

Technical Assessment of ZigZagSolar BIPV System

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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/m²/year. Factors like shading from the adjacent obstacles and inverter losses had 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 less than 4% for the three solar systems.

Keywords: ZigZagSolar, BIPV, Solar Façade, Solar Photovoltaic, Renewable Energy, NZEB

1. Introduction

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 renewable sources 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.

2. Methodology

A literature review was initially conducted to study available technologies in comparison to ZGS. Understanding the complex performance of ZGS

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. 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 root-cause analysis was done on yearly, monthly and daily level.

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 setups namely ZZS, rooftop, and vertical are analyzed to further understand how ZZS perform against well-known technologies. Finally, testing of a predictive simulation software called BIMSolar where the three setups at Wijk Van Morgen are simulated.

3. Characterization of ZigZagSolar

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 kWp with 308 PV modules installed. The solar modules are specialized 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 Wp, 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 clad with 308 ZZS units (also referred as 'cassettes' as shown in Figure 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 Wp 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.



Figure 1: Eisenhower cassette showing the position of 1 module and reflector

Inverters of ZigZagSolar are named in this manner:

- 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

As illustrated in the satellite view in Figure 2, 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.

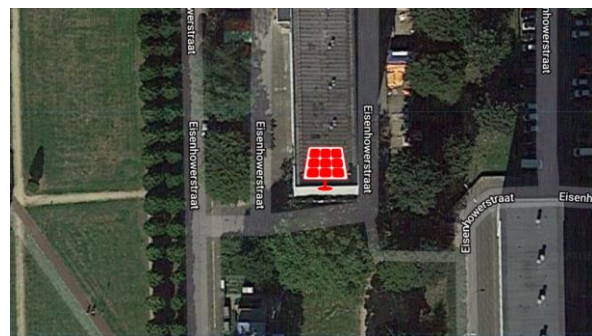


Figure 2: Satellite view of Eisenhower and surrounding obstacles

3.1 SolarEdge Power Optimizer and Inverter

Power optimizers and micro-inverters are called Module Level Power Electronics (MLPE). They are better than string inverters by optimizing the performance of each module connected to it (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 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.

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.

3.2 Internal Comparison

3.2.1 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 system. Also, inverters were not working for a short period due to break-down.

The available data from inverters started from 18th October 2017 and stopped on 25th September 2018, lasting for 339 days (approximately 11 months). Inverter 240 at top of the façade suffered the most severe operation loss whereas inverter 237 didn't encounter any operation loss. Data availability from all the optimizers are also sorted out and collected.

3.2.2 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 ZSS 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 ZSS Cassettes (300 Wp) at SolarBEAT was obtained by simple linear regression using least square method according to equation (1), 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.

$$y = mx + b \quad (1)$$

2. Assume that Eisenhower & SolarBEAT are proportional since the monthly Global Horizontal Irradiance (GHI) difference between the two sites is 2.5%. Note that both ZSS 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.

3.2.3 Overview of Results

The ZSS 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 section 4.1. 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 27264kWh/year, with an overall specific yield of 0.87 kWh/W_p. Table 1 summarizes the electrical production of one year and the expected total deviation.

Table 1: Eisenhower simulation and measurement yearly results

Simulation		Measurement		Deviation
$\frac{kWh}{year}$	$\frac{kWh}{Wp}$	$\frac{kWh}{year}$	$\frac{kWh}{Wp}$	%
36615	1.19	27264	0.89	25.5

Apart from the poor data quality, 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 and horizon blockage effect.
- 4- Efficiency of the inverters.
- 5- Inaccurate input parameters to simulation program
- 6- DC cable losses.
- 7- SolarEdge data precision.

Following in the paper, whenever it is mentioned “yearly” analysis it refers to 12 months with the compensated lost data unless stated otherwise.

