered PV system.

The impact of shading given by balconies to the modules installed next to them resulted in modules positioned distant from balconies being more performing than modules installed next to them by 0.21 h/day in the array yield and +2.1% in the percentage of producing at maximum capacity over the total production time.

The performance difference between modules with different tilt resulted in tilted modules being more performing than vertical modules by 0.8 h/day in the array yield and +6.4% in the percentage of producing at maximum capacity over the total production time.

The impact of the type of a module on its performance resulted in black modules being the most performing by 1 h/day in the array yield and +8.6% in the percentage of producing at maximum capacity over the total production time than grey modules, while by 0.4 h/day in the array yield and +3.3% in the percentage of producing at maximum capacity over the total production time than glass modules.

The impact on performance of modules installed in different directions and building locations resulted in modules installed on the left side façade being the most performing by 1.3 h/day in the array yield and +13.3% in the percentage of producing at maximum capacity over the total production time than modules on the main façade, by 0.8 h/day in the array yield and +9.4% in the percentage of producing at maximum capacity over the total production time than modules on the pergola, by 2.3 h/day in the array yield and +22.4% in the percentage of producing at maximum capacity over the total production time than modules on the right side façade.

Lastly, the analysis performed on all the categories and all the building areas together showed that the most performing category is H, modules on the left side façade, followed by categories E and F, respectively modules on the front vertical side of the pergola and modules on the South-East tilted side of the pergola.

Despite these results, there still are some limitations in the work that need to be addressed. The installed modules are of different types, and their installed capacity impacts on the performance, thus a finer analysis could be performed when analysing modules of the same type, so that their structural characteristics impacts less.
The reliability of the measured data is threaten by the scarce reliability of some sensors (mostly, irradiance and temperature). When the reliability of data will be acceptable, the analysis will give even more trustworthy results. However, the same program presented in this Thesis will work as it is, due to its generic nature, meaning that it was never taylored over the current data. Then, following the logic that this Thesis presented in performing the anaysis, it will be possible to obtain more precise results.

Regarding future directions, it would be interesting to expand the obtained results with a cost-benefit analysis so that, in situations with a limited budget, having understood which are the most important areas to target with refurbishment procedures will be useful in a trade-off between the energetic system optimization and the budget fulfillment.

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A. Appendix A

This appendix shows how the acronyms that represent the sensor names of temperature and irradiance have been found.

All these acronyms have been inserted in the model seen with an example in Table 1.

ZOLO	SELB	South-East Left Bottom
ZOLM	SELM	South-East Left Middle
ZOLB	SELT	South-East Left Top
ZOMO	SEMB	South-East Middle Bottom
ZOMM	SEMM	South-East Middle Middle
ZOMB	SEMT	South-East Middle Top
ZORM	SERM	South-East Right Middle
ZORO	SERB	South-East Right Bottom
ZORB	SERT	South-East Right Top
PZOLB	PSELT	Pergola South-East Left Top
PZOLO	PSELB	Pergola South-East Left Bottom
PZOMB	PSEMT	Pergola South-East Middle Top
PZOMO	PSEMB	Pergola South-East Middle Bottom
PZORB	PSERT	Pergola South-East Right Top
PZORO	PSERB	Pergola South-East Right Bottom
DZOLB	RSELT	Roof South-East Left Top
DZOLO	RSELB	Roof South-East Left Bottom
DZOMB	RSEMT	Roof South-East Middle Top
DZOMO	RSEMB	Roof South-East Middle Bottom
DZORB	RSERT	Roof South-East Right Top
DZORO	RSERM	Roof South-East Right Bottom
DNWLO	RNWLB	Roof North-West Left Bottom
DNWLB	RNWLT	Roof North-West Left Top
DNWMO	RNWMB	Roof North-West Middle Bottom
DNWMB	RNWMT	Roof North-West Middle Top
DNWRO	RNWRB	Roof North-West Right Bottom
DNWRB	RNWRT	Roof North-West Right Top

(a)

