TÉCNICO LISBOA

Technical Assessment of ZigZagSolar BIPV System

Mohamed Mufid Hakim

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Luís Filipe Moreira Mendes

Eng. Wim van de Wall

Examination Committee

Chairperson: Prof. Duarte de Mesquita e Sousa

Supervisor: Prof. Luís Filipe Moreira Mendes

Member of the Committee: Prof. Rui Manuel Gameiro de Castro

May 2019

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa*.*

Acknowledgments

I would like to thank Eng. Wim van de Wall and Eng. Xin Xu for guiding and supporting me throughout the process. Your continuous feedback and suggestions supplemented my work and helped me to fulfill my objectives. I also thank all the Wallvision BV team, who involved me in all aspects of the startup activities and provided me with knowledge whenever was needed.

Thanks to Dr. Luis Filipe Mendes. Your insights and expertise greatly improved the quality of my work.

Thanks also to the EIT- InnoEnergy Master's school for providing me the proper training and the professional network.

Finally, special appreciation to my parents, siblings, family and my friends, without your support and motivation, I wouldn't achieve what I'm Today.

Abstract

The utilization of solar energy by deploying innovative technologies is continuously improving. Building Integrated Photovoltaic (BIPV) is one solution to produce electricity from a renewable source. One of the issues facing the BIPV market is to have a balance between energetic and aesthetic performance. *ZigZagSolar* is an innovative BIPV technology that combines both aspects. Most of the available studies on *ZigZagSolar* are on optimizing the angles for different orientations and latitudes. The performance analysis was done on a small scale only and not widely investigated. This work analyzes in detail the performance of the largest solar façade installed in the Netherlands. Inspection of the internal and external loss factors on the measured yield is evaluated. The generated electrical output is 121 kWh/m^2/year. Factors like shading from the adjacent obstacles and inverter losses had a contribution of 11% and 3%, respectively. The comparison of *ZigZagSolar* with competitive solar technologies has shown that *ZigZagSolar* is better during winter than the rooftop by 12% and worse during the rest of the year by 7%. Nevertheless, *ZigZagSolar* is better than its direct competitor, the vertical BIPV, during the whole year by 22%. The experimental work confirmed the simulation study using *BIMSolar*. The results showed that simulation can predict the yield with a difference of less than 4% for the three solar systems.

Keywords

ZigZagSolar | BIPV | Solar Façade | Solar Photovoltaic | Solar Energy | Renewable Energy| NZEB

Resumo

A utilização da energia solar através da implantação de tecnologias inovadoras está melhorando continuamente. A energia solar fotovoltaica integrada em edifícios (*Building Integrated Photovoltaic*, BIPV) é uma solução para produzir eletricidade a partir de uma fonte renovável. Uma das questões que o mercado BIPV enfrenta é o equilíbrio entre o desempenho energético e a estética. O *ZigZagSolar* é uma tecnologia inovadora de BIPV que combina ambos os aspetos. A maior parte dos estudos realizados com o sistema *ZigZagSolar* está focada na otimização dos ângulos para diferentes orientações e latitudes. A análise do desempenho deste sistema foi realizada de forma parcial e em pequena escala. O presente trabalho analisa em detalhe o desempenho da maior fachada instalada na Holanda. Foram analisados os fatores de perda de rendimento internos e externos ao sistema. A energia elétrica gerada foi 121 kWh/m^2/year. Fatores como o sombreamento dos obstáculos adjacentes e as perdas dos inversores representaram perdas de 11% e 3%, respetivamente. A comparação entre o sistema *ZigZagSolar* e tecnologias solares alternativas mostrou que o sistema *ZigZagSolar* produziu 12% mais eletricidade durante o inverno e menos 7% no resto do ano que o sistema de montagem em cobertura, tendo produzido 22% mais eletricidade que seu concorrente direto, o sistema BIPV vertical, durante todo o ano. O trabalho experimental realizado confirmou os resultados obtidos com uma simulação realizada com o *software BIMSolar*. Os resultados mostraram que a simulação previu o rendimento dos vários sistemas com uma diferença menor que 4% em relação aos dados experimentais.

Palavras-chave

ZigZagSolar | BIPV | Fachada Solar | Energia Solar Fotovoltaica | Energia Solar | Energias Renováveis | NZEB

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List of Acronyms

ACP	Aluminum Composite Panel
AM	Air Mass
a-Si	Amorphous silicon
BAPV	Building Applied Photovoltaic
BF	Boosting Factor
BIM	Building Information Modelling
BIPV	Building Integrated Photovoltaic
BIPVT	Building Integrated Photovoltaic Thermal
CAGR	Cumulative Annual Growth Rate
CdTe	Cadmium Telluride
CIGS	Copper-Indium Gallium-Diselenide
CPV	Concentrating Photovoltaic
C-Si	Crystalline Silicon
DHI	Direct Horizontal Irradiance
DHW	Domestic Hot Water
DNI	Direct Normal Irradiance
DSSC	Dye-Sensitized Solar Cell
EPBD	Energy Performance Building Directive
EPBT	Energy Pay Back Time
EVA	Ethyl Vinyl Acetate
GHG	Green House Gas
GHI	Global Horizontal Irradiance
I_{MPP}	Maximum Power Point Current
IPCC	Intergovernmental Panel on Climate Change
I_{sc}	Short Circuit Current
MLPE	Module Level Power Electronics
MPPT	Maximum Power Point Tracking

NREL	National Renewable Energy Laboratory
NZEB	Net Zero Energy Building
OPV	Organic Photovoltaic
PCU	Power Condition Unit
P_{MAX}	Maximum Power
POA	Plain of Array
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
QD	Quantum Dots
RES	Renewable Energy Sources
STC	Standard Test Conditions
TFSC	Thin Film Silicon Cell
TMY	Typical Metrological Year
UNEP	United Nations Environment Program
V_{MPP}	Maximum Power Point Voltage
V_{OC}	Open Circuit Voltage
WvM	Wijk van Morgen
ZZS	ZigZagSolar

Chapter 1 Introduction

This chapter gives a brief overview of the work. At first, an overview of the trends in solar energy is presented followed by motivations and objectives of work. At the end of the chapter, the methodology and work structure are provided.

1.1 Background

The Intergovernmental Panel on Climate Change (IPCC) has published a report in 2018 about the effect of global warming on the well-being and ecosystem. Immediate adaptation and mitigation actions are needed to prevent exceeding the limit of 1.5 °C [1]. Buildings are a major contributor to the climatic issues we are facing. The current practices are unsustainable and have high emissions since they use energy, raw materials and it's difficult to integrate them to the circular economy. According to the United Nations Environment Program (UNEP) buildings are responsible for over 40% of the world's energy consumption and accounts for up to 30% of the total CO2 emissions and if the Business as usual scenario continues, the Green House Gas (GHG) emissions from buildings will increase [2]. The European Parliament has launched a long-term goal to reduce the GHG emissions 80-95% by 2050 compared to 1990. This goal will be met by achieving another short-term goal which states that all newly built buildings in 2018 owned by public authorities should be nearly zero energy building (NZEB) and all new buildings by 2020 [3]. NZEB is defined according to the EU's Energy Performance Building Directive (EPBD) as "The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [4]. Renewable Energy Sources (RES) can play a major role in achieving a nearly zero energy building. Other strategies exist to assist in achieving NZEB such as passive design and energy saving techniques (optimization and monitoring). The Renewable Energy Directive by the EU parliament requires all the EU countries to have at least 20% of their energy demand to be from renewable sources by 2020 and at least 32% by 2030[5]. Those clean sources will offset the negative impact of GHG emissions and allow creative business models to achieve the planned strategy.

One of the most important renewable sources is solar energy. There are various technologies to allow us to utilize this free source of energy in buildings ranging from optimizing the thermal indoor comfort and natural daylighting to using solar panels to generate heat or electricity in the built environment. Building Integrated Photovoltaic (BIPV) provide onsite energy production from a renewable source which is necessary for NZEB in terms of satisfying the electrical demand of a building and reducing emissions. BIPV is usually closer to the eye of the public compared to the rooftop. This help to promote the importance of sustainability clearly in society. Nevertheless, it is a slowly developing technology, facing many requirements and safety standards.

The solar PV technology is improving rapidly worldwide on both aspects technically and financially. The performance ratio (defined as the ratio of actual electrical output to the theoretical electrical output under STC) of PV systems has been improved from 70% up to 90%. The Cumulative Annual Growth Rate (CAGR) was estimated by 24% from 2010 to 2017. The majority of the PV module production is dominated by China and Taiwan (70%) in 2017. Europe focused on the PV installation holding a share of 28% of the total cumulative market in which China had the lead (32%). The efficiency of PV cells at the lab scale has reached 46% for multi-junction, 26.7% for Mono-crystalline, and 22.9% for CIGS Thin Film Solar Cell (TFSC). With the increase of PV efficiency, less material is needed. Therefore, the Energy Pay Back Time (EPBT) of PV systems which depends on the location and the used technology ranges from 1.5 to 2.5 years. More than half of the inverter's market is dominated by string inverter (52%) followed by central inverter accounting for 44% of the total market. Micro-inverters are the least common due to its expensive cost per installed capacity having a 1% share of the market. DC / DC power optimizers are also rarely found (3%) but still needs the use of DC / AC inverter. New development of innovative inverter technologies is being deployed such as integration of storage with inverters (hybrid inverter) or optimizing self-consumption [6].

1.2 Motivation and Objectives

PV panels integrated into the building envelope take many shapes and forms. With the rise of many different BIPV technologies, emphasis on aesthetics of BIPV is getting more and more attention. Actual performance is getting less importance for architects. One of those technologies is ZigZagSolar (ZZS) where the system was under test and development for six years until it reached the optimum aesthetics and energetic performance. Electrical energy generation analysis is therefore needed to know how the ZZS system positions itself in the NZEB competition among other BIPV technologies.

Most of the available studies performed on ZZS are done on a lab-scale in a test site facility. Studying the effects of different types of losses on the actual performance was not considered. Comparative studies between simulation and real measurement were not widely investigated.

The objective of this thesis work is to obtain a better understanding of the ZZS BIPV system among other competitive solar technologies. Evaluation of ZZS performance and investigation of the loss factors at a larger commercial scale are addressed.

By the end of this work, it is expected to answer the following research questions:

- What is the effect of different losses factors on the overall performance of ZZS?
- How does the ZZS system perform in real life against the rooftop and vertical solar system?
- How does the ZZS experimental measurement compare to the ZZS simulation result?
- What is the ZZS predictive performance compared to the rooftop and vertical solar systems using a BIPV simulation tool?

1.3 Methodology and thesis structure

A literature review was initially conducted to study available technologies in comparison to ZZS. Understanding the complex performance of ZZS required setting up a systematic and pragmatic approach. An existing ZZS project uses glass/back sheet modules called Eisenhower was taken as an initial case study. Too many data were lost which affected the results. Therefore, assessment of the results was divided into two parts internal and external comparison.

The internal part dealt with handling large datasets obtained from the ZZS system and were put under examination in Excel for further analysis. Studying the losses factors on the overall performance using root-cause analysis was done on three levels: Yearly, monthly and daily.

The external comparison part handled ZZS measurement against simulation (done by the company using MATLAB) and rooftop measurement on the same building for the purpose of commercial comparison. Another test site called Wijk Van Morgen with three installed setups namely ZZS, rooftop, and vertical are analyzed experimentally to further understand how ZZS perform against well-known technologies. Finally, testing of predictive simulation software called BIMSolar where the three setups at Wijk Van Morgan are simulated. This will help us to answer the research questions mentioned above.

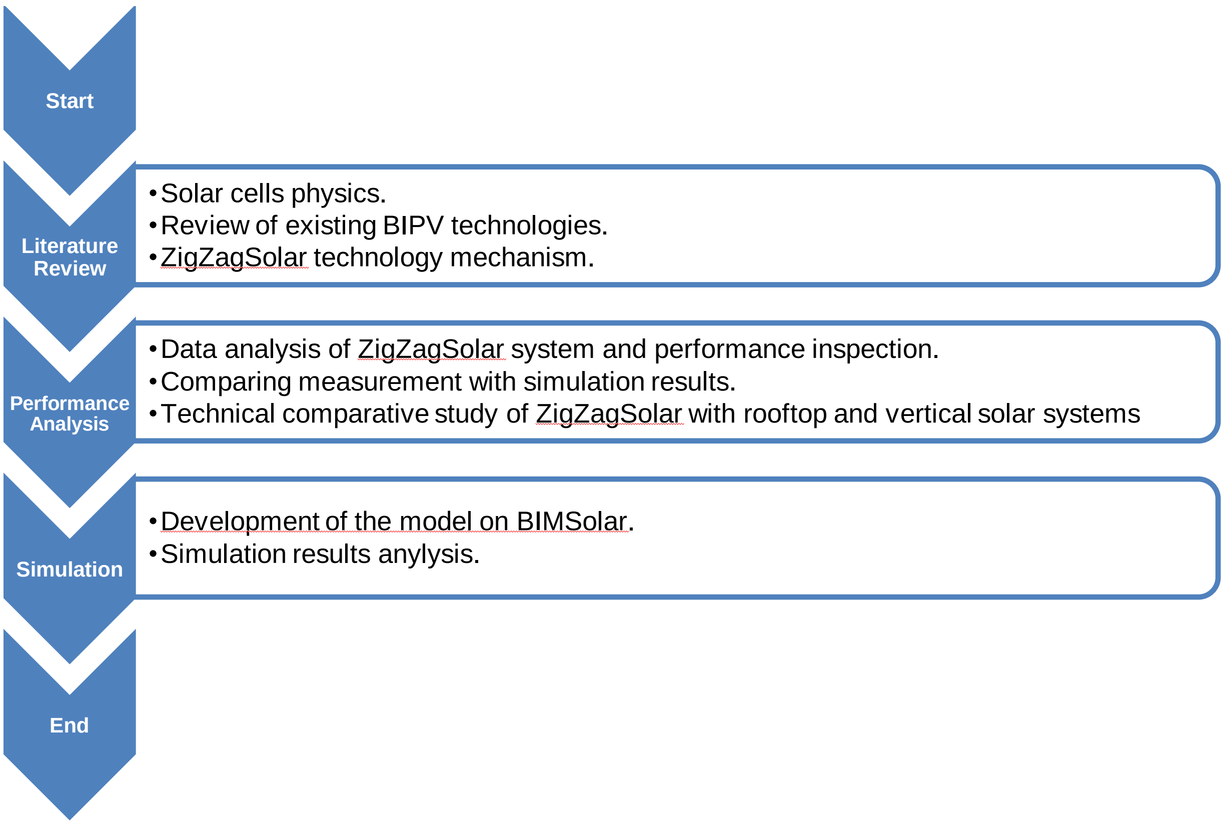


Figure 1.1: Followed methodology to execute the research project

Chapter 2 presents the working principle of solar cells. The current BIPV technologies are presented to understand the wide range of PV applicability in the built environment. ZigZagSolar technology working mechanism is lastly shown.

Chapter 3 describes in details the performance of ZigZagSolar by analyzing a large scale commercial project named Eisenhower. Additionally, the approach used to examine and troubleshoot the data gathered and the factors affected the yield are also presented.

Chapter 4 describes the potential of ZigZagSolar experimentally among two main competitive solar technologies in the market namely rooftop and vertical solar systems. The measurement results of ZZS in Eisenhower are put into comparison against the company's simulation results. In the end, a simulation study is presented to test the three main solar technologies in competitor simulation software.

Chapter 5 concludes the main findings of the conducted research work. Future work for system improvement is also mentioned in this chapter.

Chapter 2 Basic concepts & state of the art

Chapter 2 presents the working principle of solar cells. The current BIPV technologies are presented to understand the wide range of PV applicability in the built environment. ZigZagSolar technology working mechanism is lastly shown.

2.1 Principle of Operation

The solar irradiance received outside the earth's atmosphere (sometimes called as the solar constant) depends on the orbital position of the earth. The maximum value occurs at the perihelion (closest distance from the sun) and the minimum value at the aphelion (farthest distance from the sun). The standard mean value is 1366W/m^2 as reported by the National Renewable Energy Laboratory (NREL) [7]. While passing the atmosphere until reaching the earth surface, some of the sunlight is attenuated by absorption and scattering by molecules in the atmosphere such as water vapor, Carbon dioxide, Nitrogen, Oxygen, and Ozone. The extent of how much sunlight can be absorbed in the atmosphere is referred to as the 'Air mass' (AM). It is defined as the path length the light must travel through the atmosphere in relation to the shortest possible length at sea level (when the sun is overhead) [8].

The extra-terrestrial irradiance has AM0 which is the case for space applications. When the sun is overhead the AM is 1. The standard spectrum used to compare the solar cells performance is AM1.5 assumes that the normal terrestrial solar irradiance is 1000 W/m^2. Figure 2.1 illustrates the concept of the air mass. The real irradiance depends on the season, the time as well as the geographical location. There are two main methods to transform energy received from the sun. One is sun heat used in solar thermal systems to exchange heat between two bodies and the second form is sunlight used by solar photovoltaic (PV) systems. Unlike Photovoltaic panels, solar thermal applications use the full range of the solar spectrum (including infrared) and absorb photons with any amount of energy [8].

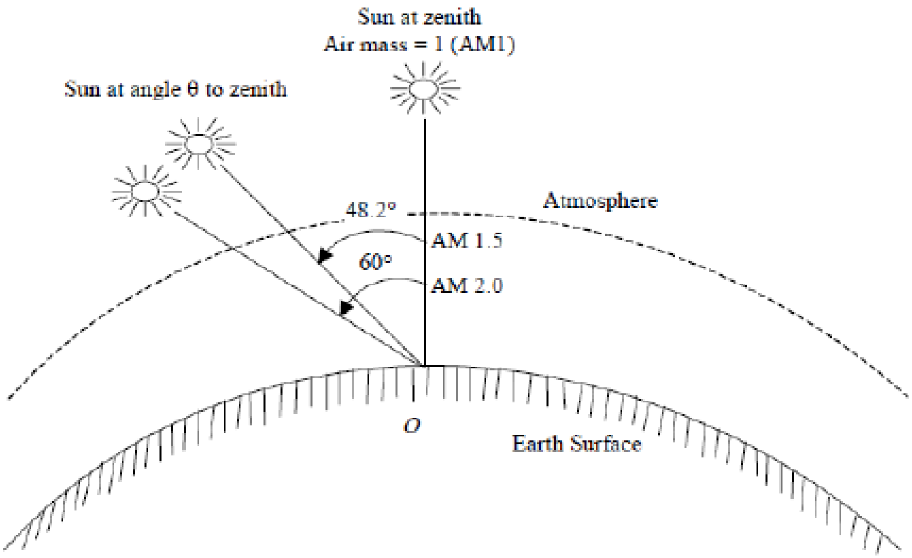


Figure 2.1: Air mass notion [9]

A typical silicon solar cell is a solid-state energy harvesting device made of intrinsic semiconductor material. The conversion process from sunlight to useful electricity is based on quantum theory. Light can be described by electromagnetic radiation made of energy packets called "photons". The energy of photons depends solely on the frequency or wavelength of the light according to equation (1) where h is Plank's constant, c is the speed of light and λ is the wavelength.

$$E = \frac{hc}{\lambda} \tag{1}$$

As Albert Einstein explained the photoelectric effect when ultraviolet light strikes a metallic surface it ejects electrons. In the case of photovoltaic effect, electrons don't escape the surface but they change their energy state. The material is doped (the process of adding impurities) to form n-type layer where the majority of negative charge carrier exist and the p-type layer where most of the positive charge carriers exist. When those two layers are added together they form a PN junction with an electric field across the junction, as shown in Figure 2.2. The visible light excites the electrons to move to higher energy levels. If the photon's energy is higher than the band gap energy, the electron breaks the weak bonds and jumps from the valence band (ground state) to the conduction band (excited state) leaving a hole behind it. The excited electrons are then collected using conductive terminals. If the photon's energy is less than the energy band gap, the electron is not excited and the energy is absorbed as heat. Similarly, the excess energy of the excited electrons is converted into heat [10].

