ZIGZAG STRUCTURE IN FAÇADE OPTIMIZES PV YIELD WHILE AESTHETICS ARE PRESERVED

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ABSTRACT: In the Netherlands, the possibilities for façade PV applications draw more attention lately due to a combination of government incentives, declining PV-module prices and upcoming legislation from the European NZEB-directive (2010/31/EU). In this context, start-up company Wallvision has introduced a ZigZag structured façade in which the PV-modules are hidden from ground level, and the decorative panels are customized to the aesthetical preferences of the architect. Understanding the PV-yield as a function of the geometry and other system components is crucial. For this purpose a customized geometrical model has been developed that can handle the varying solar path and the specular and diffuse reflection of the decorative panels. The experimental validation of the model is done with a newly built test façade (of 3 x 3 ZigZag cassettes, area ~ 20m^2) in the SolarBEAT outdoor research facility of SEAC. Measurements include the irradiance at various points and kWh-yield per minute time interval. The aesthetic aspect of the ZigZag façade is as important as the PV-performance part of the product, and is therefore included in this paper.
Keywords: Façade, PV System, Modelling

1 INTRODUCTION

Façades are a significant part of the potential BIPV market area. Up till now, facades did not get the same amount of attention as flat and pitched roofs in the Netherlands. This is logical, as one recalls that rooftop PV (whether it is BAPV or BIPV) gives more yield per invested kWp than a vertical façade PV system. And this rooftop part of the total PV-market is still not completely cashed in the Netherlands. However, things are changing rapidly due to a combination of incentives from the government and declining prices for PV-modules and other system components. The incentives are: net-metering scheme for households and kWh-subsidy for larger (>15 kWp) systems. On top of that, the NZEB-directive for Europe (2010/31/EU) is being rolled out in the Netherlands. This made people aware of the fact that for new-built houses since 1 January 2015, PV is an effective option for meeting the criteria for energy performance. Moreover it is expected that from the end of 2018 for government buildings and from the end of 2020 for all utility buildings the criteria for near zero energy building have to be met. A PV generating part of the building skin could be crucial to meet these new energy criteria. Therefore several start-up companies are exploring the opportunities of PV façades. Among them, the company Wallvision has introduced a ZigZag structured façade in which the PV-modules stay out of sight for pedestrians and other traffic in the streets at ground level (see Figure 1).

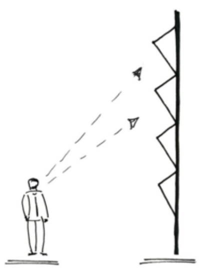

Figure 1: Sketch of the ZigZag structured façade principle.

Only the decorative panels are visible and give the façade a customized aesthetics (see Figure 2). Customization includes various materials, colors and prints, like e.g. a company logo. The assembly of one PV-module and one decorative panel with the same width is called a ZigZag-cassette. Optionally the decorative panel can also be chosen in such a way that it has a maximum light reflection onto the PV-module below, to maximizethe PV-yield.

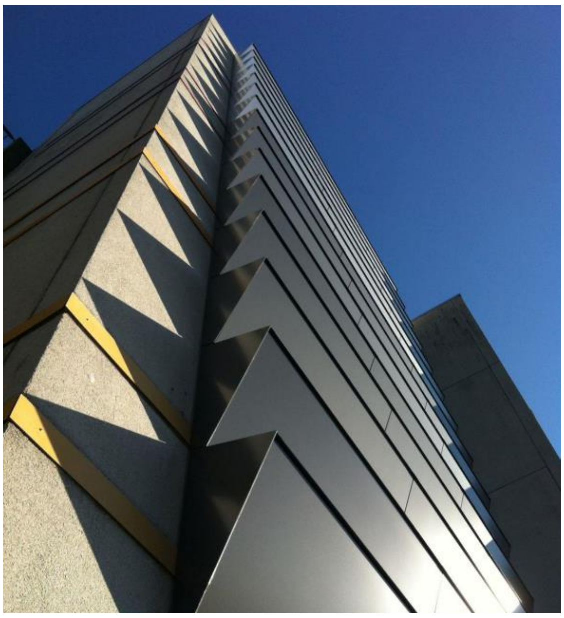

Figure 2: Picture of first commercial ZigZagSolar façade, taken from ground level. Decorative panels in this façade are colored from dark gray at the lowest row till light gray at the uppermost row.