ZWLB	SWLT	South-West Left Top
ZWLM	SWLM	South-West Left Middle
ZWLO	SWLB	South-West Left Bottom
ZWMB	SWMT	South-West Middle Top
ZWMM	SWMM	South-West Middle Middle
ZWMO	SWMB	South-West Middle Bottom
ZWRB	SWRT	South-West Right Top
ZWRM	SWRM	South-West Right Middle
ZWRO	SWRB	South-West Right Bottom
NOLB	NELT	North-East Left Top
NOLM	NELM	North-East Left Middle
NOLO	NELB	North-East Left Bottom
NOMB	NEMT	North-East Middle Top
NOMM	NEMM	North-East Middle Middle
NOMO	NEMB	North-East Middle Bottom
NORB	NERT	North-East Right Top
NORM	NERM	North-East Right Middle
NORO	NERB	North-East Right Bottom
PNWLB	PNWLT	Pergola North-West Left Top
PNWLO	PNWLB	Pergola North-West Left Bottom
PNWMB	PNWMT	Pergola North-West Middle Top
PNWMO	PNWMB	Pergola North-West Middle Bottom
PNWRB	PNWRT	Pergola North-West Right Top
PNWRO	PNWRB	Pergola North-West Right Bottom

(b)

Figure 81: *Tables showing the meaning of temperature sensors acronyms, in Dutch and English.*

ZOO	SET	South-East Top
ZOM	SEM	South-East Middle
ZOB	SEB	South-East Bottom
DZO	RSE	Roof South-East
DNW	RNW	Roof North-West
ZWB	SWT	South-West Top
ZWM	SWM	South-West Middle
ZWO	SWB	South-West Bottom
NOB	NET	North-East Top
NOM	NEM	North-East Middle
NOO	NEB	North-East Bottom
NWB	NWT	North-West Top

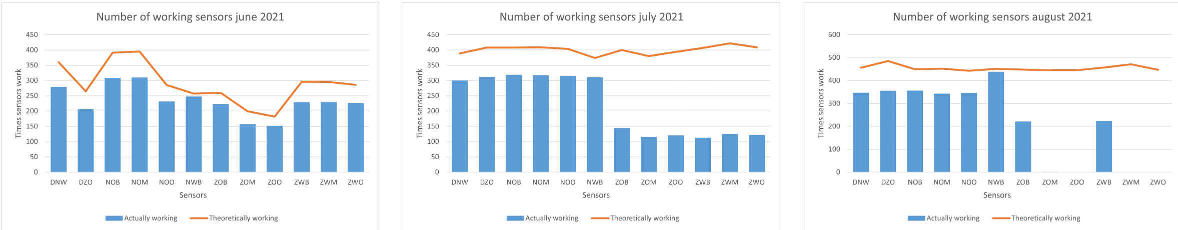
Figure 82: *Table showing the meaning of irradiance sensors acronyms, in Dutch and English.*

B. Appendix B

During the data analysis, many times has been noticed that some irradiance and temperature sensors did not work. Thus, an analysis has been performed in order to understand the reliability of sensors.

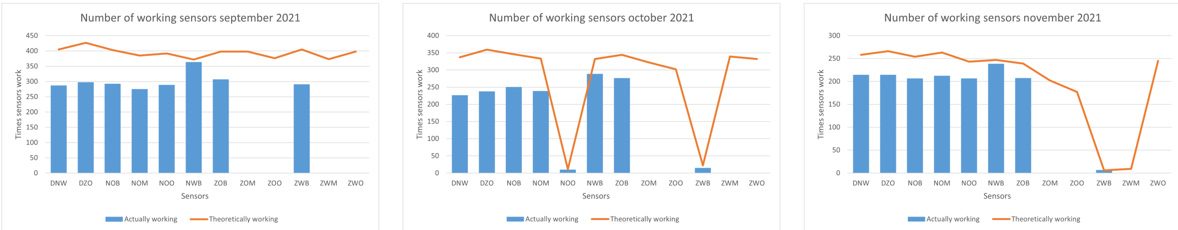
The analysis shows the difference, for each sensor, between the data they give that are reasonable and the total data they give.

Figures 83 to 87 show the monthly analysis for irradiance sensors.