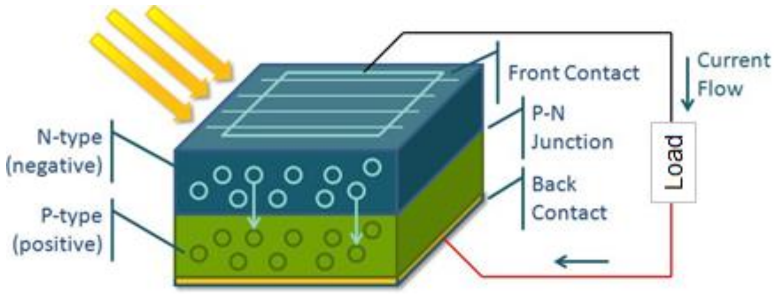


Figure 2.2 Solar Cell Structure. Adapted from [11]

2.2 Solar cells technologies

With the continuous research & development of solar technologies for different applications, various types of solar cells are available depending on the material used [6] [12] [13].

- First Generation: Crystalline silicon

  This type is sometimes referred to as "wafer-based. It is the most developed and common type on the market with the highest efficiency. There are two subcategories:

  - Mono/single crystalline: pure silicon single crystals undergo a controlled process to cut the large ingots into pseudo-square small wafers. The efficiency of this type at the lab scale reached 26.7%.
  - Multi/polycrystalline: The name refers to the molecular structure of silicon that has defects (grain boundaries). The process is cheaper than mono-crystalline but less efficient at 22.3%.

- Second Generation: Thin film

  Second generation cells are cheaper than first-generation solar cells since they require less semiconductor material, the thin film thickness is in the order of 1-4 µm. They can be deposited on any cheap substrate such as glass, plastic or polymer with a flexible structure for a wide range of applications. Three types of second-generation cells:

  - Amorphous silicon (a-Si): The molecular arrangement of a-Si is non-crystal structure. Hence less efficient modules. This type works well under high temperature and low light conditions. Efficiency has reached about 13%.
  - Copper-Indium-Gallium-Diselenide (CIGS): CIGS is among the most preferred thin films since it has the highest efficiency of 22.9%. They have a longer time span without significant degradation.
  - Cadmium Telluride (CdTe): Although CdTe has good optical and chemical properties for the development of thin films. Cd is considered a toxic substance and hazardous on the ecosystem. Recycling Cadmium is very expensive. The efficiency of this type reached 21%.

- Third Generation

  Third generation cells are under research and not yet available for commercial use. The available technologies are as follows:

  - Nanocrystal-based solar cells: sometimes named as “Quantum Dots” (QD) Solar cells. The crystal size is in the range of few nanometers. Trends are focused on replacing the semiconductor materials available in bulk quantity such as Si and CdTe with QD. In this type of cells, 1 photon can generate several electron-hole pairs up to 7.
  - Polymer-based solar cells: Sometimes called as OPV. Their main property is flexibility to be applied on different surfaces because of the polymer substrate. Efficiency reached over 20%.
  - Dye-sensitized solar cells (DSSC): This type of cells has a special processing method using a natural dye. The substrate can be flexible and transparent with a low production cost. Efficiency reached over 10%. Some challenges may include degradation of the dye when it is exposed to infrared and ultraviolet light.
  - Multi-junction solar cells: Multi-junction solar cells are used widely in Concentrating Photovoltaic (CPV) technology where sunlight is focused on using mirrors or reflectors on a tiny PV cell. Efficiency reached up to 40%.
  - Perovskite solar cells: This is the latest discovery in the solar cell research industry. Unlike conventional technologies, Perovskite solar cells don’t require expensive and complex processing steps. Similar to the DSSC, Perovskite cells have an issue with their stability and durability. Efficiency at the cell level has reached 23.7% in February 2019, It drops around to half at the module level.

2.3 From a solar cell to a solar system

A solar cell is the smallest unit in photovoltaic systems. The output of one crystalline silicon PV cell is 0.5 to 1 volts and a few amps. Solar cells are not enough to operate most of the practical applications since they are fragile (under outdoor conditions) and have low power. Cells are interconnected and arranged in series to achieve higher useful DC voltage forming a PV module with the required power and protection. Nowadays, standard PV modules consist of 60 or 72 cells connected in series. A PV module structure consists of a tempered glass layer for protection with high transmittance to maximize the visible light absorption. The solar cells are then encapsulated between two Ethyl Vinyl Acetate (EVA) layers. At the bottom, typically a back sheet layer called Tedlar is used for protection. Figure 2.3 shows a typical structure of a PV panel. Some modules use glass as the back sheet, namely double glass or glass-glass modules.

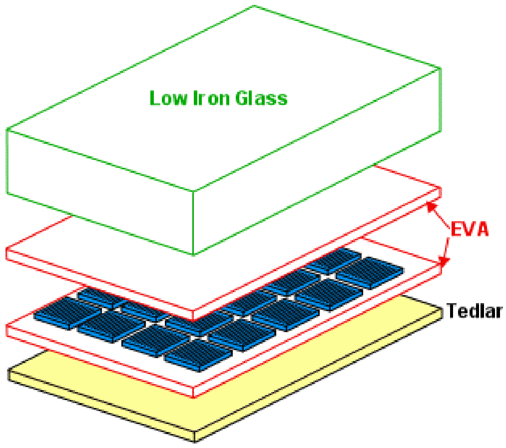


Figure 2.3 PV module structure [14]

The PV module is connected to several other modules in series making a PV string with a higher overall voltage. A string can be connected to other strings in parallel in order to have a PV array with a larger current. A scheme of the solar cells and modules arrangement is shown in Figure 2.4. The series or parallel configuration of modules depends on the application power demand.

When connecting cells or modules, the connection should have the same electrical current in case of serial connection or voltage in case of a parallel connection in order to avoid any mismatch. For protection purposes, a bypass and blocking diodes are used to avoid power losses. Since the solar irradiance is variable for different locations during the day, the use of power condition unit (PCU) is necessary to control the power supply to/from a battery in case off-grid DC application or grid connected. Figure 2.5 indicates a full solar system. Further protection devices are sometimes used such as disconnecting switches and circuit breakers.

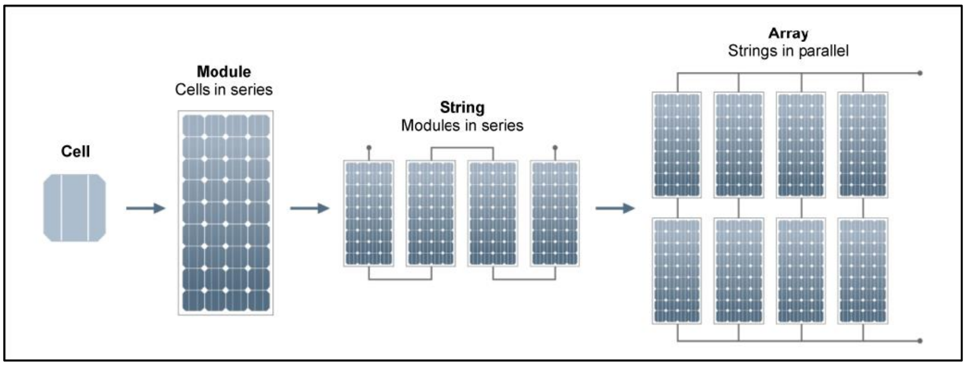


Figure 2.4 Building block of a solar array [15]

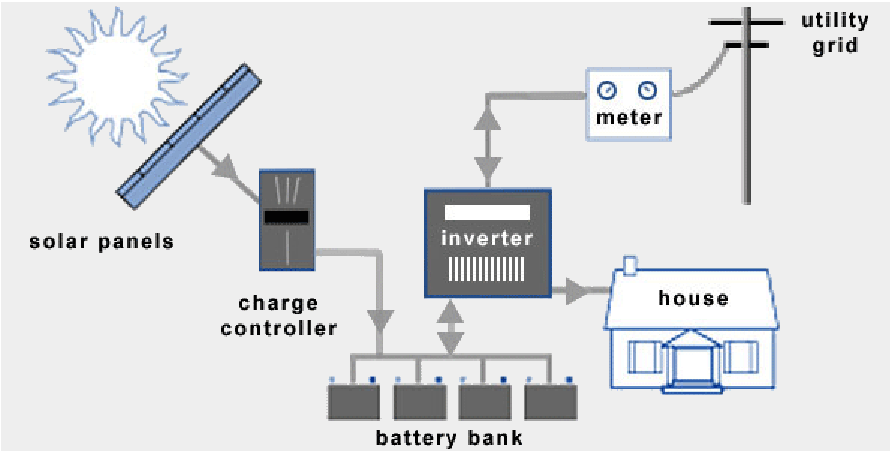


Figure 2.5 Complete Solar PV System [16]

2.4 Background of MPPT

On the I-V curve and power curve as presented in Figure 2.6, PV cells work at a single operating point where they have a specific current (I) and voltage (V). The short circuit current (I_{sc}) is the generated current when the voltage is zero. The open circuit voltage (V_{oc}) is the voltage when the current is zero. Under specific irradiance and temperature, the PV cell works at a maximum power point current (I_{mpp}) and maximum power point voltage (V_{mpp}). The product of I_{mpp} and V_{mpp} is the maximum power (P_{max}). The generated current increases with the increase of irradiance whereas the voltage decreases with the increase of the cell's temperature.

The values of I and V correspond to a particular resistance of the load, which is equal to V / I as specified by Ohm's Law. Conversely, PV cells output maximal power only when they are connected to that particular load resistance. The maximum power point tracking (MPPT) is responsible to find the I_{mpp} and V_{mpp} and constantly adjust the load resistance to that point. Many inverters are equipped with an MPPT device which is a DC-DC converter used to gather current and voltage data through an algorithm. The load resistance is changed by changing the duty cycle ratio of the DC-DC converter until reaching the maximum power point.

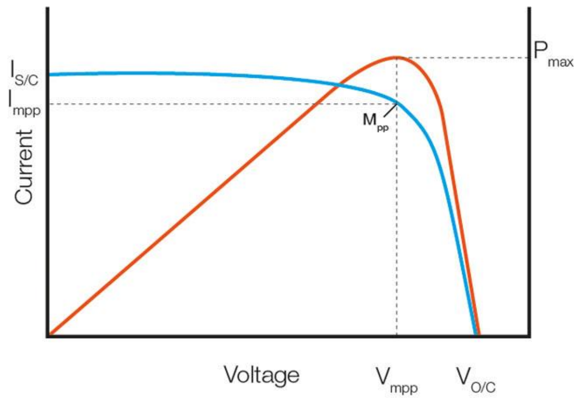


Figure 2.6 IV Curve and Power Curve [17]

2.5 State of the art

2.5.1 Integration Categories

The architectural requirements such as thermal comfort and natural lighting as well as the construction budget will determine the total solar area where the solar panels will be installed. There are three ways of integrating photovoltaic into the built environment explained below.

Building Applied Photovoltaic

Building Applied Photovoltaic (BAPV) adds solar panels on top of the building structure, if BAPV is removed they don't affect the building envelop functionality. It is mostly used on existing buildings. Generation of clean electricity will be the source of savings only [18]. This type of integration can be applied to roof and façade, as demonstrated in Figures 2.7.

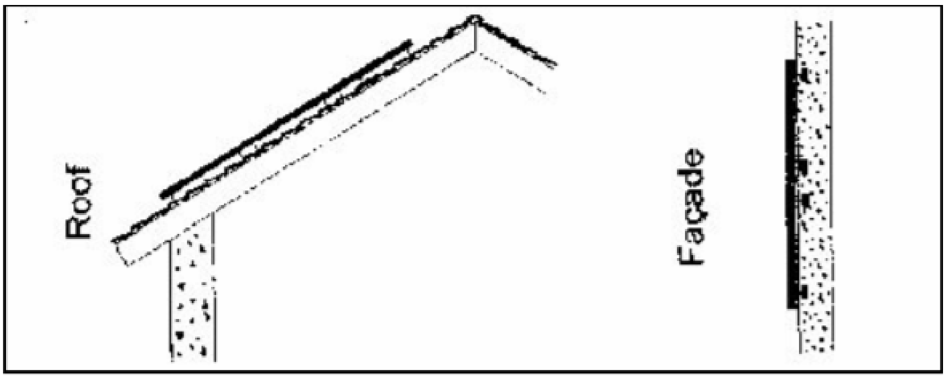


Figure 2.7 BAPV Integration methods [19]

Building Integrated Photovoltaic

Building Integrated Photovoltaic (BIPV) integrate solar panels into the building, they replace construction elements of a building. This integration method is mostly used in new and refurbished buildings where it can be considered during the architectural designing phase. BIPV can serve as a building fabric reducing the overall cost of a building while producing clean electricity and saving on utility bills. The design adds a visual architectural beauty to a building with the possibility of customization.

There are many different names of existing applications in the BIPV industry without a general consensus within the PV community. Therefore, the following naming was found to be the most convenient to be followed in literature. There are 2 integration methods of PV panels to existing and new building envelops [19], [20], [21], [22], [23], and [24]:

BIPV for roofs

- Pitched Roofs

- In-roof mounting systems

This system uses standard modules on sloped roofs where they replace a portion of the tiles with solar modules. An extra foil might be needed to prevent any water leakage (Figure 2.8).

Figure 2.8 In roof BIPV system [25]

- Full-roof solution

The full roof system takes over the entire roof tiles and replaces its functionality. A full roof solution is more aesthetically appealing since appearance homogeneity is considered as an architectural technical challenge. It is also more economical than in-roof system since it utilizes the whole roof area for maximum energy production. Building this type requires having good mechanical durability and water tightness resistance (Figure 2.9).

Figure 2.9 Full-roof BIPV system [26]

- Prefabricated Solar Roofs

From its name, the solar roof is being fabricated off-site to lower the installation cost and save time while maintaining higher accuracy of building the construction element, unlike the full-roof solution where it is installed on-site (Figure 2.10).

Figure 2.10 Prefabricated BIPV roof system [21]

- Solar Tiles

Roof tiles (large sized or small, such as shingles, slates, etc) are replaced with tiles made from plastic, clay or any other substrate deposited with PV laminate. In the meantime, this is considered to be an uneconomical product of the BIPV industry. Every piece of solar tile has its own electrical connection which becomes complex to ensure weatherproof connection with a large number of tiles. An example of such a system with various customizations is shown in Figure 2.11.

Figure 2.11 Solar Tiles [27]

- <u>Flat and curved roofs</u>
- Flexible laminates (BIPV Foil)

Thin and light flexible solar modules such as thin film and OPV are usually used for this application type when crystalline modules can't be applied. This type is categorized under BIPV section because studies show that they have the potential to replace building elements in the future (Figure 2.12).

Figure 2.12 BIPV foil [28]

BIPV for façades

- <u>Curtain wall</u>

The façade wall is covered with cladding elements sometimes called as "warm façade". The material is usually composed of glass and aluminum. This system doesn't have any ventilation gap between the cladding and the building wall. A curtain wall should satisfy all the building requirements such as thermal and noise insulation as well as visual appearance (Figure 2.13).

Figure 2.13 BIPV curtain wall [29]

- <u>Solar glazing and windows</u>

The level of indoor transparency is controlled by the distance between the cells and the type of modules (transparent/translucent). Colored solar panels can be used optionally to provide different light transmittance and aesthetical architecture using C-Si or TFSC technology. It can be applied to windows and façades as well as roofs (Figure 2.14).

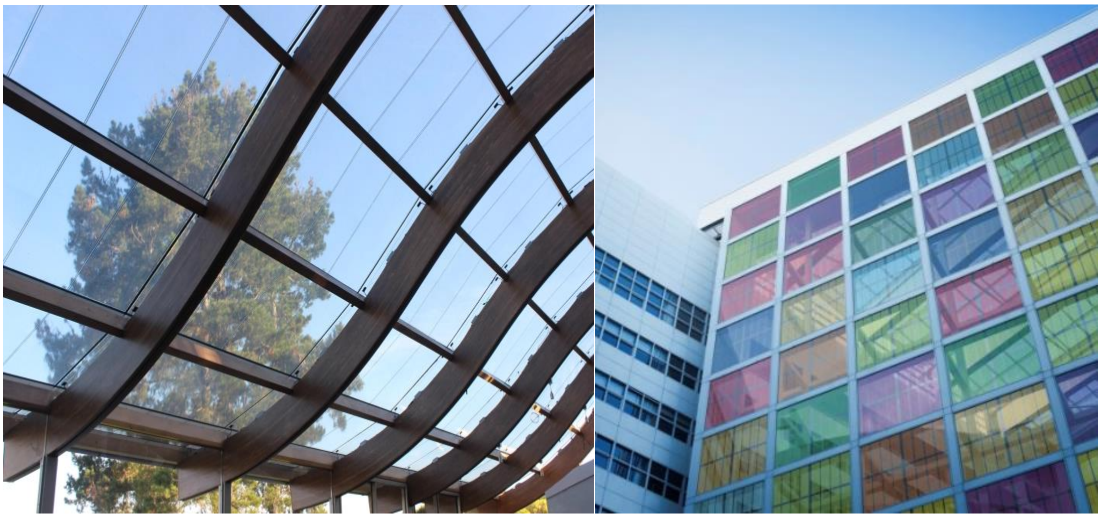


Figure 2.14 On the left showing transparent solar windows [30]. On the right showing glazed windows with various colors [31].

- <u>Accessories</u>

BIPV accessories are shadow devices that are not related to the building skin directly which PV panels can be integrated. Some examples are canopies, balconies, and sunshades. They control the light intensity transmittance while providing clean energy and shade consequently, offering a controlled temperature zone (Figure 2.15).

Figure 2.15 Canopy BIPV on the left [32]. Window blinds BIPV on the right [33]

Building Integrated Photovoltaic Thermal

The building envelop has been used as sun-facing wall (solar wall) application with a various configuration where there is a control of directional heat flow inside the walls. Utilizing this heat will provide indoor thermal comfort [34]. Photovoltaic panels incorporated into a building usually converts 6-18% of the incoming solar energy to electrical energy. The rest is wasted as heat to the surrounding. The wasted heat instead can be converted to useful heat by using a hybrid system called Building Integrated Photovoltaic Thermal (BIPVT). The process as illustrated in Figure 2.16 is done by circulating a coolant fluid in a gap maintained between the solar panels and the building wall. The coolant fluid used is water or air passed behind the PV panel to cool down the panel's temperature which improves the electrical performance significantly. The useful heat gained by the fluid is being used for space heating or domestic hot water (DHW) either by direct means or using a heat pump. This system is sometimes referred to as "cold façade". BIPVT can be adapted to new and existing buildings with various configurations. There are two types of BIPVT, one is an opaque type which can be applied to roofs and walls only. The second is semi-transparent which can be applied to windows, roofs, and walls if there is daylighting or to walls and roofs if it is without daylighting [35].