3.2.4 Shading Effect

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 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 operating fully during May and July. 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 the lost data. 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 which is caused by measurement errors. According to a technical note published by Solar Edge [6], they reported that their hardware has an accuracy of ±2% whereas the energy

measurement which is calculated indirectly has an accuracy of $\pm 5\%$.

Left	Middle	Right	Left	Middle	Right
297	267	271	4.6	6.0	4.5
312	284	278	0.0	0.0	2.0
293	278	284	5.9	2.0	0.0
277	279	263	11.0	1.6	7.3
290	268	261	6.9	5.7	8.3
262	262	268	15.9	7.8	5.9
288	266	256	7.7	6.4	9.9
271	262	254	13.0	7.8	10.6
283	263	266	9.1	7.4	6.5
259	258	246	17.1	9.2	13.3
260	248	238	16.7	12.6	16.1
262	247	239	16.0	12.9	15.9
238	234	235	23.6	17.6	17.1
High Yield	Low Yield		Small Loss	High Loss	

a) b)

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

3.2.5 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 Wp 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

Table 2: Yearly inverter efficiency and yield losses

	Inverter 240	Inverter 239	Inverter 238	Inverter 237
AC (kWh)	7117	6958	6412	5894
DC (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 2.

From Table 2 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% when working between 20% and 50% of rated DC input. 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.

3.2.6 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 (2) where $P_{AC,max}$ is the nominal or rated power of the inverter.

$$\frac{DC}{AC} \text{ oversizing}(\%) = \frac{P_{DC}(STC)}{P_{AC,max}} * 100\% \quad (2)$$

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 12 months. If the inverters are replaced with a bigger capacity inverters (such as SE7600H), the DC/AC ratio would be 1.01 leading to a significant reduction in 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 3.2.5, 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 4 shows an example of the clipping effect during a day for all the inverters in February. 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

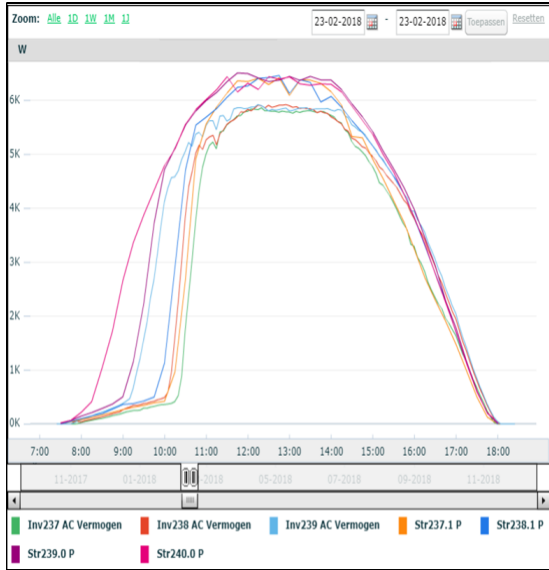


Figure 4: Inverter clipping during winter

3.2.7 Cable loss

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 mm² cross-section area (11 AWG). Copper wire typically has a resistance of 4.13 Ω/km. 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, based on that the energy lost is found. According to the climatic weather data, the number of sun hours on average is 1604 hours for 305 days in the area of Sittard where the installation is located. The estimated amount of yield lost across the cables is 305 kWh.

3.2.8 Total Losses Summary

The energy operation loss is 8.4%. If one considers adding all the 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 5 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.

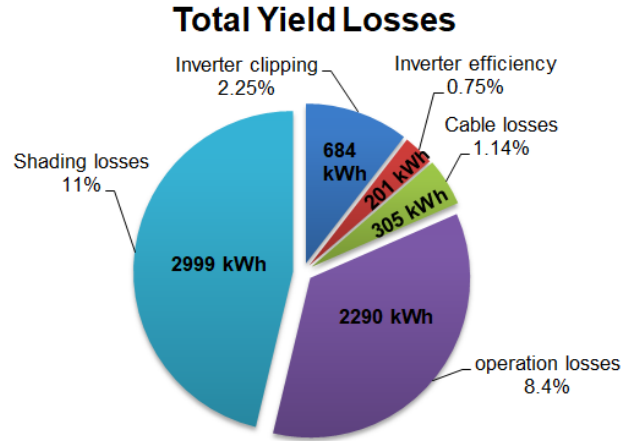


Figure 5: Electrical generation and percentage share of yield losses for each source