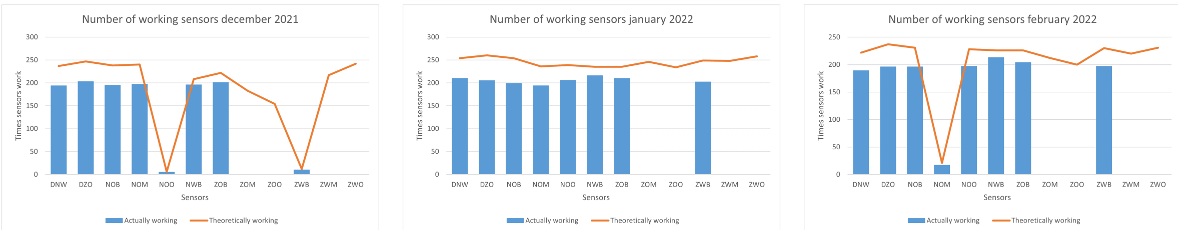
(a) (b) (c)

Figure 83: *Percentage of realistic values over total values given for each irradiance sensor, divided by month (June 2021, July 2021, August 2021).*



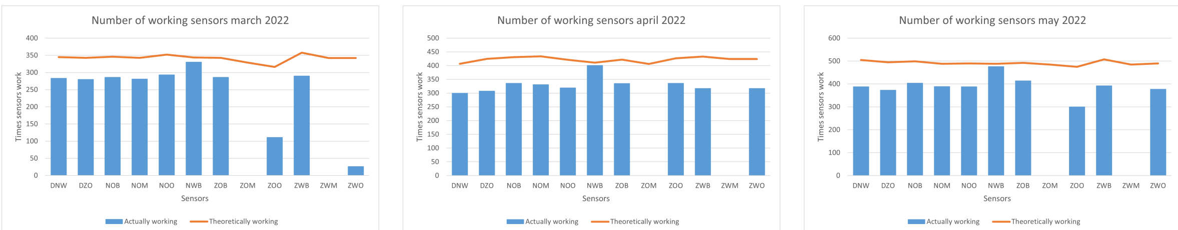
(a) (b) (c)

Figure 84: *Percentage of realistic values over total values given for each irradiance sensor, divided by month (September 2021, October 2021, November 2021).*



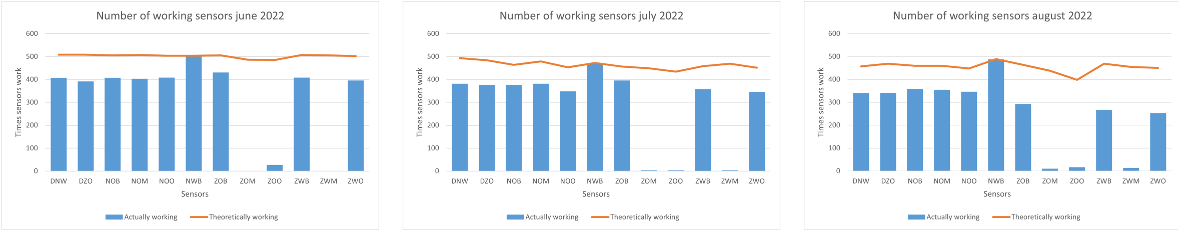
(a) (b) (c)

Figure 85: *Percentage of realistic values over total values given for each irradiance sensor, divided by month (December 2021, January 2022, February 2022).*



(a) (b) (c)

Figure 86: *Percentage of realistic values over total values given for each irradiance sensor, divided by month (March 2022, April 2022, May 2022).*



(a) (b) (c)

Figure 87: *Percentage of realistic values over total values given for each irradiance sensor, divided by month (June 2022, July 2022, August 2022).*

Each plot has values represented with columns, that are the number of times sensors give reasonable values, and a line, that represents the number of times sensors give values in total. The more each column is close to the line, for the correspondent sensor and month, the more accurate its values are.

From the plots can be seen that sensors ZOM, ZOO, ZWM and ZWO are the most problematic, overall. Respectively, they give reasonable values in no months (except for August 2022, where it gives a very small percentage), 6 months (of which 4 months only small percentages), 3 months (of which only one with a quite high percentage) and 8 months (of which 1 month has a very small percentage and 2 months have not a sufficiently high percentage).