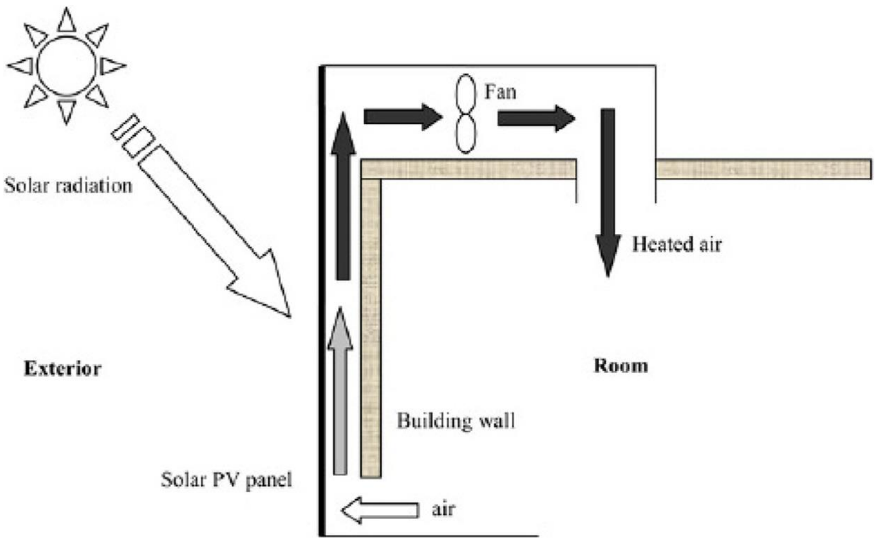


Figure 2.16 PV cooling process in BIPVT [35]

2.5.2 PV modules encapsulation

The traditional solar components used in BIPV technologies as a construction material are standard modules with aluminum frame or frameless modules with laminated glass (commonly used) to provide better mechanical property and avoid grounding the modules saving money and material. C-Si is usually used for building applications with a share of 75% for roof applications and 54% for façade applications. Thin film technology is also becoming popular due to its price and appearance relatively similar to the building outlook used by 15% in roof applications and 8% for façade applications [20].

There are two encapsulation methods for solar panels, as displayed in Figure 2.17 [19]:

- Glass-plastic back sheet. The back sheet is Tedlar can be transparent or translucent. An interlayer sheet usually used called EVA.
- Glass-Glass. The back sheet is replaced with another glass sheet. The interlayer adhesive can be made from resins or EVA.

An experimental study published at the IEEE Journal of Photovoltaics reported that bifacial glass/back sheet solar modules offer more power under standard test conditions (STC) due to scattering the light by the back sheet and reflection. Glass/glass modules, on the other hand, offer more power under outdoor conditions because of the transparency of the back sheet capturing additional diffused irradiance from the rear side because of the albedo collection. The study recommended the glass-glass encapsulation for bifacial solar cells with significant cost reduction benefit over the glass/back sheet encapsulation [36]. Glass/Glass modules have more durability and extreme weather resistance such as high temperature and storms with less Power Induced Degradation problems (PID) compared to glass/back sheet modules. Choosing mono-facial or bifacial modules depends on the installation configuration and light exposure. Customization of modules is possible with different size, shape and cell type to fulfill the building architectural requirement.

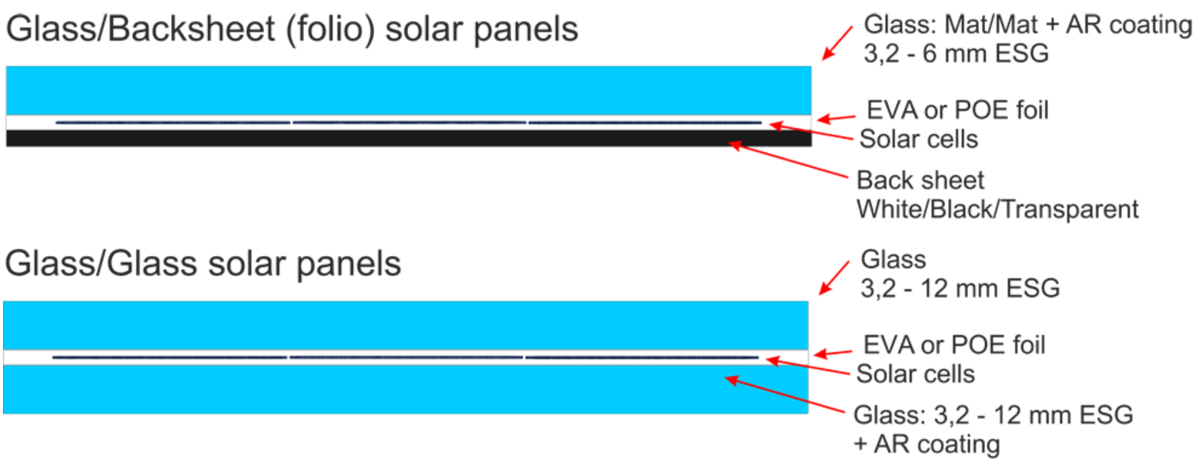


Figure 2.17 Glass/Glass VS Glass/back sheet panels [37]

2.6 ZigZagSolar technology

ZZS is an innovative architectural BIPV façade technology developed by Wallvision BV. It combines energetic and aesthetics in one cladding. Figure 2.18 shows the ZZS applied to façade and balconies.

Figure 2.18: ZonneGevel façade prototype on SEAC facility [38]

ZZS system consists of solar panels tilted at an optimal angle of capturing the direct beam. The solar panels receive extra diffused irradiance from a decorative panel with good reflection properties sometimes called "reflective panel". The overall performance will, therefore, increase depending on the weather condition and the geographical location in addition to the orientation of the façade. A single PV panel combined with an aluminum reflective panel making one ZZS unit called "cassette".

ZZS has the advantage of generating higher power during the early and late time of the day capturing the maximum possible sunlight, especially during winter time.

The PV panels are hidden in such a way not to be visible to the pedestrians as shown in Figure 2.19. Only the aesthetical panels will determine the overall façade outlook, they can be customized according to the architectural design requirements (material, texture, color, logo, etc...) [39].

There are three different PV panel technologies have been tested in a ZZS structure namely: standard C-Si, thin-film (CIGS) and recently glass/glass C-Si.

The ZZS is a grid-connected system connected to the grid of a building. The output from the panels is DC which is converted to useful AC electricity using an inverter. The optimizer (MPPT device) is sometimes used depending on the cost/benefit analysis of a project.

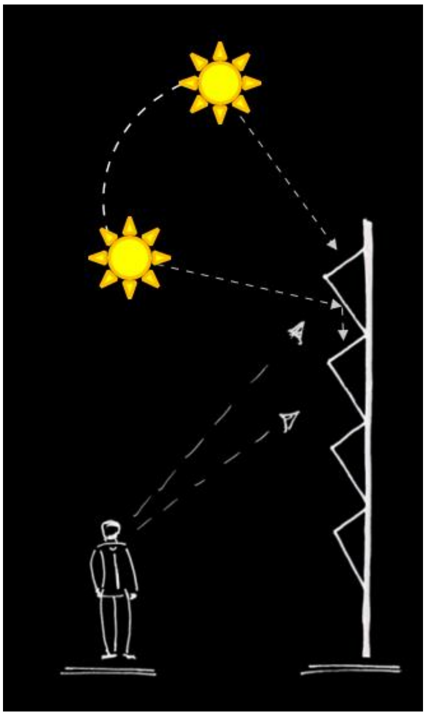


Figure 2.19: Direct and Indirect Irradiance on ZZS PV Panel [40]

Chapter 3 Characterization of ZigZagSolar

Chapter 3 describes in details the performance of ZigZagSolar by analyzing a large scale commercial project named Eisenhower. Additionally, the approach used to examine and troubleshoot the data gathered and the factors affected the yield are also presented.

3.1 System Description

The Eisenhower project is located in the Dutch city of Sittard. The project is so far the largest solar façade in Netherlands which has a capacity of 30.8 kW_p with 308 PV modules installed. The solar modules are special-sized supplied by Metsolar from Lithuanian. Each module is 1.78 meters long and 0.355 meters wide and consists of 22 mono-crystalline silicon cells (2 by 11). Modules are claimed to have rated power of 100 W_p, but flash data indicated peak powers are on average 104 W. The south façade of the apartment building is 35 meters high and 14 meters wide and is cladded with 308 ZZS units (also referred as 'cassettes' as shown in Figure 3.1) distributed among 44 rows (7 panels in each row). Every 3 PV modules in a column are connected in series with one optimizer (model name P300) supplied by SolarEdge, except one optimizer connected with 2 modules at the bottom. About every 26 optimizers are connected to one SolarEdge single-phase inverter (model name SE6000H) of 6000 W rated power. Such a combination of optimizers and inverters is a unique technology of SolarEdge.

PV modules are also installed on the roof of the building for generating power, providing a perfect chance for making the comparison between ZZS and traditional PV. The rooftop array consists of 130 standard-sized PV panels of 300 W_p capacity. Panels are west or east oriented but very low tilted, almost flat. Each panel has one optimizer from SolarEdge. There are 5 inverters of the same type connected to rooftop panels. This comparison will be shown later in Chapter 4.

Figure 3.1: Eisenhower cassette showing the position of 1 module and reflector [40]

Inverters of ZigZagSolar are named in this manner, as shown in Figure 3.4:

- Inverter 240 is connected to 26 optimizers and 78 solar panels, at the top of the façade
- Inverter 239 is connected to 26 optimizers and 78 solar panels, at the middle top of the façade
- Inverter 238 is connected to 25 optimizers and 75 solar panels, at the middle bottom of the façade
- Inverter 237 is connected to 26 optimizers and 77 solar panels, at the bottom of the façade

The process of producing a ZZS cassette starts with the Aluminum Composite Panel (ACP) supplied by Plano Plastics in the Netherlands. The ACP is cut using a laser cutting machine according to the designed customized profiles. The ZZS structure is composed of aluminum fixation, nose profile, and strips. The fixation is used to tighten the PV panel to the cassette and connect the cassette to the upper cassette. The nose profile is the insertion gap of the PV panel to keep it in place. Leaving a small space in the insertion gap was intended in order to allow the PV panel to be removed in case maintenance is needed. In between each two PV panels, there is an aluminum piece called strip to cover the gap between the two panels to avoid the accumulation of dust and water as shown in Figure 3.2. Finally, the ZZS system is hanged on the façade using the hooks provided by the Dutch company Creative Cladding B.V.

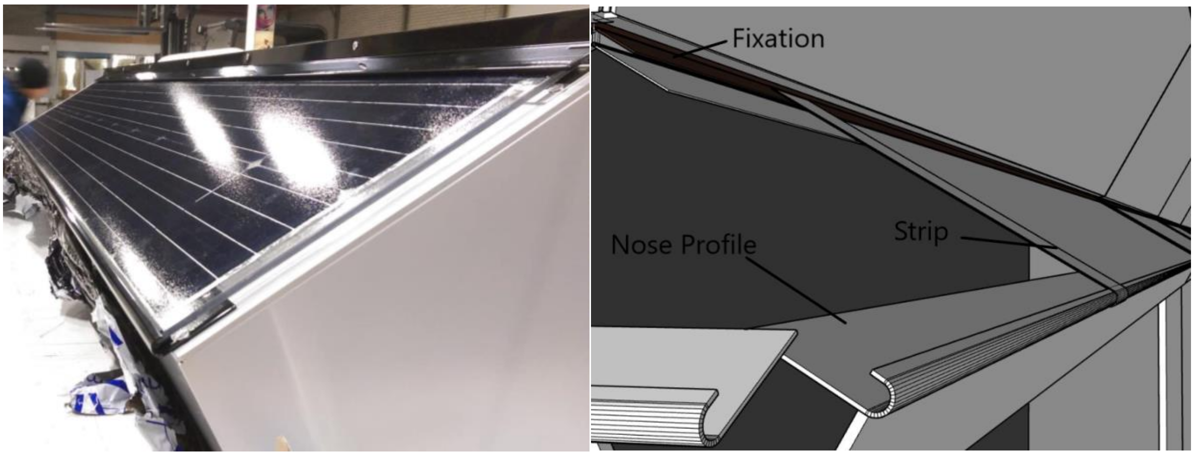


Figure 3.2: On the left shows one complete assembled cassette. On the right shows the position of fixation, nose profile and strip parts in a model.

As illustrated in the satellite view in Figure 3.3, to the west of the apartment building is Eisenhower Park. A smaller garden is in the south. About 10 meters southeast of the building is another apartment building of the same height (referred to as 'adjacent building' below), which may project shadow to the PV array on the façade.

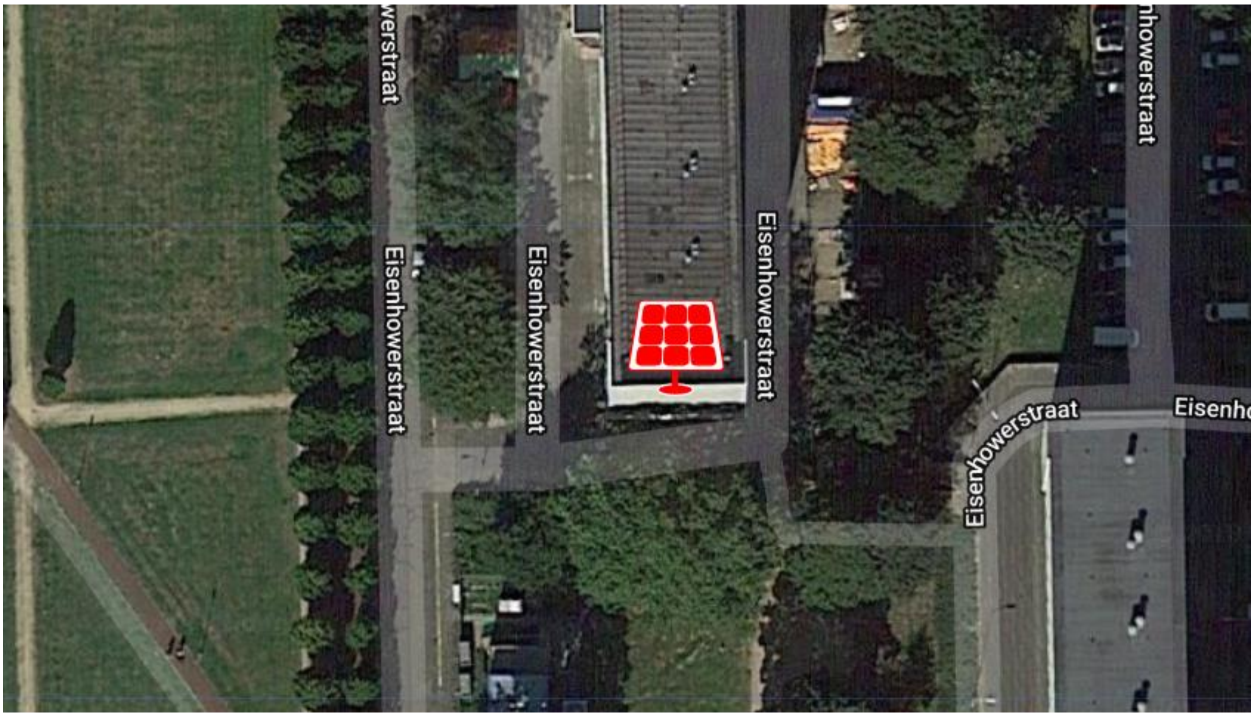


Figure 3.3: Satellite view of Eisenhower and surrounding obstacles

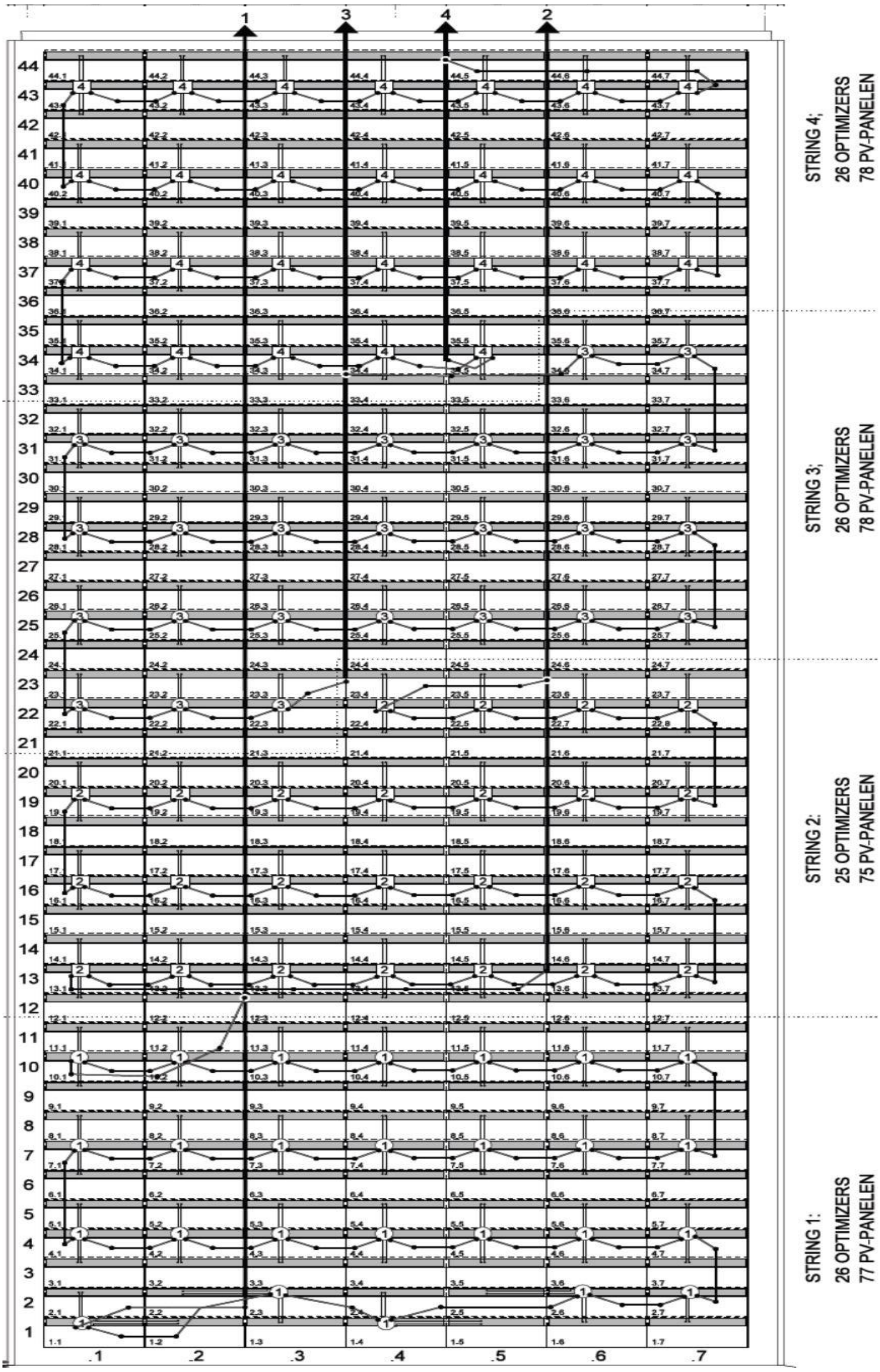


Figure 3.4: Map of inverters and optimizers in Eisenhower project [40]

3.2 SolarEdge Power Optimizer and Inverter

Power optimizers and micro-inverters are called Module-Level Power Electronics (MLPE). They are ideally better than string inverters by optimizing the performance of each module connected to it (reduce the effect of shading, dirt, mismatch, etc.) and monitoring the performance of each module. On the other hand, string inverters only optimize the whole string of modules connected to it.

Unlike micro-inverters and string inverters where MPPT function and DC-AC conversion are combined, SolarEdge has a special typology of power optimizer and inverter which does the job respectively.