This working principle may sound quite easy. But understanding the electrical performance of the whole façade is fascinatingly complex. First of all, the trajectory of the sun follows a certain path depending on the exact location of the installation. Even in a small country like the Netherlands this gives rise to variations influencing electrical performance. As one can imagine, the incoming total sun light (as a sum of a direct and a diffuse contribution) is reflected -both specular and diffuse- by the decorative panel and will partly hit the underlying PV-module. Albedo effects of the surrounding built environment have a different effect on the PV yield opposed to 'standard' vertically installed PV-modules. The tilt angles of the product itself are adjustable. Wallvision, SEAC and Technical University Eindhoven are a.o. participating in the Dutch ZonneGEVEL-project aiming to conduct an extensive research on the performance of this ZigZag-structured façade.

2 HOW CAN THE ELECTRICAL PERFORMANCE BE UNDERSTOOD

The major research question of the ZonneGEVEL-project is to fully understand the electrical performance of a ZigZag-structured façade including the following aspects:

- Location of installation (latitude, longitude).
- Orientation towards the sun (azimuth: from East via South towards West, even installations towards NE and NW are investigated). Please note that the renovation market of the Dutch building sector is much larger than the new-built market. And the façade in a renovation project is generally not adjustable anymore.
- Geometry of the ZigZag-cassette (length & width PV-module + length & width reflector + tilt angle β of the module & angle α_{ref} between decorative panel and vertical).
- Albedo of ground reflection, ρ_{ground}.
- Decorative material (with a reflection decomposed towards direct & diffuse light).

In order to answer this question, it is needed to have a clear understanding of the irradiance falling on the PV-module for any moment of the day, any day of the year, and with respect to all above mentioned possible variations of the ZigZag-cassette installed at any location on Earth were potential customers like to utilize their façade. Therefore the research is clearly split in a two-step approach. In the first part of the project, focus is set on the irradiance research. Thereafter (starting around mid-2016), the measured and modelled irradiance will be used as input to predict AC-kWh yield, which will be validated with electrical measurements. Clearly this paper focusses on the irradiance research, but also some preliminary AC yield measurements are presented.

3 EXPERIMENTAL SETUP

A vertical test façade of width 6.6 m and height 4.5 m is built in the SolarBEAT facility. This outdoor research infrastructure for innovation on BIPV(T) has been presented to the solar community in the previous two PVSEC conferences [1][2]. The upper part of the test façade gives room for 3 rows of 3 ZigZag-cassettes with β=32° and α_{ref}=28°. The lower part of the test façade gives room for a grid of 2 rows with 5 CIGS-modules incorporated in a innovative façade mounting system; see Figure 3.

Figure 3: Picture of the ZonneGEVEL test façade. The upper part holds 3 rows of 3 ZigZag-cassettes. The lower part holds 10 CIGS-modules. Pyranometer and photodiodes are used for measuring irradiance (yellow circles).

4 IRRADIANCE MODELING

4.1 Two dimensional geometrical modeling

Because of the complexity of the PV-system, it was decided to start modelling the irradiance in the cross-sectional cut of the ZigZag-cassette (see Figure 4).

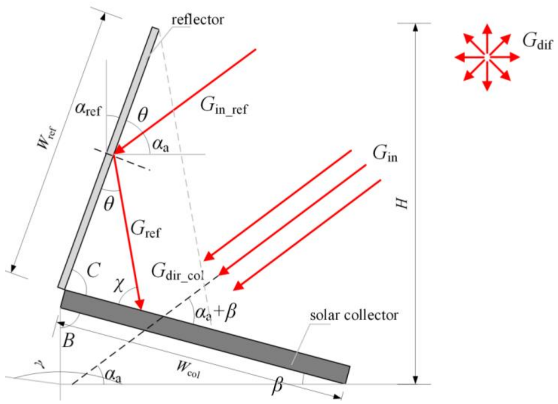

Figure 4: Cross-sectional cut of the ZigZag-cassette as starting point of first geometrical modelling.