The most accurate sensor is NWB, which frequently has a percentage of reasonable values close to 100% and never reaches a low percentage, thus can be said that it is the most reliable.

All other sensors do not perform too bad, especially sensors DNW, DZO, NOB, NOM and NOO, which always have quite a high percentage of reasonable data.

From this irradiance sensors analysis has been deducted that they are not always reliable in giving values, the reason could be some issue in their setup or just malfunctioning in some moments.

Figures 88 and 89 show the annual analysis for temperature sensors.

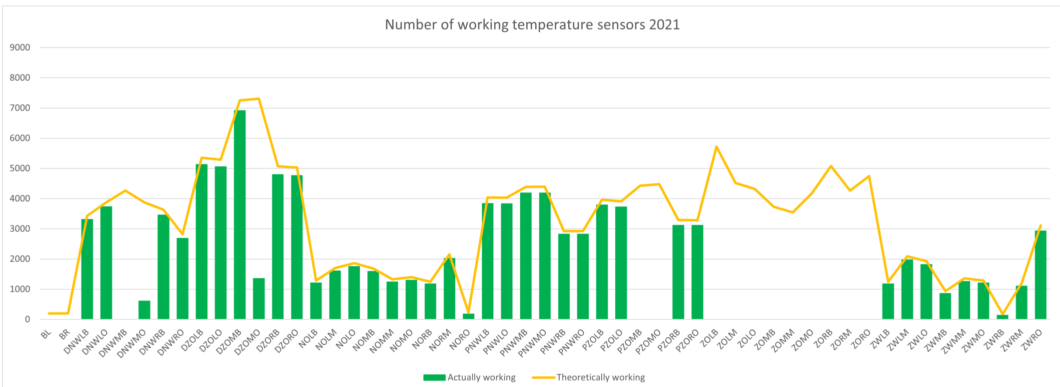


Figure 88: *Percentage of realistic values over total values given for each temperature sensor, for 2021.*

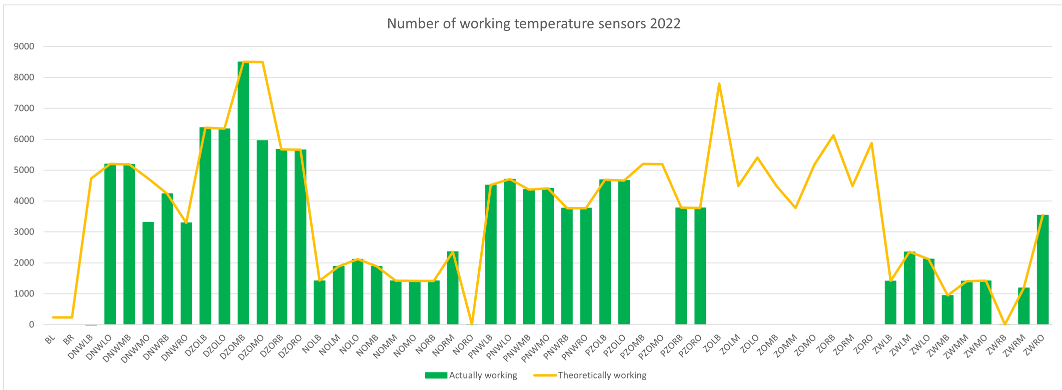


Figure 89: *Percentage of realistic values over total values given for each temperature sensor, for 2022.*

Each plot has values represented with columns, that are the number of times sensors give reasonable values, and a line, that represents the number of times sensors give values in total. The more each column is close to the line, for the correspondent sensor, the more accurate its values are.

In both 2021 and 2022 the most problematic sensors are PZOMB, PZOMO, ZOLB, ZOLM, ZOLO, ZOMB, ZOMM, ZOMO, ZORB, ZORM and ZORO, which never give reasonable values. These sensors are all positioned on the main façade. In 2021, also sensor DNWMB did not give values and sensor DNWMO gives a very small percentage of values. In 2022, sensor DNWLB gives no values.

Sensors BL and BR are not assigned to any module, because of the missing module positioning cited at the end of Section 3.2.

All other sensors perform quite well, thus can be reliable in giving the correct data.