The SolarEdge power optimizer is a buck-boost converter with MPPT controller that has two feedback communication loops. Firstly by adjusting the PV module's operating voltage and current to ensure maximal output power. Then, in an independent process, the power optimizer works as a DC-DC converter to increase or decrease the output voltage again. The reason for doing so is the fact that SolarEdge inverter always works at a fixed voltage (e.g. 350 V for SE6000H) to ensure optimal DC-AC conversion efficiency. The following example illustrates the mechanism of SolarEdge typology.

Supposed 10 PV modules of 200 W_p are connected to power optimizers individually as illustrated in Figure 3.5. Under STC conditions, the PV array would generate 2000 W exactly. To maintain 350 V at the inverter, the string should have a current of 2000/350 = 5.7 A. Then each power optimizer should adjust the voltage to 200/5.7 = 35 V. If MPP voltage of the PV module is 32 V, the power optimizer increases the output voltage and decreases the current of the module slightly.

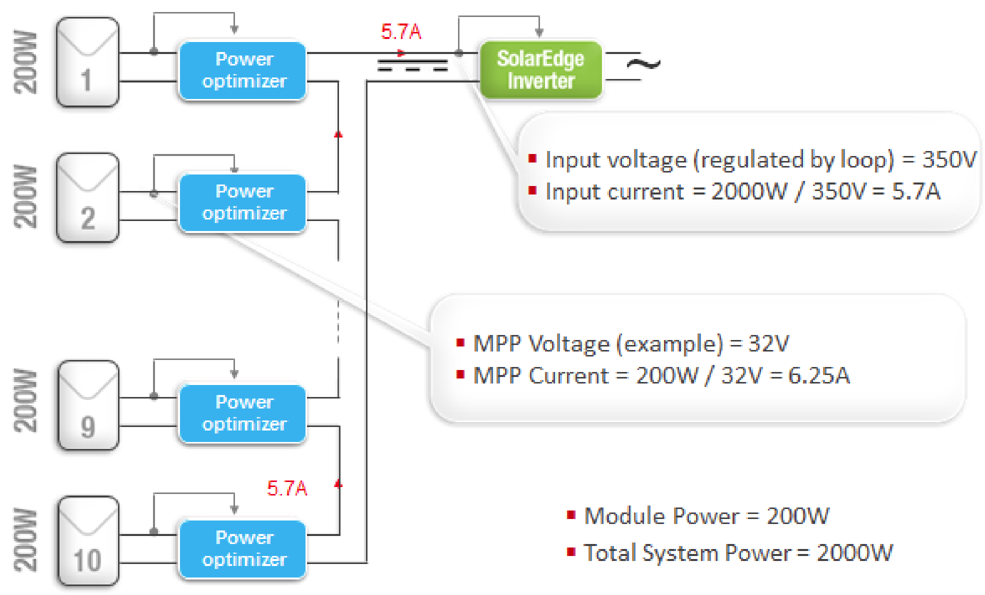


Figure 3.5: SolarEdge power optimizers working under no shading conditions

In a non-ideal situation, as shown in Figure 3.6, where 1 PV module is shaded and only generates 80 W, the string current must be 1880W/350V= 5.37 A to maintain 350 V at the inverter. Then for nonshaded modules, the output voltage is increased from MPP voltage 32 V to 37.2V (200W/5.37A). And for the shaded module, the output voltage is on the contrary reduced to 80/5.37 = 14.9 V from its own MPP voltage say 28 V [41].

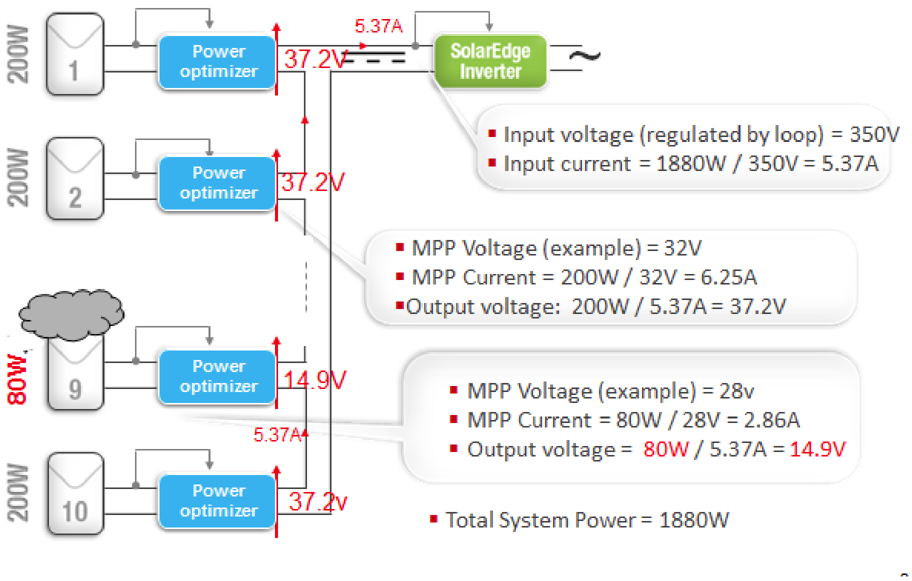


Figure 3.6: Effect of shading on SolarEdge power optimizers

SolarEdge inverters limit the output power to their rated power and drop excessive energy. As confirmed by the official support, SolarEdge optimizer P300 also limits the output to 250 W.

3.3 Herman Solar Power Distributor

In Eisenhower project, solar power goes to Herman Solar Power Distributor (*Herman de Zonnestroomverdeler*) after inverters. The device is supplied by LENS B.V.

Herman's meter function is to measure the electrical consumption and distribute the electricity generated by PV installations to individual households and measure the distribution so that households can be billed accordingly. In Eisenhower project, the investor of PV installation wanted to sell the electricity to the tenants of the building. The investor is the local social housing company (Wonen Limburg) who actually owns the Eisenhower building. The tenants will be charged at the consumer's price which is a different price than selling it to the grid. In case the tenant is not consuming the electricity, they will receive profit from selling it to the grid at the same price of consumption. This is why Herman meter is needed for the project. Herman meter isn't an MPPT or conversion device but distribution and measurement.

Measurements of Herman meter can be used to cross-check SolarEdge's monitoring results.

3.4 Performance Analysis

The analysis of the system has been divided into two main groups, an internal and external comparison in order to have a fair and consistent judgment. Chapter 3 deals with the internal part where the real measurement results of the ZZS system are studied on different time scales. Furthermore, detailed investigations of the potential losses factors are analyzed. In the next chapter, the external comparison will be discussed where the analysis of ZZS against simulation and other solar technologies are presented.

Internal Comparison

a) Data Quality

The Eisenhower project has been running since 18th October 2017 after being commissioned. The performance of PV arrays on both façade and roof are constantly monitored and recorded. However, a portion of data was lost due to technical malfunction of SolarEdge monitor (data acquisition system). Also, inverters were not working for a short period due to inverters break-down.

Available data from inverters started from 18th October 2017 and stopped on 25th September 2018, lasting for 339 days (approximately 11 months). Table 3-1 and Table 3-2 give an overview of data availability. Inverter 240 at top of the façade suffered the most severe operation loss and inverter 237 didn't encounter any operation loss.

Table 3-1: Data availability of inverters and their losses on the façade

Inverter	Data available from	Data available till	Data lost on	% Time operation loss (day/day)	% Energy operation loss (kWh/kWh)
240	28 Oct 2017	25 Sep 2018	18 to 27 Oct 2017 All May 2018 1,2 &3 June 2018	13%	13.5%
239	30 Oct 2017	25 Sep 2018	18 to 29 Oct 2017	3.5%	0.81%
238	29 Oct 2017	25 Sep 2018	18 to 28 Oct 2017	3.2%	0.73%
237	18 Oct 2017	25 Sep 2018	None	None	0%

Table 3-2: Data availability of optimizers and their losses on the façade

Optimizers	Data available from	Data available till	Data lost on	% Time operation loss (day/day)
240.0.1 to 240.0.17	28 Oct 2017	25 Sep 2018	18 to 27 Oct 2017 All May 2018 1,2 &3 June 2018	13%
240.0.18 to 240.0.26	17 Nov 2017	25 Sep 2018	18 to 31 Oct 2017 1 to 16 Nov 2017 All May 2018 1 to 25 June 2018	25%
239.0.1 to 239.0.17	30 Oct 2017	25 Sep 2018	18 to 29 Oct 2017	3.5%
239.0.18 to 239.0.26	17 Nov 2017	25 Sep 2018	18 to 31 Oct 2017 1 to 16 Nov 2017	8.5%
238.1.3; 238.1.4; 238.6 to 238.1.10; 238.1.18	29 Oct 2017	25 Sep 2018	18 to 28 Oct 2017	3.2%
238.1.1; 238.1.2; 238.1.5; 238.1.19 to 238.1.22	17 Nov 2017	25 Sep 2018	18 to 31 Oct 2017 1 to 16 Nov 2017	8.5%
237.1.1 to 237.1.3; 237.1.6; 237.1.8 to 237.1.13; 237.1.17 to 237.1.19; 237.1.22; 237.1.24	18 Oct 2017	25 Sep 2018	None	0%
237.1.4; 237.1.5; 237.1.7; 237.1.14 to 237.1.16; 237.1.20; 237.1.21; 237.1.23; 237.1.25; 237.1.26	17 Nov 2017	25 Sep 2018	18 to 31 Oct 2017 1 to 16 Nov 2017	8.5%

The Herman meter showed higher yield from inverter 237 to 239 than SolarEdge's results except inverter 240 were higher by SolarEdge than Herman. The overall difference between the two measurement devices is about 3.4%.

b) Data Restoration

As shown in the previous section, monitor data that are available so far do not cover a full year, making them unsuitable for commercial presentation since only full-year performance has reference value in the PV industry. Also, a large portion of the data was missing during the period. Therefore, restoration of data is very necessary before they are put into further evaluation. Another existing ZZS system located in SolarBEAT facility in Eindhoven, a city in the northwest of Sittard has been used to interpolate the missing data in Eisenhower. The procedure of restoring the missing data was done as follow:

1. From the Plain of Array (POA) solar irradiance data at SolarBEAT, the performance yield of three ZZS Cassettes (300 W_p) at SolarBEAT was obtained by simple linear regression using least square method according to equation (2), where y is the dependent variable (yield), x is the independent variable (irradiance), b is the y-intercept and m is the slope are determined to minimize the square of residual.

$$y = mx + b \qquad (2)$$

2. Assume that Eisenhower & SolarBEAT are proportional since the monthly Global Horizontal Irradiance (GHI) difference between the two sites is 2.5% using the Photovoltaic Geographical Information System (PVGIS), a tool developed by the European Commission [47]. Note that both ZZS systems have the same module specification and tilt.
3. Calculate the yield of Eisenhower for the missing time period. For the inverter, it was possible to substitute on a daily level because there was not many data to be restored. Whereas the optimizer is restored on a monthly level since there are 103 optimizers which require a lot of time.
4. Synthetic data are created for the period from October 2017 to the starting date of each inverter and optimizer. The months of May and June were restored for inverter 240 and Optimizer 240. The last few days of September 2018 has been restored as well for all the inverters and optimizers.

The data presented in Table 3-3 are full-year electricity production data on the AC and DC sides without voids unless otherwise noted.

Table 3-3: Compensated yearly data of all optimizers and inverters

	Optimizer DC (kWh)				Inverter AC (kWh)			
Month	**240**	**239**	**238**	**237**	**240**	**239**	**238**	**237**
Oct	418	401	379	273	408	391	369	262
Nov	255	244	231	167	248	238	225	160
Dec	85	81	72	63	83	78	68	60
Jan	199	190	171	149	192	185	165	142
Feb	621	636	577	532	603	615	553	507
Mar	561	548	506	480	544	530	484	457
Apr	809	794	733	695	781	769	703	663
May	1047	1008	948	909	1010	964	901	859
Jun	716	676	634	613	720	698	649	622
Jul	977	979	921	894	939	944	884	852
Aug	939	919	857	806	908	892	824	771
Sep	701	673	612	566	680	653	588	541

c) Overview of Results

The ZZS yield results were expected to be 31860 kWh/11 months according to results of computer simulation performed by the company using MATLAB (Xin Xu, personal communication, October 15, 2018), with an overall specific yield (defined as the ratio of produced electricity to the installed capacity) of 1.03 kWh/W_p (for whole year 36615 kWh with estimated specific yield shall be 1.19 kWh/W_p). The simulation will be discussed in further details in the next chapter. The real measurement results without any compensation of missing data were 24951 kWh/11 months, with an overall specific yield of 0.81 kWh/W_p. If all the missing data were substituted, the yield would be about 27264 kWh/year, with an overall specific yield of 0.87 kWh/W_p. Table 3-4 summarizes the electrical production of one year and the expected total deviation.

Table 3-4: Eisenhower simulation and measurement yearly results

Simulation results		Measurement results		Deviation
(kWh/year)	(kWh/W_p)	(kWh/year)	(kWh/W_p)	(%)
36615	1.19	27264	0.89	25.5

Apart from the poor data quality that caused energy production loss, the difference between expectation and reality in energy yield could be from some other sources:

1- Clipping effect of the inverters and the optimizers.
2- Malfunction of the optimizers and connection/communication losses.
3- Shading effect.
4- Efficiency of the inverters.
5- Inaccurate input parameters to simulation program
6- DC cable losses.
7- SolarEdge data precision.

Following in the thesis, whenever it is mentioned “yearly” analysis it refers to 12 months with the compensated operation loss unless stated otherwise.

d) Shading Effect

Yearly Data

In order to study the shading effects, the right, middle and left vertical columns of cassettes are taken out for analysis. The optimizers in Figure 3.7 are ordered by descending order from top to bottom. The reason why the first or second top optimizers (belonging to inverter 240) have even less energy yield than lower ones, which should have more, was thought that inverter 240 was not working in May 2017 and on some days of June. The actual reasoning behind it is that data of some hours on days when the daily sum was available were lost for inverter 240. This makes the first optimizer perform worse than the lower ones even after compensating their energy operation loss. Therefore the 2nd highest optimizer is set as a reference of 100%. One can notice how the results are declining from the top towards the bottom optimizer. Yield measurements are not strictly descending in Figure 3.7, which is just caused by measurement error (data acquisition). According to a technical note published by Solar Edge [42], they reported that their hardware has an accuracy of ±2% whereas the energy measurement which is calculated indirectly has an accuracy of ±5%.

The total shading loss is estimated by the difference between the total actual electrical production compared with the product of the top row of optimizer by the number of rows , resulting in 11% energy losses per year. From Figure 3.7, it can be seen that higher rows are less influenced than lower rows because higher rows have a better view of the sky. Also, left columns are less influenced than the right columns, because the adjacent building is on the right (southeast). Therefore, the highest energy production is located in the top left part of the building and the lowest energy production is at the extreme bottom right side of the building.

Left	Middle	Right
297	267	271
312	284	278
293	278	284
277	279	263
290	268	261
262	262	268
288	266	256
271	262	254
283	263	266
259	258	246
260	248	238
262	247	239
238	234	235

High Yield — Low Yield

a)

Left	Middle	Right
4.6	6.0	4.5
0.0	0.0	2.0
5.9	2.0	0.0
11.0	1.6	7.3
6.9	5.7	8.3
15.9	7.8	5.9
7.7	6.4	9.9
13.0	7.8	10.6
9.1	7.4	6.5
17.1	9.2	13.3
16.7	12.6	16.1
16.0	12.9	15.9
23.6	17.6	17.1

Small Losses — High Losses

b)

Figure 3.7: a) Heat map of the 3 columns of optimizers representing the yield in kWh. b) Heat map of the 3 columns of optimizers showing the kWh losses in percentage.

Monthly Data

The optimizers from the middle column have been analyzed on monthly basis to see the seasonal variation effect on the yield as we go from optimizer in the top row (240.0.9) to optimizer in the bottom row (237.1.18). From Figure 3.8, it can be noticed that the difference between the top row and lowest row is small in spring and winter because the sun is in a lower position in winter and therefore the top row is easier to be blocked by the adjacent building.

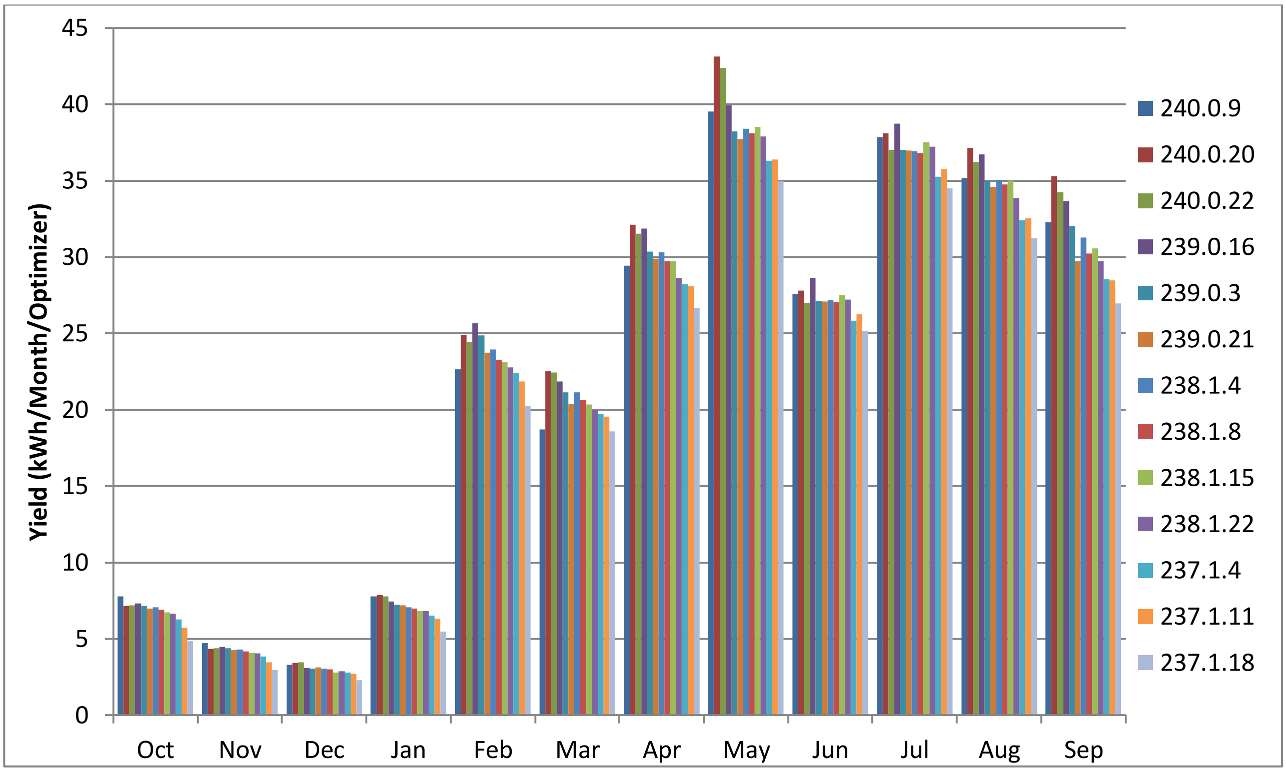


Figure 3.8: Monthly yield of the middle column of optimizers

In summer, there is less shading from the adjacent building but less reflection from the decorative panel. In winter, the effect of reflection is more but also more shade from the adjacent building.

Daily and Hourly Data

Figure 3.9 shows the electricity produced by the middle vertical column of optimizers on 4 sunny days in the year. As we go from left to right (highest to lowest optimizers), the yield decrease. The reduction in yield was higher during winter and spring than summer (flatter pattern). This coincides the conclusion from monthly data. The reason those dates are presented is that the period did not encounter any operation loss. Similarly, autumn was not presented since it has flaw data.