4. External Comparison

4.1 Eisenhower (Simulation VS Measurement)

The company has developed a dedicated simulation tool for its ZZS system using MATLAB. 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 6, it can be seen that the simulation fails most during spring and summer seasons whereas it has reasonable convergence during winter and autumn.

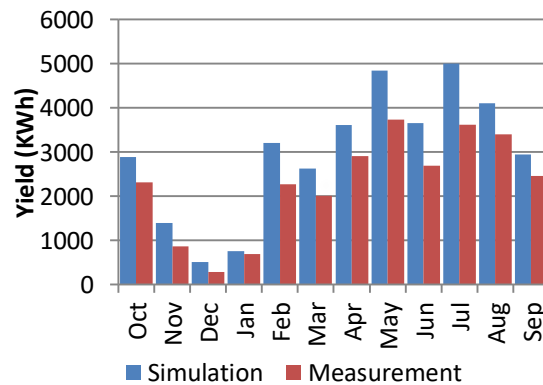


Figure 6: ZZS Simulation VS Measurement

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 online 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 specular component and 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 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%. Table 3 shows the top part (240) of the ZSS 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 3: Simulation and measurement difference for each ZSS 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

4.2 Eisenhower Experimental Comparison (Rooftop VS ZSS)

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 ZSS 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 kWp extra for rooftop). Additionally, the orientation of the rooftop is east-west oriented with a tilt angle of 15° whereas the ZSS tilt is 32°. 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 7 shows the specific yield of ZSS and rooftop. The ZSS is competitive with the rooftop with an average specific yield difference of 0.16 kWh/Wp. ZSS showed different kWh/Wp depending on positions of the inverter, ranging from 0.73 kWh/Wp to 0.86 kWh/Wp whereas the rooftop has almost similar rates for all the inverters around 0.95 kWh/Wp. Given the fact that ZSS

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.

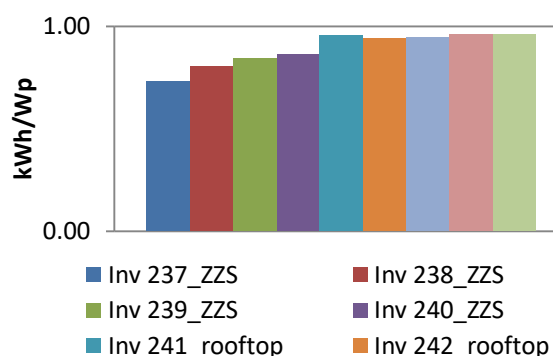


Figure 7: Yield produced (unrestored data) per installed capacity of ZSS and rooftop

4.3 Wijk Van Morgen Experimental comparison (Rooftop VS ZSS 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 BIPV, a ZSS, 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 8 shows the position of each solar system facing the southern direction. The top row represents the rooftop since the tilt angle is 32° whereas the standard tilt angle of rooftop in the Netherlands is 37°, therefore this would have a very small difference in the yield production. Directly below the rooftop is the ZSS system with the decorative reflective panels. The reflector type used is grey trespa panel sheet. To the right of ZSS and rooftop, the vertical solar system is located.



Figure 8: Wajk van Morgen ZSS rooftop and vertical BIPV system

Figure 9 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.