The total irradiance falling on the PV-module is now described by:

$$G_{tot\_col} = G_{in} + G_{dif} + G_{ref} \quad (1)$$

where: G_{tot_col} is the total irradiance on the PV-module, G_{in} is the beam irradiance that is not obstructed, G_{dif} is the (isotropic) diffuse irradiance, and G_{ref} is the reflected beam irradiance. For time resolution, it was decided to start with a one hour step interval, because of two reasons: a) it keeps simulation times for a full-year analysis (8760 hours) acceptable, b) TMY-data is generally available in a one hour time resolution. This

2D-model is used on various locations with façade orientation of E, S, SW and W, and also for many variations of the geometry of the ZigZag-cassette and the material of the decorative panel. We present the results for a South façade installed in Helsinki, with a decorative panel that is reflecting quite efficiently. The cassette geometry has been varied in the maximum possible range of module tilt angle β, and decorative panel angle α_{ref}; see Figure 5.

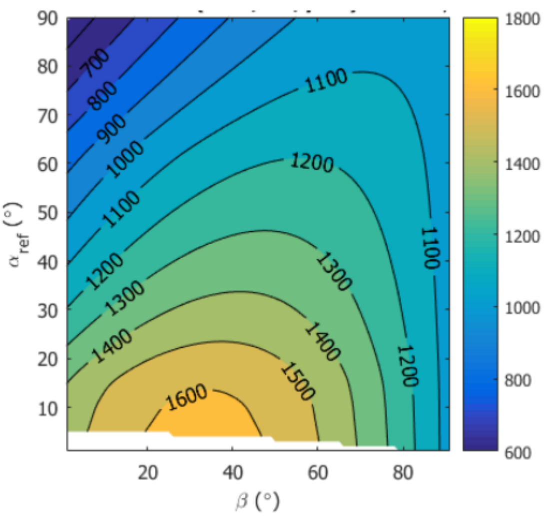

Figure 5: Total irradiance in kWh/m^2/year as function of module tilt β, and angle between decorative panel and vertical α_{ref}.

Now we can search for optimal angles at which the irradiance onto the PV-panel is maximum. The color plot of Figure 5 shows this maximum irradiance for low α_{ref} and β around 35°. It should be noted that these are results for one ZigZag-cassette. Low α_{ref} implies that fewer cassettes will fit in the total façade. That is not an issue for very large façades. However, when one would like to maximize the total yield of the façade, then this gives an additional constraint. From the -more time consuming- calculations of multiple cassettes we observed that the optimum is shifting towards less steep decorative panels.

4.2 Three dimensional geometrical modeling including the HDKR-diffuse model.

Although the model gave many insights into a ZigZag structured façade, it was recognized by experts that the diffuse light modelling is insufficiently taken into account. Therefore a major upgrade of the model has been made. The total irradiance is now described by:

$$G_{tot\_col} = G_{in} + G_{dif\_iso} + G_{dif\_cs} + G_{dif\_hz} + G_{ref\_ground} + G_{ref\_obj\_sp} + G_{ref\_obj\_dif} \quad (2)$$

with a newly decomposition into three diffuse terms and three reflected terms. It goes beyond the scope of this paper to explain each term in full detail. In short the diffuse terms with subscripts iso, cs, and hz respectively, refer to isotropic diffuse, circumsolar diffuse, horizon brightening diffuse. The reflection terms with subscripts ground, obj_sp, and obj_dif respectively, refer to ground reflected, object specular reflected, and object diffuse reflected. As for diffuse irradiance, there are several models with a different treatment of the three components. Comparison and evaluation have been made continuously [3][4][5]. Here the model developed by Reindl et al. [5] is used because of its superior accuracy [6], which was an improvement to the works of Hay and Davies [7] and Klucher [8], therefore abbreviated as the HDKR model. As for reflected irradiance, the presented terms are written down from text book material [9] following the route via a view factor. An extensive paper about the model is soon to be published in a scientific journal.

For this more accurate model, it is important to consider the precise location of the receiving spot of the irradiance. Therefore a grid has been put on the PV-module. For each grid point the irradiance is calculated with formula 2 as a function of time. The coding is done in Matlab®. The user has multiple options to visualize the results; see e.g. Figure 6.