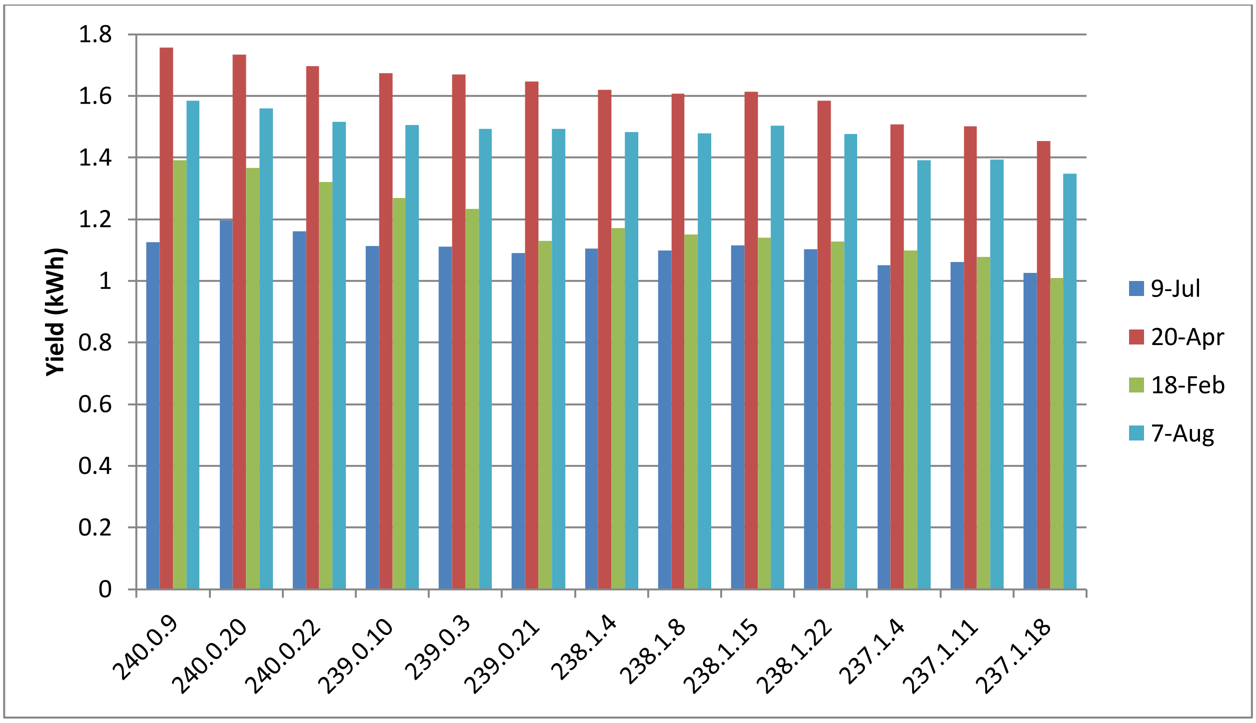
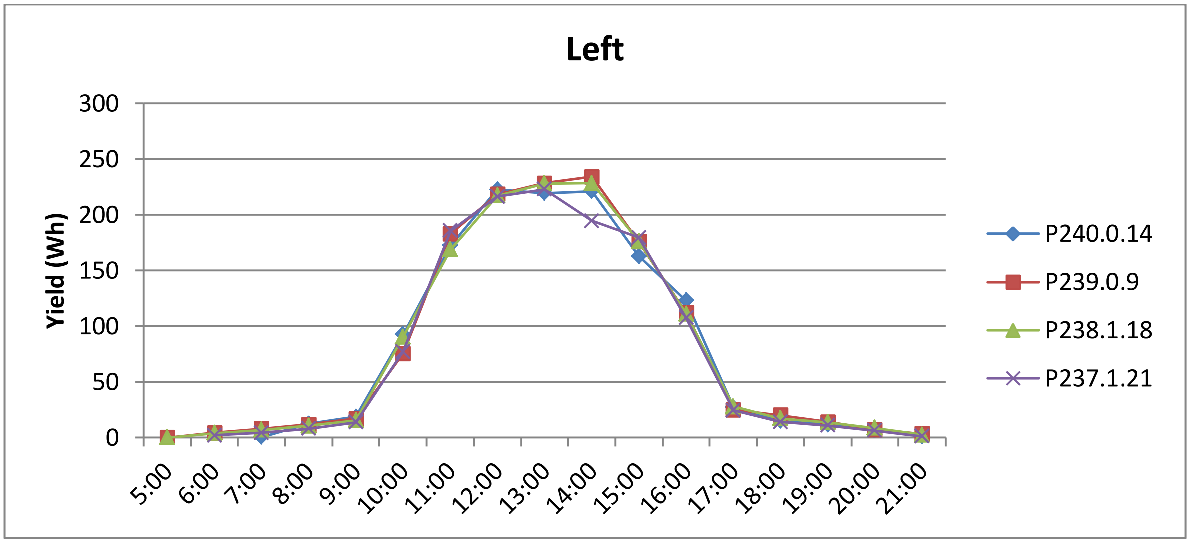


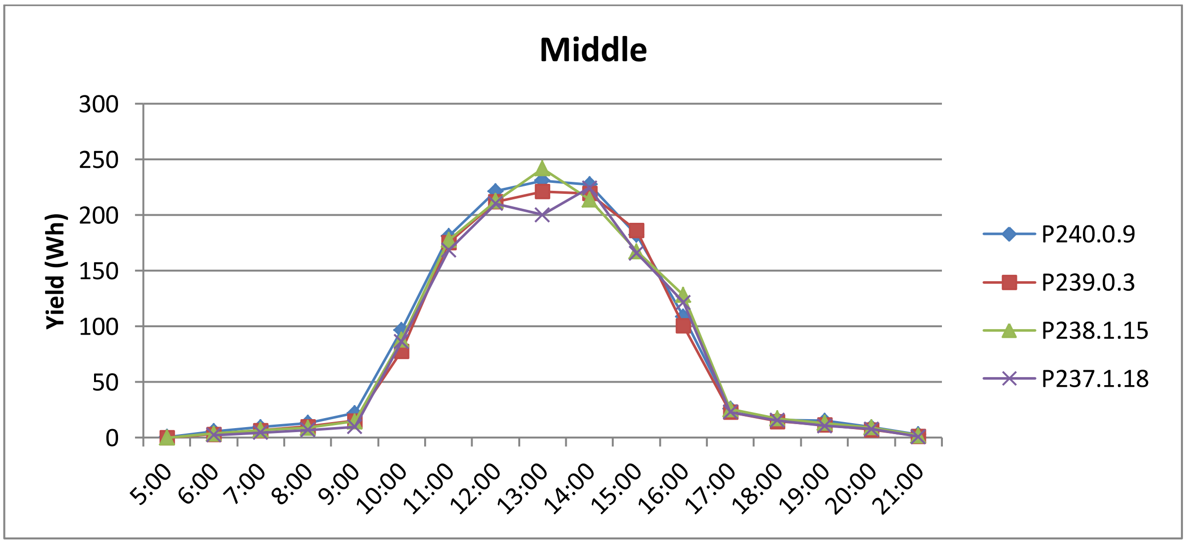
Figure 3.9: Daily yield on selected sunny days of the middle column of optimizers

Studying the optimizers yield on hourly basis required analyzing four optimizers selected from the left, middle and right columns to show the change of yield throughout the sunny days of 29 June and 23 February on an hourly basis. Some interesting pattern can be noticed from Figure 3.10 and Figure 3.11, hence that the lines connecting the points in the figures don't represent value but rather to help reading the graphs:

1. Though sunrise took place at around 5 AM in summer, the façade is completely shaded until about 9 AM because the sun was behind the façade.
2. Similarly, from about 5 PM the façade is completely shaded again.
3. In summer, the sun rises to high altitude in a short time so the effect of the adjacent building is not obvious.
4. On a winter morning, left and top optimizers firstly get unshaded ahead of right and bottom ones, making lines in Figures 8 a) to Figure 8 c) separate from each other on the left of the graphs.
5. On summer and winter afternoon, lines are concentrated because there's no source of shading in the west of the façade.



a)



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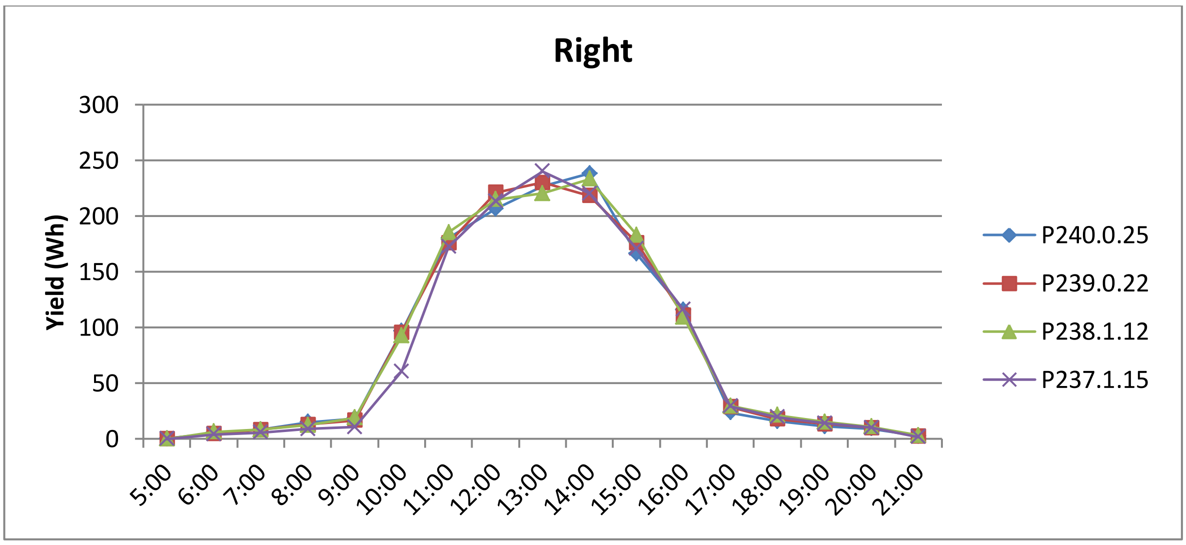
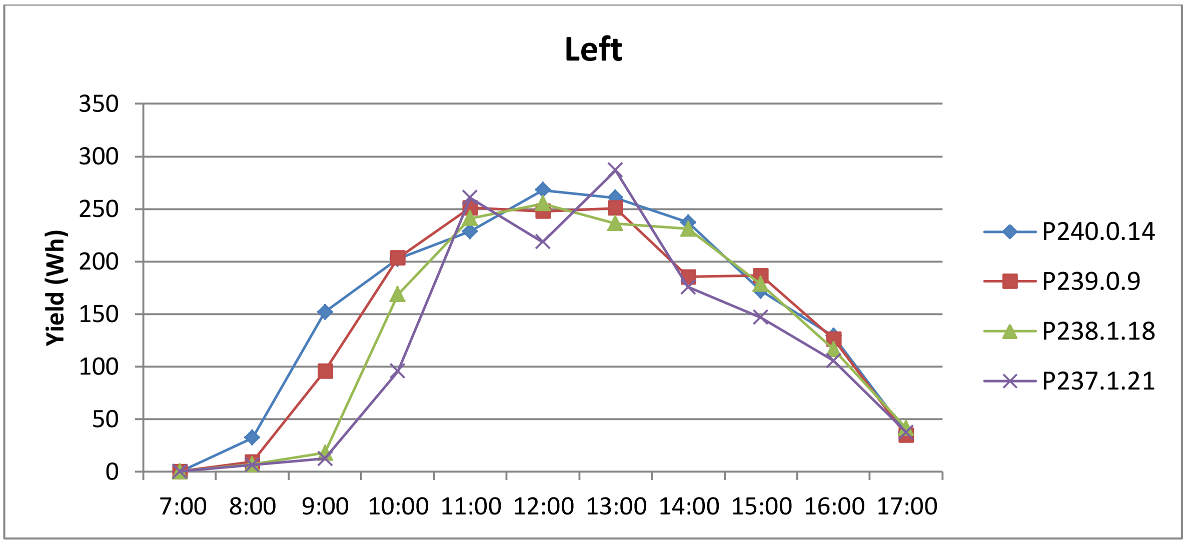
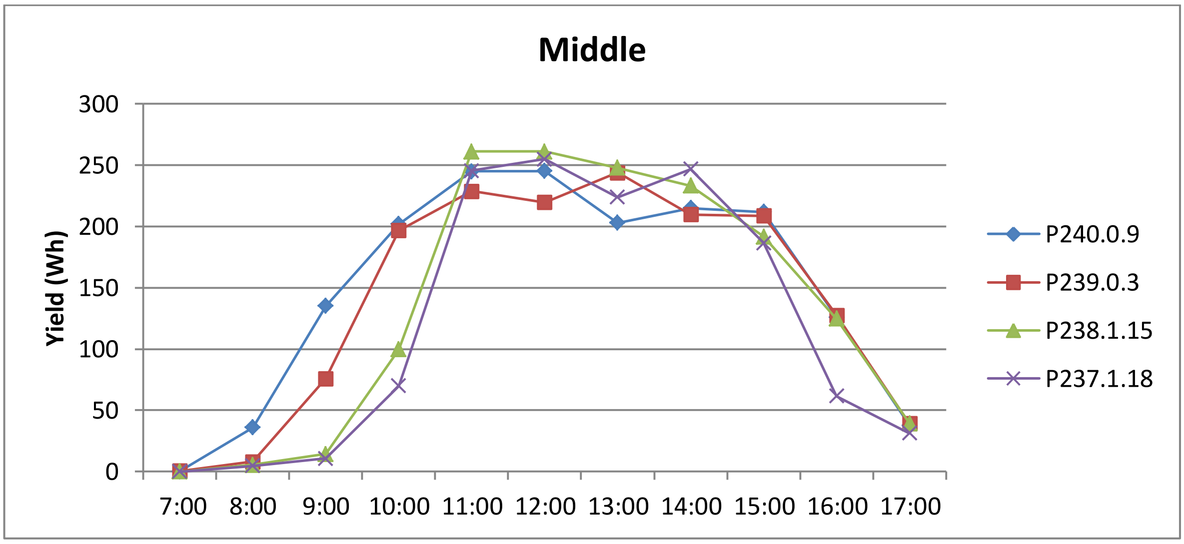


c)

Figure 3.10: Hourly yield of optimizers on 29 June. a) Left Column b) Middle Column c) Right Column



a)



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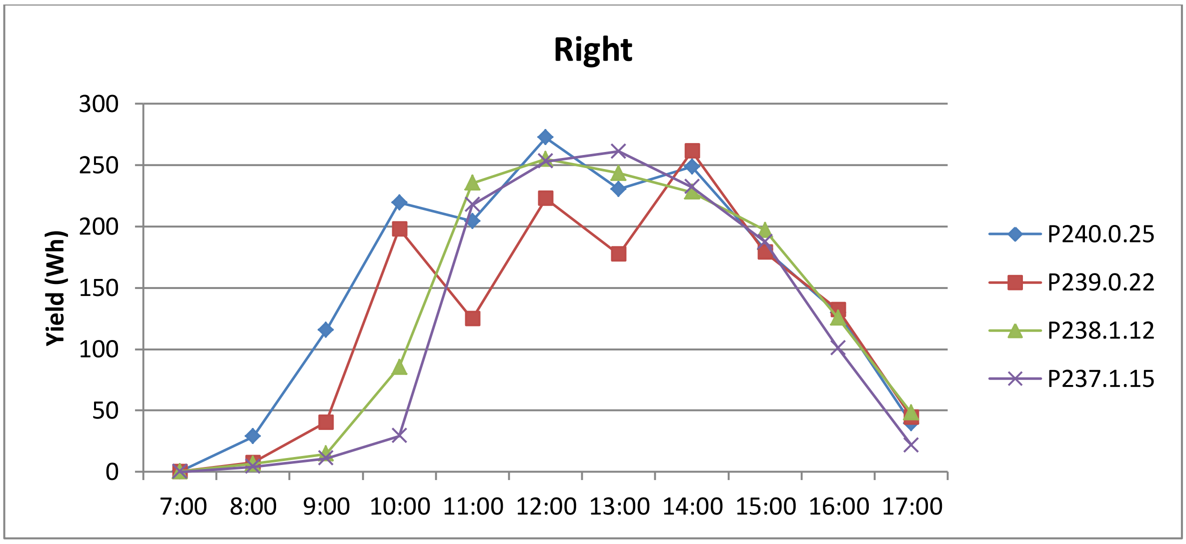


c)

Figure 3.11: Hourly yield of optimizers on 23 February. a) Left Column b) Middle Column c) Right Column.

e) Inverter Efficiency

The efficiency of the inverter depends heavily on the input DC power in relation to the inverter's rated power. Normally, the inverter operates close to the rated DC input power. The efficiency starts to decrease when it is below 20% of the DC rated power. Inverters also have a self-protection mechanism called clipping, in which inverters limit the output power to the rated power in case input DC power exceeds the maximum allowable limit.

In Eisenhower project, optimizers are right sized by matching 300 W_p of PV modules with one optimizer of 300 W. But inverters, which have 6 kW, are oversized:

- Inverter 240 is 30% oversized
- Inverter 239 is 30% oversized
- Inverter 238 is 25% oversized
- Inverter 237 is 28% oversized

Therefore, inverters in Eisenhower project are likely to clip. SolarEdge's optimizers and inverters record and monitor data independently, providing an approach to analyze clipping.

Yearly Data

Table 3-5: Yearly inverter efficiency and yield losses

	Inverter 240	Inverter 239	Inverter 238	Inverter 237
Inverter AC output (kWh)	7117	6958	6412	5894
Optimizer DC output (kWh)	7327	7150	6641	6148
Losses (kWh)	210	192	229	253
Losses (%)	2.9	2.7	3.4	4.1
Inverter Efficiency (%)	97.1	97.3	96.6	95.9

Optimizers 240.0.1 to 240.0.17 stopped data recording for about 44 days and 240.0.18 to 240.0.26 stopped for about 85 days, while the inverter's data logging functioned well, making DC input less than reality. Consequently, data were compensated and efficiency was recalculated as shown in Table 3-5.

From Table 3-5 it can be deduced that the shown energy losses are a combination of clipping effect and conversion efficiency process of the inverter. The energy losses are larger for the lower inverters of Eisenhower because the DC input power is the lowest and therefore the efficiency is the lowest since it is highly dependent on the rated input power.

According to SolarEdge datasheet of inverter SE6000H, the inverter has an average efficiency of 99.25%. Consequently, the inverter efficiency losses due to conversion from AC to DC can be estimated in a reliable way. The estimated loss is around 201 kWh/ year.

Monthly Data

Table 3-6: Monthly inverter efficiency and yield losses

	Inverter 240		Inverter 239		Inverter 238		Inverter 237	
	Efficiency (%)	kWh losses (%)	Efficiency (%)	kWh losses (%)	Efficiency (%)	kWh losses (%)	Efficiency (%)	kWh losses (%)
Oct	97.6	2.4	97.5	2.5	97.4	2.6	96.0	4.0
Nov	97.3	2.7	97.5	2.5	97.4	2.6	95.8	4.2
Dec	97.6	2.4	96.3	3.7	94.4	5.6	95.2	4.8
Jan	96.5	3.5	97.4	2.6	96.5	3.5	95.3	4.7
Feb	97.1	2.9	96.7	3.3	95.8	4.2	95.3	4.7
Mar	97.0	3.0	96.7	3.3	95.7	4.3	95.2	4.8
Apr	96.5	3.5	96.9	3.1	95.9	4.1	95.4	4.6
May	96.5	3.5	95.6	4.4	95.0	5.0	94.5	5.5
Jun	100.6	-0.6	103.3	-3.3	102.4	-2.4	101.5	-1.5
Jul	96.1	3.9	96.4	3.6	96.0	4.0	95.3	4.7
Aug	96.7	3.3	97.1	2.9	96.1	3.9	95.7	4.3
Sep	97.0	3.0	97.0	3.0	96.1	3.9	95.6	4.4

Table 3-6 shows the efficiency and energy losses for each inverter on a monthly basis. It can be noticed that the monthly results confirm the yearly results. However, June has shown efficiency above 100% even after substituting the missing data of both the inverter and the optimizer, this is due to data loss (data acquisition) by optimizers on an hourly level making it seems less than the inverter output. In other words, the internal feedback loop between the optimizers and inverters wasn't functioning properly. Although optimizers 237,238 and 239 has no lost data in June, their DC measurements are always less than AC. Optimizer 240 has missing data in June but even after data restoration, the DC was still less than AC.