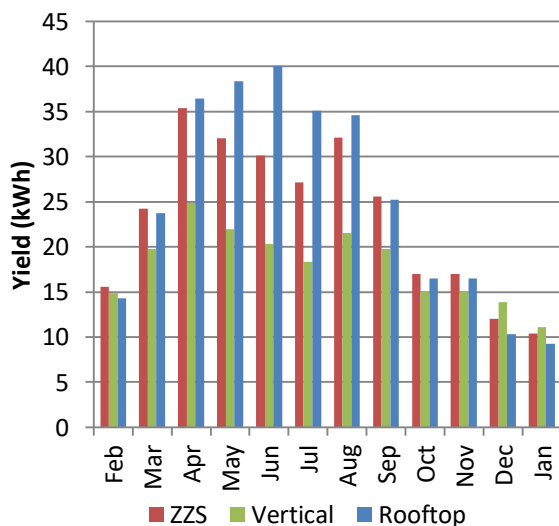


Figure 9: Monthly measured yield of ZZS, rooftop and vertical system

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. The vertical offers more electricity in winter by around 3% and the ZZS offered around 22% more for the whole year.

4.4 Wijk Van Morgen simulation (Rooftop VS ZZS VS Vertical)

Currently, there is no available software that can simulate the ZZS system apart from the company's simulation software. However, there are different commercial software that can simulate the performance of conventional solar systems. BIMSolar is a 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 [7].

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 Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) has been extracted with the format of Typical Metrological Year (TMY) from the Photovoltaic Geographical Information System (PVGIS), a tool developed by the European Commission [8].

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 10 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 10: 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 11 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.

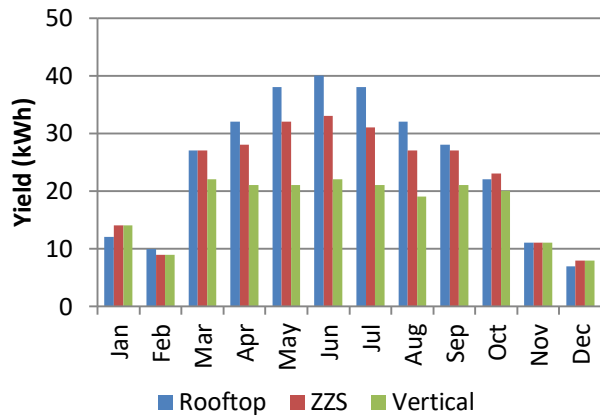


Figure 11: Monthly predicted yield of the three solar systems

Table 4: 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 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 12 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 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.

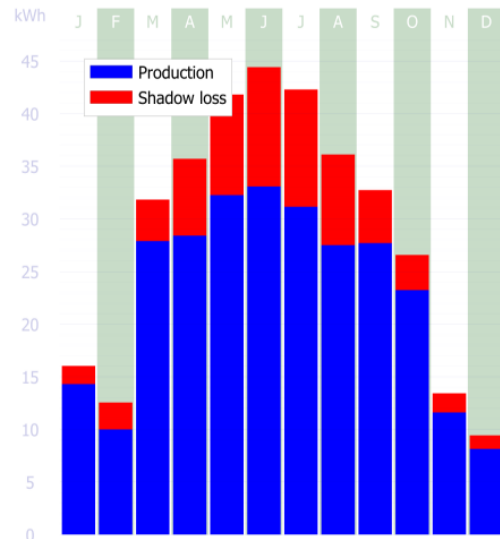


Figure 12: Production loss by shadow for ZZS

5. 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 data loss affected the calculated yield to decrease by around 8.4%.

Several factors affected the overall performance of 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 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 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/Wp to be 1.02 kWh/Wp.

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 data 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 comparison ZZS with rooftop per watt peak 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 at Wijk van Morgen with the simulation using BIMSolar concluded that the simulation can predict the yield 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/Wp/year whereas the rooftop and vertical has 1.05 kWh/Wp/year and 0.74 kWh/Wp/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.

Utilization of the façade area and turning it into an energetic solar façade while providing aesthetical architectural appearance to the building envelop 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 which is usually occupied (pipelines, storage tanks, etc.).

6. 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 3rd-party monitoring device.

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. It is advised to conduct an economic analysis of the ZZS in comparison to other competitive technologies to understand the viability of each technology.

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