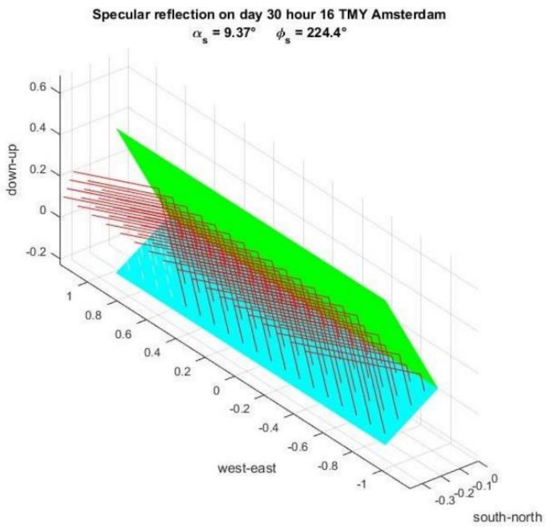

Figure 6: The intensity and direction of the specular reflection component only, for an arbitrary moment. Animated movies for full days are also available.

For the remainder of this paper, we will show the irradiance at exactly the middle of the PV-module, as this is also the location of the pyranometer in the experimental setup.

5 MEASUREMENT RESULT (IRRADIANCE & ELECTRICAL)

5.1 Irradiance

At SolarBEAT a central solar measurement station measures every minute the DHI, DNI, and GHI [1][2]. Moreover on the pitched roof of the nearby test cabin (just visible in Figure 3) the G_{POA} is measured under 35°. These irradiance measurements are a kind of reference. Now, in the ZigZag-façade the global vertical irradiance (GVI) is measured, and the G_{POA} in the middle of the cassette, as seen in Figure 3. These are all plotted in Figure 7 for the 11th May 2016. We deliberately picked this day because it shows many steep variations in irradiance, which is the most difficult situation to model. If the model succeeds on this kind of day, then it will also succeed on completely sunny and overcast days.