Daily Data

As stated earlier, inverters have lower conversion efficiency when DC input power is less than 20% of the rated power. This is visible on the plots of efficiency in Figure 3.12 (calculated by dividing AC output from inverter by DC input from optimizers) VS DC input powers.

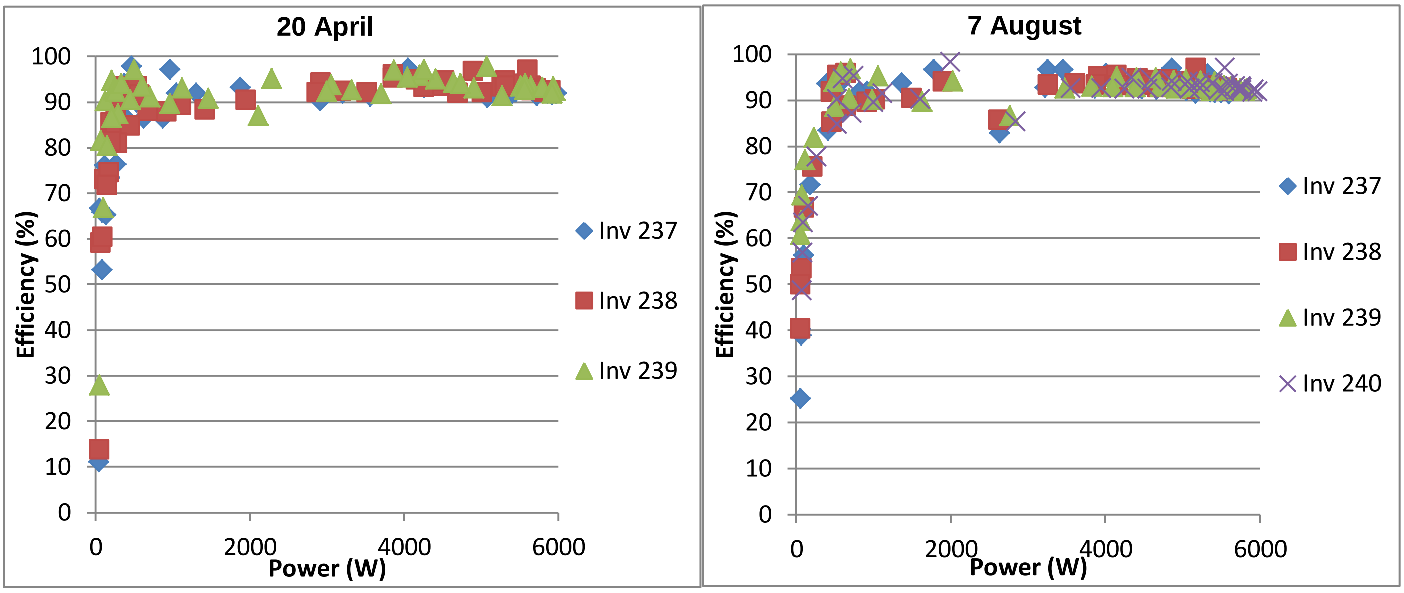


Figure 3.12: Inverter Efficiency on a daily level on two selected days

f) Inverter Clipping

The clipping of the inverter occurred more frequently in spring than in summer according to the statistics of clipped energy. In summer, there is indeed more sunshine, but in spring the decorative reflector is more effective due to optimal incident angles on the PV panels which resulted in more intense POA irradiance.

The DC/AC ratio is defined according to SolarEdge as the ratio of installed array STC DC capacity in Watts to the maximum inverter AC capacity in Watts as illustrated in equation (3) where $P_{AC,max}$ is the nominal or rated power of the inverter.

$$\frac{DC}{AC}\,oversizing(\%) = \frac{P_{DC}\,(STC)}{P_{AC,max}} * 100\% \qquad (3)$$

The system in Eisenhower has DC/AC ratio of 1.28 which resulted in losses around 885 kWh (about 3% losses of the total energy produced) for the 4 inverters during the operation period. If the inverters were replaced with a bigger capacity inverter (such as SE7600H), the DC/AC ratio would be 1.01 leading to significant reduction of losses. Therefore, the extra €800 investment (€200 per inverter) is essential since 885 kWh would worth €185, which means the payback period of the extra upfront cost is about 4.3 years.

As we already know the total amount of energy lost due to the inverter and we found out the losses due to the inverter efficiency in section e, this in turn, led us to calculate the clipping losses by subtracting the total inverter losses from the inverter efficiency losses providing us a reliable approach to evaluate clipping.

Figure 3.13 and Figure 3.14 show the clipping effect during a day for all the inverters in February and May. The phenomena can be understood by observing the string DC input how they exceed the limit of 6 kW while the inverter AC output is flattened below the maximum allowable limit.

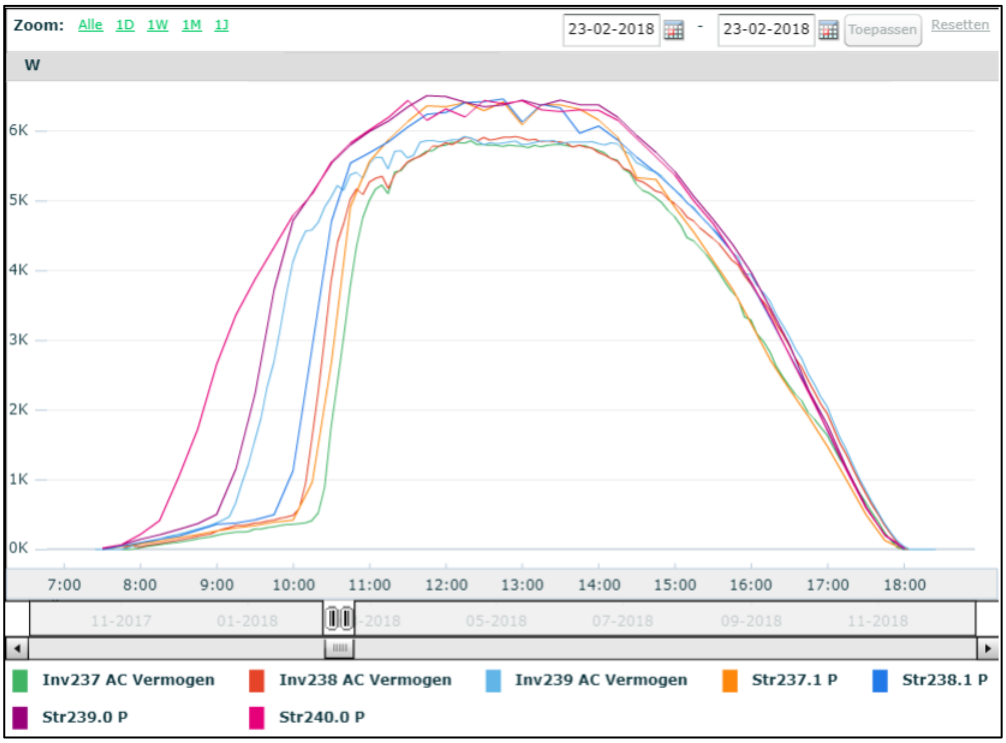


Figure 3.13: Inverter clipping during winter

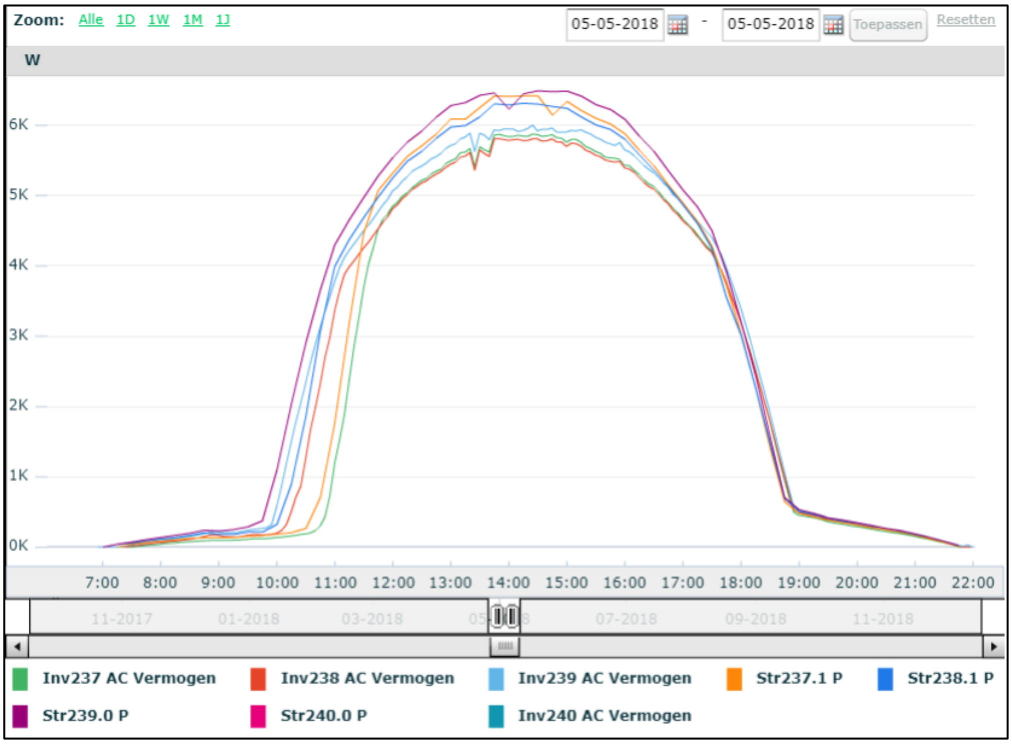


Figure 3.14: Inverter clipping during spring

g) Cable Loss

MPPT ensures PV panels (almost) always operate at peak power point regardless of the loads they are connected to. But some energy may be dissipated as heat on cables due to Joule effect. In this section, the energy loss on the cable is evaluated.

In Eisenhower project, solar power goes through 4 segments of cables until the end user, which are:

1. Solar DC cable (MC4 cable) from PV module's junction box to power optimizer
2. DC string cable from power optimizer to the inverter
3. AC cable from the inverter to Herman meter
4. AC cable from Herman meter to end users

Power optimizers are close to modules, so segment can be neglected for shortness. Segment 3 is also extremely short as Herman meter and inverters are placed in the same place. Segment 4 is insignificant because Herman meter is the end point where solar power is measured and thereby billed. All the loss after Herman meter is paid by users. Therefore, only segment 2 is worth analyzing.

The resistance of cables is usually expressed in Ohm per kilometer of length. SolarEdge required DC wire of at least 4 mm^2 cross-section area (11 AWG). Copper wire typically has a resistance of 4.13 Ω/km [43]. The exact length of cable for every inverter in Eisenhower project is unknown, so 0.1 km is assumed, which has 0.413 Ω resistance. The voltage drop across DC cable is firstly evaluated according to Ohm's law using the average current value, and based on that the power loss is found. According to the climatic weather data [44], the number of sun hours on average is 1604 hours for 305 days in the city of Sittard where the installation is located. As a result, the estimated amount of yield lost across the cables is 305 kWh.

h) Total Losses Summary

The energy operation loss is 8.4%. If one considers adding all the other energy losses and retrieve the missing data to the actual measured output from all the inverters, the yield would be around 31453 kWh/year, with a specific yield of 1.02 kWh/W_p.

The pie chart in Figure 3.15 displays the share of each energy loss source per year. The major loss source is the shading effect which is responsible for about half of the losses (11%). At the second-ranking come the operation losses contributing to 8.4 % of the total losses. The inverter clipping, which has a smaller share than the previous two sources, is responsible for 2.25%. The smallest loss sources are cable losses and inverter efficiency with 1.14% and 0.75%, respectively.

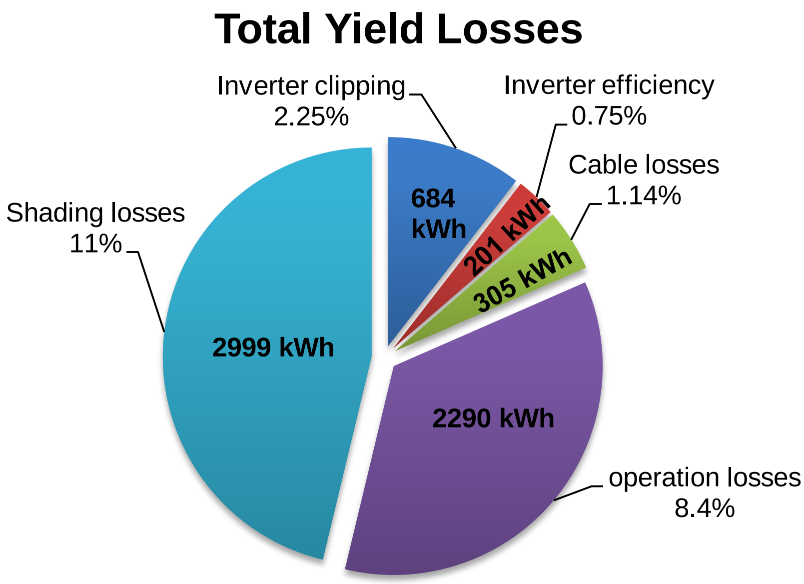


Figure 3.15: Electrical generation and percentage share of yield losses for each source

Chapter 4 External Comparison

Chapter 4 describes the potential of ZigZagSolar experimentally among two main competitive solar technologies in the market namely rooftop and vertical solar systems. The measurement results of ZZS in Eisenhower are put into comparison against the company’s simulation results. In the end, a simulation study is presented to test the three main solar technologies in competitor simulation software.

4.1 Eisenhower project

4.1.1 ZZS Simulation VS Measurement

The company has developed a dedicated simulation tool for its ZZS system using MATLAB. Currently, there is no commercial simulation tool that allows simulating a complex system such as ZZS. A potential simulation tool that is still under development will be shown later in the thesis. The ZZS yield results were expected to be 36615 kWh/year (Xin Xu, personal communication, October 15, 2018). The real measurement results were different 27264 KWh/year, note that the compensated data was used in the analysis. By comparing the simulation results with the real measurements of Eisenhower, the difference is around 25.5%.

From Figure 4.1, it can be seen that the simulation fails most during spring and summer seasons whereas it has reasonable convergence during winter and autumn.

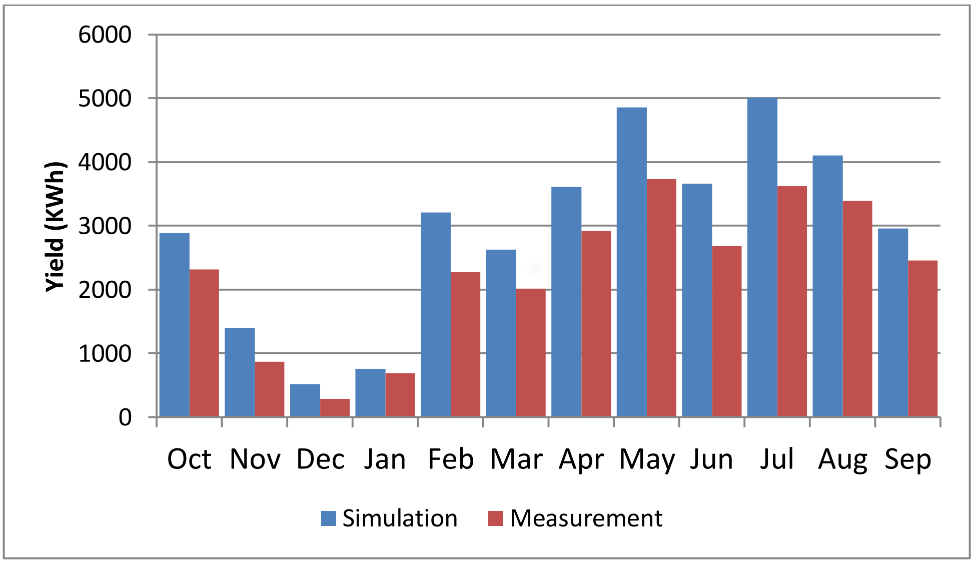


Figure 4.1: ZZS Simulation VS Measurement

The reason behind this seasonal deviation is because the inverter loss was higher in spring/summer than winter/autumn and the clipping occurred mostly in spring. Additionally, the data acquisition loss on hourly level from the power optimizer was more in summer and spring according to the SolarEdge monitoring platform. The simulation didn't account for the shading effect from the adjacent building which affected the results significantly. The reflectivity of the decorative panel is inaccurate since the reflection model used is a simplified model into a specular component and an isotropic diffuse component. The diffuse component, which is the important component, is different for each surface (different angle of reflection). Furthermore, there are other input parameters to the model that are inaccurate such as the variance of the PV module's performance under outdoor conditions. The irradiance data used in the simulation were obtained from the SolarBEAT weather station in Eindhoven. The monthly GHI irradiance difference between the setup location and the weather station location is around 1% using PVGIS [47]. Table 4-1 shows that the top part (240) of the ZZS has a smaller difference compared to the lower parts since they are affected by the horizon and bigger shading effect from the neighboring building. The measured difference between the top and bottom inverter is 14.8% which matches the shading results from the optimizers as discussed in the shading effect section.

Table 4-1: Simulation and measurement difference for each ZZS inverter

Inverter #	237	238	239	240
Simulation (KWh)	9155	8916	9272	9272
Measurement (KWh)	6210	6607	7152	7295
Difference %	32.2	25.9	22.9	21.3

4.1.2 Experimental comparison Rooftop VS ZZS

The purpose of having this comparison is to present which technology is more commercially attractive. For instance, when a client would like to install a solar system but he doesn't know which one to choose. Here comes the advantage of cladding with ZZS on buildings with large façade area where the rooftop area is small and not enough space. It is important to mention that the capacity of both systems is different (around 9 kW_p extra for rooftop). Additionally, the orientation of the rooftop is east-west oriented with a tilt angle of 15º whereas the ZZS tilt is 32º, as shown in Figure 4.2. Therefore, this kind of comparison is to showcase both applications to see how would be their performance. The analysis didn't take into account the compensated data since the rooftop data can't be restored as we don't have access to it.

Figure 4.2: Rooftop and ZZS in Eisenhower [40]

Yearly and Monthly Data

Figure 4.3 shows the measured yield of ZZS compared to the rooftop in individual months. Inverter 237 to 240 (left 4 bars in each month) are for ZZS and from 241 to 245 (right 4 bars in each month) are for the rooftop. As expected, the ZZS is better than rooftop during winter and autumn whereas rooftop is better during spring and summer. Counter-intuitively, ZZS was expected to be better than the rooftop in spring. This is because the sun path profile in spring has higher altitude which is close to summer's altitude. As a result, due to seasonal variation more diffused light is collected by the rooftop making it higher than ZZS in spring. Even though rooftop has extra installed capacity than ZZS, the ZZS performed better in winter and autumn than rooftop.

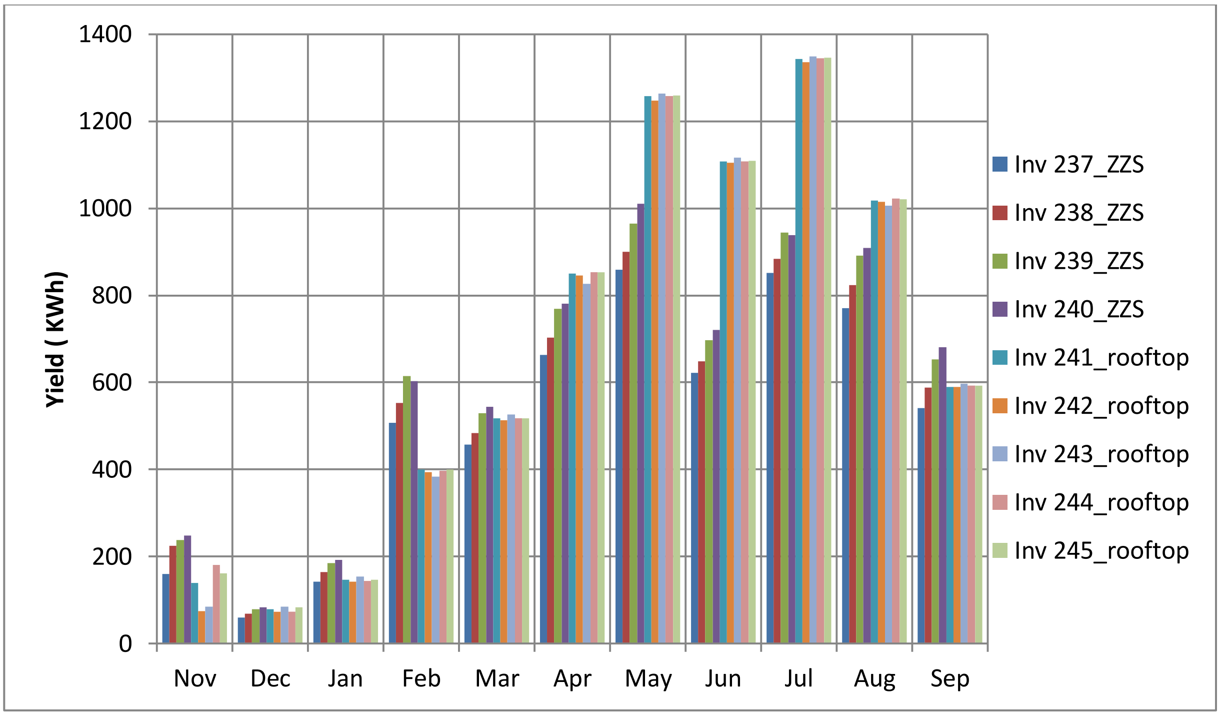


Figure 4.3: Monthly Yield (unrestored data) of ZZS and rooftop System

Figure 4.4 shows the specific yield of ZZS and rooftop. The ZZS is competitive with the rooftop with an average specific yield difference of 0.16 kWh/W_p. ZZS showed different kWh/W_p depending on positions of the inverter, ranging from 0.73 kWh/W_p to 0.86 kWh/W_p whereas the rooftop has almost similar rates for all the inverters around 0.95 kWh/W_p. Given the fact that ZZS suffered longer and worse operation losses than rooftop, and also the extra 9 kW_p for the rooftop, the difference in specific yield would be smaller if data were intact.

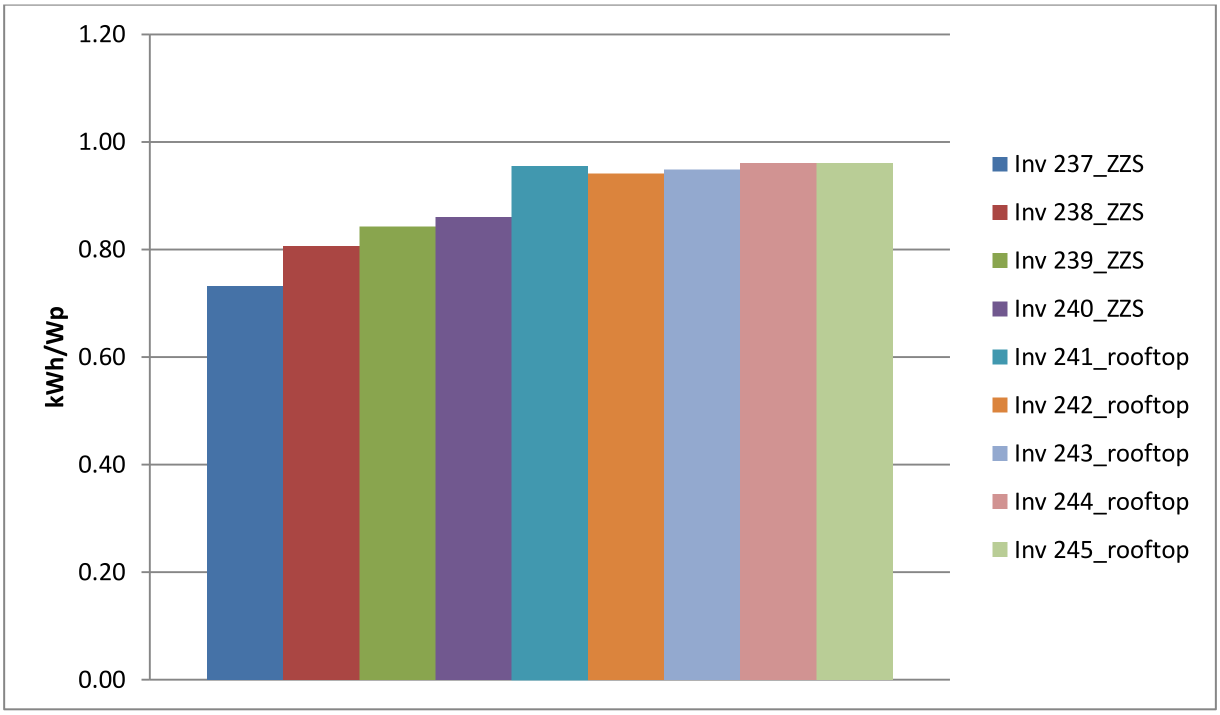


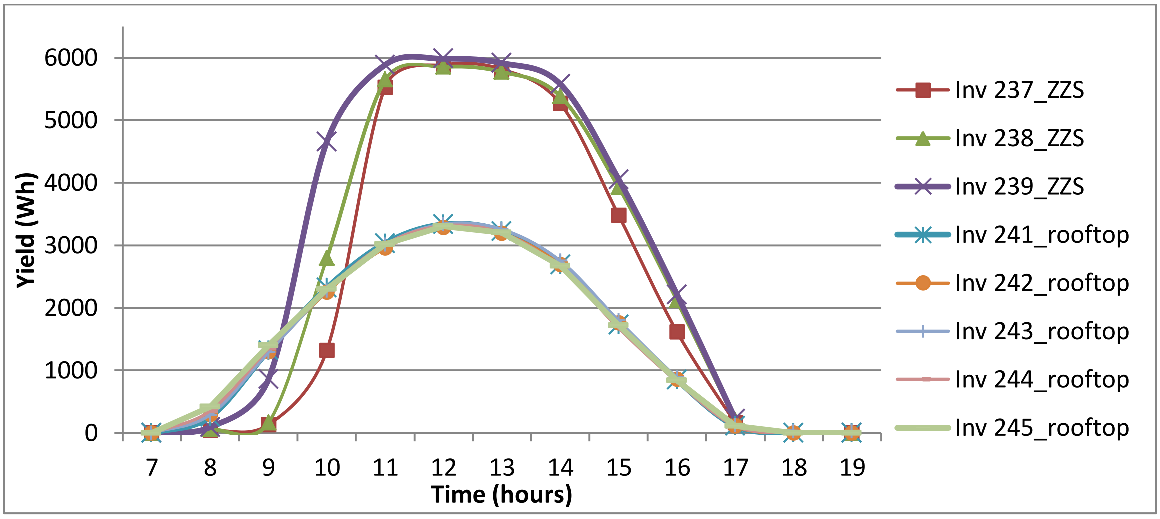
Figure 4.4: Yield produced (unrestored data) per installed capacity of ZZS and rooftop

Hourly Data

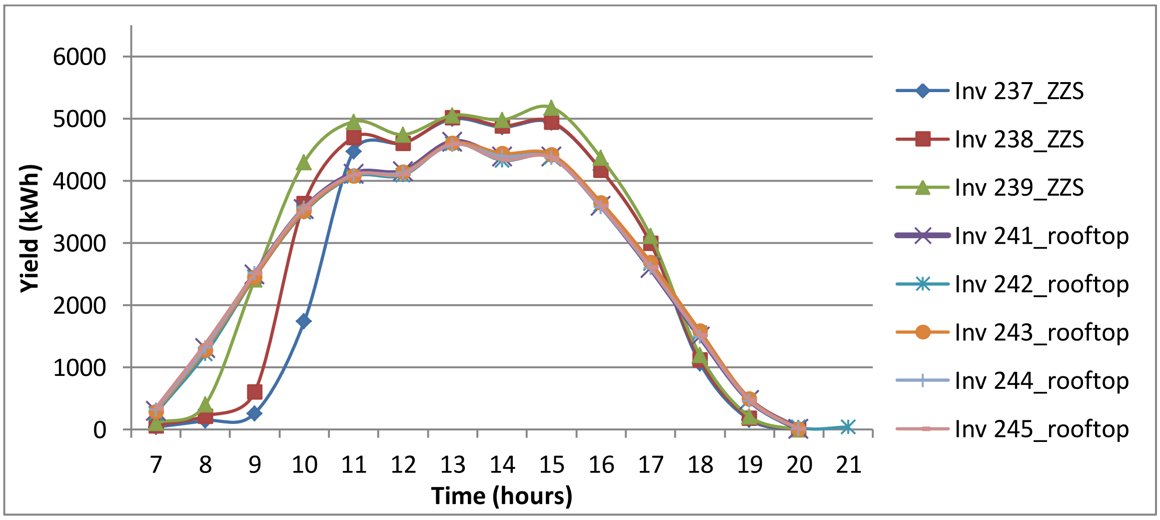
Figure 4.5 a) and Figure 4.5 b) shows the inverters' hourly yield during winter and autumn. ZZS produced a higher yield than the rooftop, where in winter it showed its best performance. Despite the good performance of ZZS, the month of December in 2017 was the darkest since 30 years [45]. The irradiance in 2017 was merely 12 kWh/m^2 which resulted in a lower yield than expected. If the irradiance was like the usual average irradiance of December which is around 22 kWh/m^2, the electrical yield would almost double.

It can be seen from Figure 4.5 c) that the rooftop system performed better than ZZS in summer. The ZZS has a partial self-shading effect due to the reflector which projects some shadow on the PV panel close to the fold point of the reflector and PV panel. The rooftop has a significant advantage in the yield during the first and last 4 hours of the day, during when ZZS was having self-shading, but at noon both systems have similar output because self-shading of ZZS was gone.

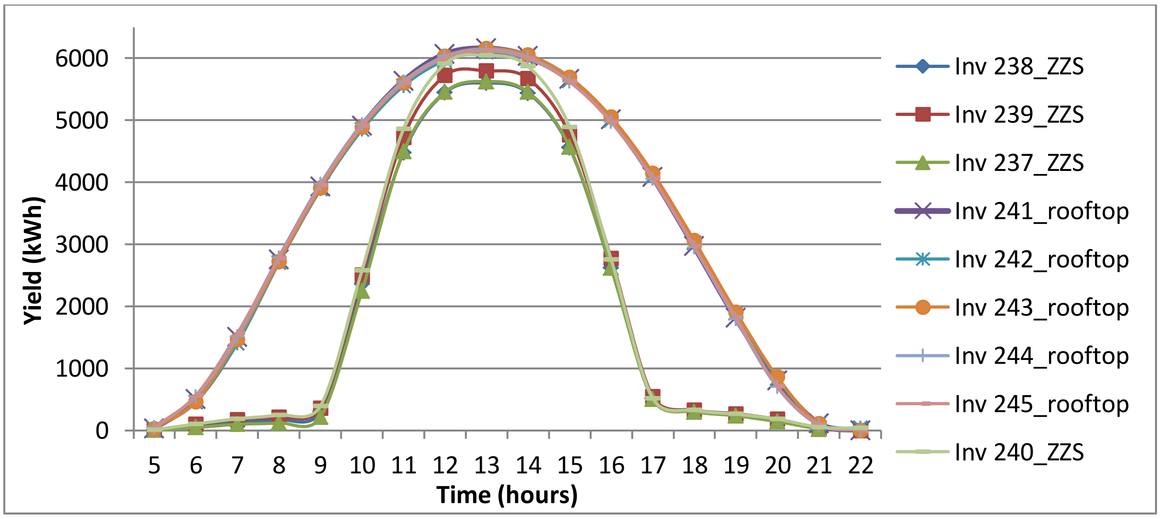
Effects of the adjacent building are visible in all the graphs. For example, in Figure 4.5 a), in the morning between 6 to 9 o'clock ZZS performed worse than rooftop because sunbeam was blocked by the adjacent building, however, ZZS soon turned around from 9 o'clock when shading by the adjacent building disappeared.



a)



b)



c)

Figure 4.5: ZZS VS Rooftop yield on a sunny day in: a) winter b) autumn c) summer

4.2 Wijk Van Morgen project

4.2.1 Experimental comparison Rooftop VS ZZS VS Vertical

A test site called Wijk van Morgen (WvM) is installed in the town of Heerlen, which is not far from the Eisenhower project in Sittard. In WvM a vertical PV array, a ZZS system, and a rooftop system are installed. All of the three systems consist of 3 panels of the same area and specification produced by Stafier. Each panel consists of 22 mono-crystalline silicon cells and has a peak power of $^{95\ Wp}$. The 3 panels of each system are connected to one Enphase micro-inverter of 250 W. A comparative analysis of the energetic performance of the three systems is shown in this section.

Figure 4.6 shows the position of each solar system facing the southern direction. The top row represents the rooftop since the tilt angle is 32º whereas the standard tilt angle of rooftop in the Netherlands is 37º, therefore this would have a very small difference in the yield production. Directly below the rooftop is the ZZS system with the decorative reflective panels. The reflector type used is grey trespa panel sheet. To the right of ZZS and rooftop, the vertical solar system is located.

Figure 4.6: Wajk van Morgen ZZS, rooftop and vertical BIPV system [adapted from 40]

Figure 4.7 shows the measured yield of ZZS compared to rooftop and vertical in individual months starting on February 2015 to January 2016. As expected, the ZZS is better than rooftop for all the months during winter and autumn whereas rooftop is better during spring and summer. On the other hand, when comparing the vertical system with ZZS it can be seen that the ZZS is much better than the vertical system where it produced a higher yield during all the year except December and January.

The company has changed the reflector type in the year of 2016 from trespa sheet into a mirror film. The data is only available from September 2016 to January 2017. The yield has increased by an average of 30% compared to ZZS with a trespa sheet. Furthermore, the performance has improved by about 28% when comparing to vertical and rooftop.

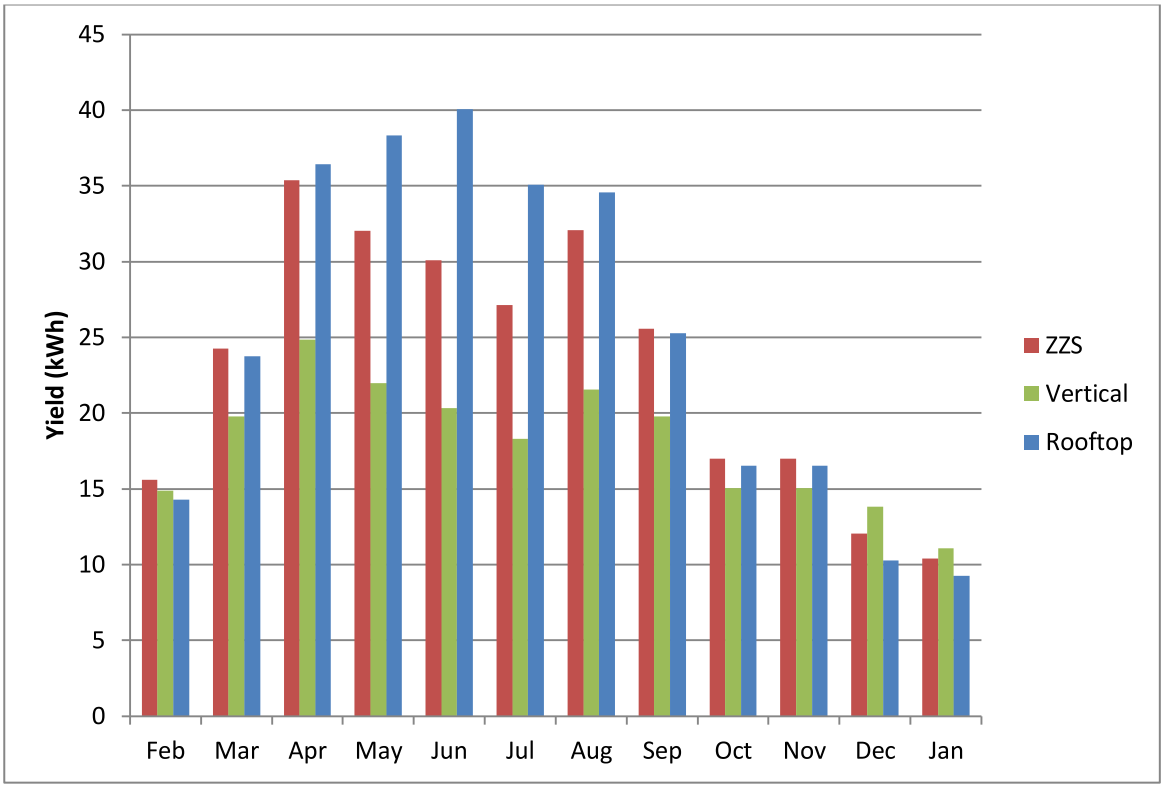


Figure 4.7: Monthly Yield of ZZS, rooftop and vertical system

From the observation of Figure 4.8, the ZZS is competitive with the rooftop with a specific yield difference of 0.07 kWh/W_p while the ZZS resulted in a higher specific yield than the vertical with a specific yield difference of 0.22 kWh/W_p. This shows the value of ZZS against the conventional way of producing electricity by utilizing the façade area instead of using the smaller space of the roof. Therefore, the ZZS is superior to the vertical system in terms of specific yield.