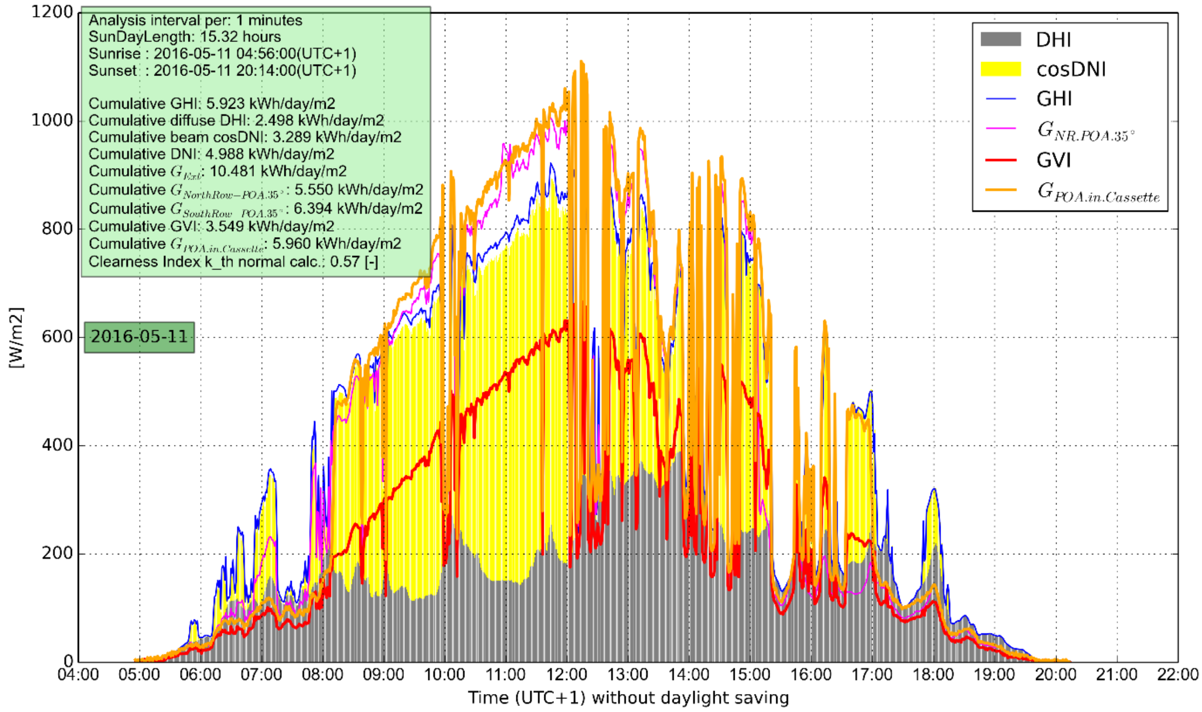

Figure 7: GHI (blue), cosDNI is the beam perpendicular to horizontal (yellow), DHI (grey), GVI (red), G_{POA} of nearby pitched 35° roof (magenta), and G_{POA} 'inside the cassette' (orange) as a function of time for the irradiance fluctuating 11th May 2016. In the green text box, the daily cumulative values are given.

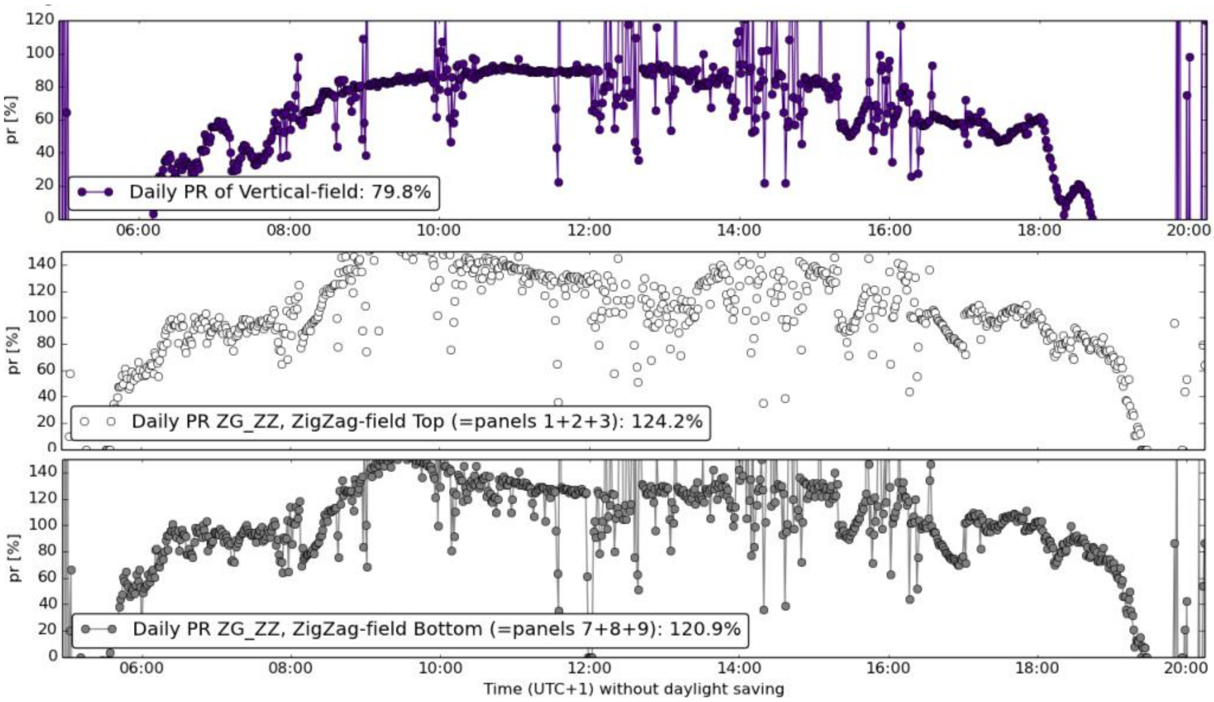

Figure 8: Measured AC Performance Ratio (PR) per minute. Top subplot: PR of reference vertical system. Middle subplot: PR of Top row of ZigZag-cassette with white reflector. Bottom subplot: PR of Bottom row of ZigZag-cassette with grey reflector. Same pyranometer (GVI) has been taken for calculating all 3 subplots.