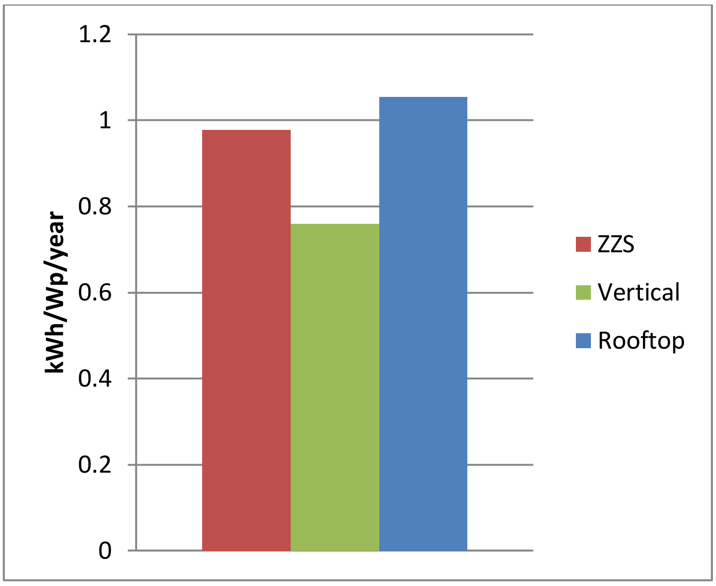


Figure 4.8: Yield produced per installed capacity of ZZS, rooftop and vertical

Boosting Factor

The Boosting Factor (BF) is the extent of boost of performance by ZZS to the rooftop or the vertical on a monthly basis. Both systems should have the same installed capacity in order to make the comparison consistent. The BF can be calculated using equation (4) where $\mathbf{E}_{\mathbf{ZZS}}$ is the monthly output of ZZS and $\mathbf{E}_{\mathbf{Competitor}}$ is that of rooftop or vertical system.

$$\mathrm{BF} = \frac{\mathrm{E}_{\mathrm{ZZS}}}{\mathrm{E}_{\mathrm{Competitor}}} \tag{4}$$

From Figure 4.9 it can be noticed that the BF is above 1 for winter and autumn when comparing ZZS to the rooftop. In spring the BF starts to drop below 1 reaching a minimum value of 0.75 in summer. In autumn the BF value is sort of saturated and starts to increase in winter reaching a maximum value of 1.17. The rooftop is exposed to more diffused irradiance since it sees all the sky whereas the ZZS sees only half of the sky while facing the southern direction. The ZZS offers more electricity in winter by around 12% and the rooftop offered 7% more for the whole year.

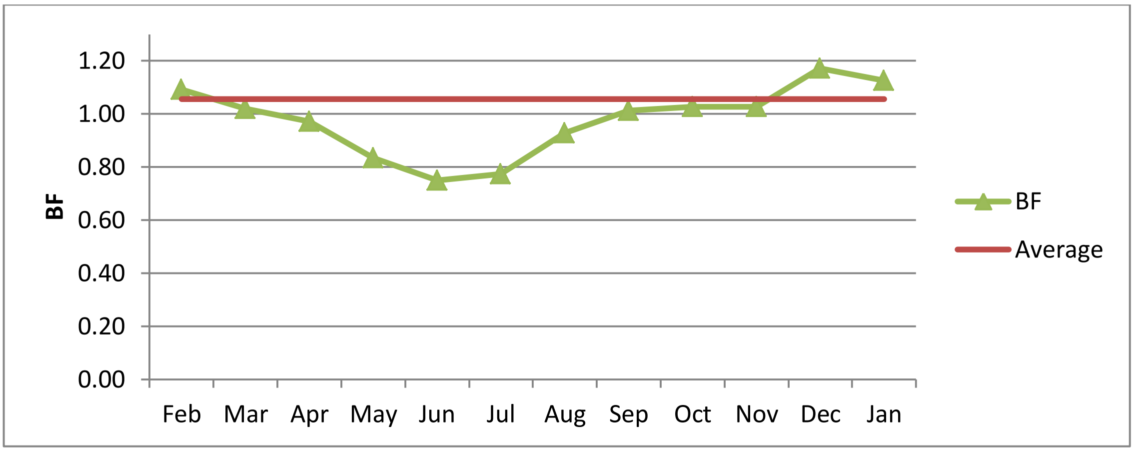


Figure 4.9: Monthly Boosting factor of ZZS against rooftop

The BF of ZZS to vertical is bigger than 1 for all the months except December and January, as displayed in Figure 4.10. The BF starts to increase gradually in spring until reaching a maximum value of 1.49 in August. After the summer period, the BF starts to decrease and reach a minimum value of 0.87 in December. The vertical offers more electricity in winter by around 3% and the ZZS offered around 22% more for the whole year.

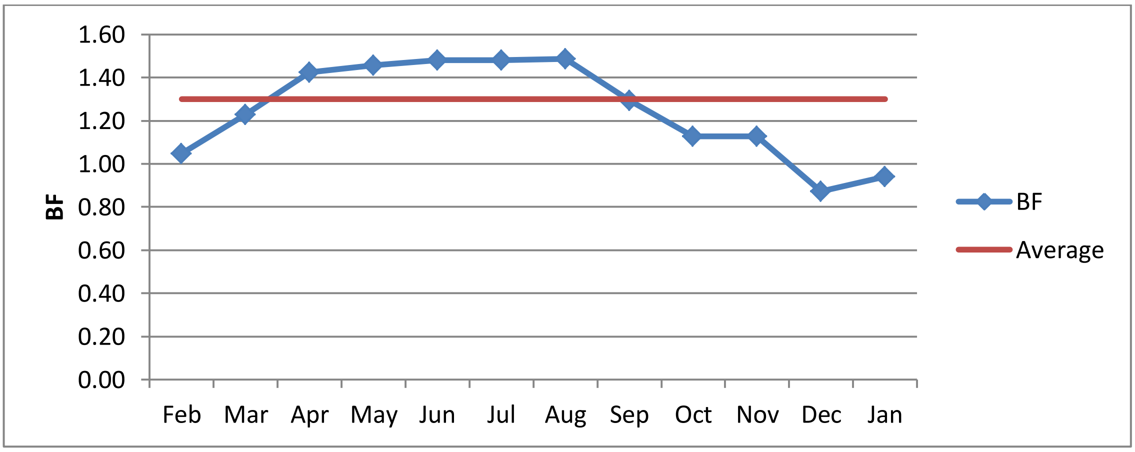


Figure 4.10: Monthly Boosting factor of ZZS against vertical

4.2.2 BIMSolar Simulation

The company's simulation tool predict the results accuratly only. Most of the available commercial software can't simulate the performance of ZZS accurately. BIMSolar is new simulation software which is not commercialized yet, developed by EnerBIM, a French company specialized in Building Information Modeling (BIM) through modeling the energetic performance of PV in the built environment. The software support in the decision making process during the early assessment stage by predicting and visualizing the performance of any BIPV or BAPV project [46]. In this section, the three solar systems (ZZS, rooftop, vertical) of the test site WvM are simulated in BIMSolar. Eventually, we will validate this simulation by comparing it to the actual experimental results from section 4.2.1.

BIMSolar is compatible with various file types since it is only allowed to import models into it. The physical model was initially built in SketchUp Pro 2018. Once the model is imported to BIMSolar, the local weather data file, date and location are inserted for the location of WvM in Heerlen. In the test site of WvM, there is no available weather data to use it in the BIMSolar model. Therefore, the irradiance forecast such as GHI, Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) has been extracted with the format of Typical Metrological Year (TMY) from PVGIS [47].

The irradiance model developed by BIMSolar has a possibility to select the precision level (fast, balanced or accurate). The details of the PV module and its cells have been specified such as cell dimension, interlayer details, encapsulation, and glazing. Some other optical parameters like reflectance and transmittance of the material used can be specified as well for better results. The electrical parameters of the real micro-inverter used are also inserted such as input current, voltage, and the number of strings per MPPT. Just like the experimental setup location of each system, Figure 4.11 shows the three solar systems to be analyzed where the panels on the right are the vertical BIPV, the panels on the top row are for the rooftop (without reflector) and the bottom row is for ZZS (with reflector).

Figure 4.11: Model of the three solar systems on BIMSolar

In order to consider the effect of the decorative reflective panel in simulation, a reflection factor is represented by the albedo which describes the extent of a surface to reflect sunlight. The lighter the color of a surface (such as snow and ice) the higher the albedo, and the darker it is the lower the albedo. The albedo of every surface in the model is different and therefore should be identified independently.

- Ground: 20%
- Building: 50%
- Aluminum Reflector (RAL 9006): 70%

Results

Figure 4.12 shows the AC electrical production from each inverter of the three solar systems for the year 2015. The simulation showed that in winter both ZZS and vertical systems have more yield than rooftop except February the rooftop was higher by 1kWh. During spring and summer, the rooftop was the dominant and ZZS was better than vertical. In autumn ZZS was the best during October only and the other months are close to the results of the rooftop.

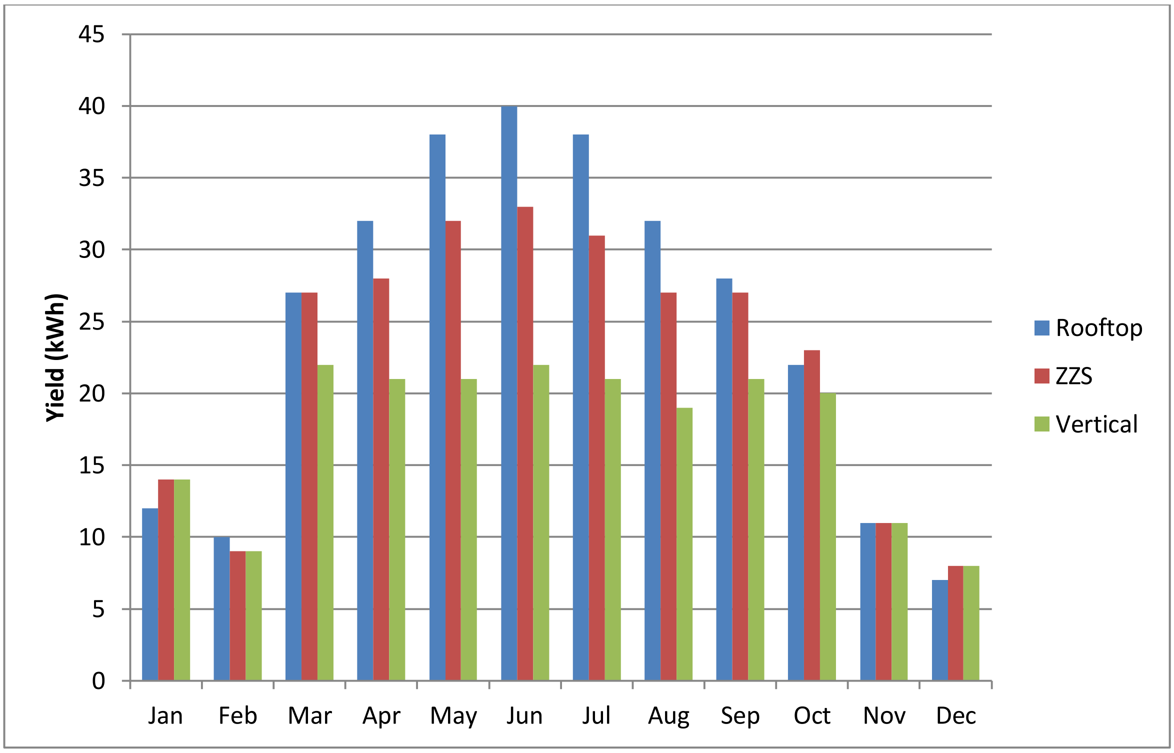


Figure 4.12: Monthly yield of the three solar systems

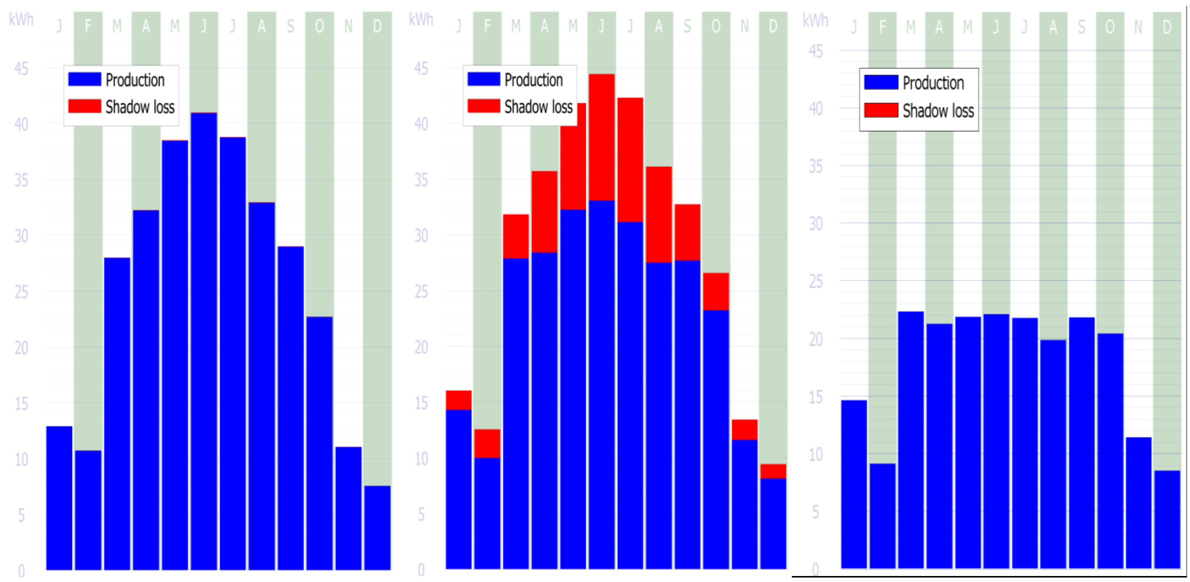
The specific yield of the rooftop system is 1.05 kWh/W_p/year. Unlike the vertical BIPV which has a specific yield of 0.74 kWh/W_p/year, ZZS has a specific yield of 0.94 kWh/W_p/year with a difference of 10.5% in contrast to rooftop system.

Table 4-2: Yield comparison of simulation and measurement for the three solar systems

Solar System	Rooftop	ZZS	Vertical
Simulation (kWh)	299	268	211
Measurement (kWh)	300	279	217
Difference (%)	0.49	3.80	2.54

It can be seen from Table 4-2 that the simulation results are very close to the experimental results. The difference was smaller for rooftop than the other two systems where ZZS has the highest difference. The reason behind it is because the ZZS has the most variable input parameters that could be different than reality such as the shadow loss and reflectivity of the trespa panels.

Several sources of lost energy have been predicted by the simulation. In Figure 4.13 one can notice how the effect of shadow on ZZS increases gradually and reach a peak in summer then the loss starts to decrease in the winter season. This variation is related to the sun position in the sky at different altitude resulting in variable shadow loss. The total loss per year is 19%. On the contrary, shadow loss from the rooftop system is almost negligible, approximately 0.1% whereas the vertical system showed no shading losses. The simulation predicted that the losses from mismatching and cable losses are negligible while the production loss due to temperature was responsible for about 8%. Investigation on minimizing the effect of the shadow loss is not studied here since the tilt angle of both the reflector and PV panel are already optimized for the Netherlands.



a) b) c)

Figure 4.13: Production loss by shadow for a) Rooftop b) ZZS c) Vertical

Chapter 5 Conclusion

This chapter concludes the main findings of the conducted research work. Future work for system improvement is also mentioned in this chapter.

Conclusion

The ZigZagSolar BIPV system performance has been studied in details. The obtained measurements from the Eisenhower project were examined and found to be defected with many missing data. Finding a replacement of the poor data quality was done by linear regression for a better understanding of full-year performance. The operation loss affected the calculated yield to decrease by around 8.4%.

Several factors affected the overall performance of the ZZS system in Eisenhower. The main reasons for the deviation between expectation and measurement are shading from the adjacent building and inverter clipping. Assessing the shading effect through studying the optimizers was complex since the yield of many days was missing. After obtaining the restored data, the observation noticed was there is still fluctuation in the yield from top to bottom row of optimizers. This is mainly due to instrumental measurement error and missing hourly yield of some optimizers. The total shading loss was found to be 11% with a bigger difference between the top and bottom optimizers in summer than other seasons.

The yield losses component due to Inverter resulted in 2.25% losses from clipping and 0.75% losses from conversion efficiency. DC cables had 1.14% yield losses from the overall yearly output. Incorporating all the losses and substituting the missing data has shown the specific yield would increase from 0.81 kWh/W_p to be 1.02 kWh/W_p.

The difference in the Eisenhower simulation and measurement is relatively high during summer and spring whereas it is lower during autumn and winter, this is due to the inverter loss (clipping and conversion loss), data acquisition loss on hourly level of some optimizers, and inaccurate reflectivity input. The overall difference was found to be 25.5%. Detailed evaluation of shading loss, inverter efficiency, inverter clipping, and operation loss showed simulation is accurate if all the losses are deducted. Therefore, the results would be better if there were no internal or external effects.

The experimental specific yields of each solar system are as follows:

- Eisenhower Rooftop: 0.95 kWh/W_p/11 months
- Eisenhower ZZS inverter 240: 0.86 kWh/W_p/11 months (0.98 kWh/W_p/year)
- Eisenhower ZZS inverter 239: 0.84 kWh/W_p/11 months (0.89 kWh/W_p/year)
- Eisenhower ZZS inverter 238: 0.81 kWh/W_p/11 months (0.86 kWh/W_p/year)
- Eisenhower ZZS inverter 237 (bottom): 0.73 kWh/W_p/11 months (0.76 kWh/W_p/year)
- Wijk van Morgen Rooftop: 1.02 kWh/W_p/11 months (1.05 kWh/W_p/year)
- Wijk van Morgen Vertical: 0.72 kWh/W_p/11 months (0.76 kWh/W_p/year)
- Wijk Van Morgen ZZS: 0.94 kWh/W_p/11 months (0.98 kWh/W_p/year)

The comparison per watt peak ZZS with rooftop showed that ZZS is better during winter than the rooftop on average by 12% and the rooftop offered more 7% for the whole year. On the other hand, ZZS is better than the vertical during the whole year by an average of 22% where both systems had similar performance in winter (vertical offered 3% more than ZZS).

The comparative analysis of the experimental work of Wijk van Morgen with the simulation using BIMSolar concluded that the simulation can predict the yield properly with a difference less than 4% for all the systems with a good estimation of potential sources of energy lost. This can be extremely important during the early assessment stage of a project to consider any changes to the design by visualizing the outcome. The study showed that ZZS has a specific yield of 0.94 kWh/W_p/year whereas the rooftop and vertical has 1.05 kWh/W_p/year and 0.74 kWh/W_p/year, respectively. The energy lost due to shadow is highest during summer and lowest during winter and autumn. The study predicts that ZZS panels have 19% loss due to shading, the rooftop and vertical with almost no shadow loss.

Utilizing the façade area and turning it into an energetic solar façade while providing aesthetical architectural appearance to the building envelope is what makes the ZZS superior to the vertical BIPV. Additionally, ZZS is competitive with rooftop by using a larger area than the rooftop area.

Future Work

The Eisenhower ZZS system was down several times because the inverters were oversized too much. It is recommended to replace the inverters in Eisenhower project with higher capacity inverters in order to minimize the losses of clipping and also to reduce the chance of equipment failure. The cost of the newly replaced inverter is expected to have a payback period of around 4 years. This would be an optimal solution to guarantee both safety and quality. In addition to that, the SolarEdge monitoring platform was not always reliable as noticed from the large amount of data lost due to the optimizer-inverter communication losses. It is recommended to install some third-party monitoring devices.

The company should improve its simulation by incorporating the effect of shading from the surrounding obstacles and all the inaccurate variable inputs such as the reflectivity of the decorative panels. This will lead us to reach a better understanding when comparing simulation with measurement.

The simulation performed in BIMSolar accounted only for the diffused reflection of the reflector without the specular reflection component which could be the main reason for the simulation to be less than real measurement. Another limitation is the weather input data could be inaccurate since the TMY was used. The results could change if TMY data for a different time period is used. It is recommended to investigate the improvement of the model by obtaining the irradiance data from a local weather station which can provide better results. The simulation study can be further improved and make it closer from reality by considering adding the albedo of the black parts (the nose profile and strips). Consequently, this would affect the temperature loss results from the simulation.

Techno-economic investigation of whether to add power optimizer in future ZZS projects should be considered in order to avoid the communication loss since the power optimizer and inverter act as a single point of failure in the string. It is advised to conduct an economic analysis of the ZZS in comparison to other competitive technologies to better understand the viability of each technology.

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