It should be noted from Figure 7, that the pyranometer inside the cassette (orange line) receives the same amount of irradiance as the pyranometer on the nearby pitched roof (magenta line). On the one hand inside the ZigZag-cassette, the hemisphere is blocked more, giving lower reception of diffuse light. On the other hand inside the ZigZag-cassette, an extra amount of reflected light is received. Apparently for this example day, both effects are of the same order of magnitude and the net result is the observation that the PV-module in the ZigZag cassette receives as much irradiance as a pitched roof PV-module under the same angle. It remains to be seen (and doubtful) if this will hold for all the days of the year. The upcoming one full year of outdoor measurement will give an answer to this interesting question.

5.2 AC Electrical yield

As explained earlier in this paper, we do not have yet the precise relation between AC electrical yield and irradiance. But we assume a linear relationship between yield (e.g. kWh total row per minute) and irradiance integrated over the area in the cassette, e.g. [kWh/m^2] * (area PV-modules in row) per minute. An assumption which is questionable because we suspect that the irradiance is quite non-uniform distributed over the PV-module. But it would be very unsatisfactory to ignore the first electrical yield results from the new experimental setup. Therefore we present the AC performance ratio for the same day as the irradiance plot; see Figure 8.

First of all it can be seen that the vertical system has a PR=80% which is good. As all PRs are calculated with the same vertical pyranometer GVI, it is possible to compare the subplots with each other. So, in the middle subplot, we observe a different pattern which is caused by the continuously varying effect of reflection into the cassette. At the end of the day, the PR=124%. This is much more than 100%, because the specific yield (expected yield) is calculated based on the vertical pyranometer. One should note that the ZigZag-cassette construction prevents the façade to be fully covered with PV-modules. Hence when taking this geometry effect into account, the PR drops well below 100%, even below 80% for cassette geometries needed for optimal yield in North-West Europe. Finally in the bottom subplot, the pattern is very similar to the middle subplot, from which it can be concluded that the different decorative panels are not influencing the yield that much. At the end of the day, the PR=121%, which is 'just' 3% lower than the result of the white decorative panel.

5.3 Validation of Irradiance modelling

The installation of the pyranometer in the ZigZag-cassette enables us to validate the irradiance model. The advanced 3D model has been run with a time step of one minute. Real measured GHI, DNI, and DHI from the central measurement station have been used as input (opposed to the default TMY-data that one would take when modeling a virtual installation in an arbitrary city).

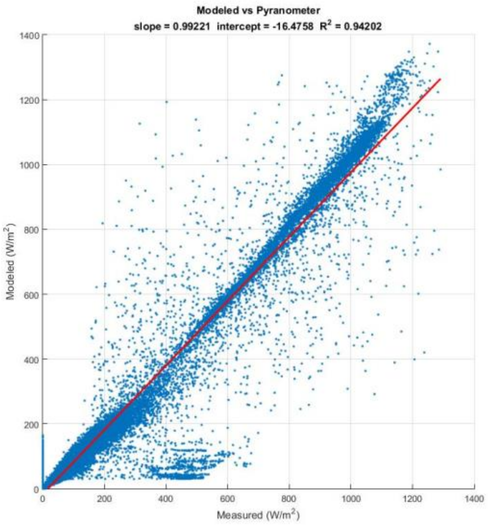

Figure 9: Modelled irradiance versus measured irradiance for the pyranometer in the middle of the central ZigZag-cassette. Every minute during daytime of May 2016 is incorporated without any filtering.

In the scatter plot of Figure 9 it can be seen that the modelled irradiance correlates quite well (R^2=0.94) with measured irradiance. One should note that May 2016 has more than 25000 minutes during daytime. Points far away of the central part are expected to be resulting from moments at which the irradiance fluctuates quite heavily. One cloud of points is clearly pointing towards a remaining issue: during sunrise and sunset, the model is severely underestimating irradiance. The reflection on nearby objects and the hemisphere blockage at the low solar angles are not modelled correctly, because these nearby objects are not taken into account. This is clearly a point of attention for future modelling work.

6 AESTHETICS

Aesthetics are very subjective and difficult to quantify. Each customer will have his own preferences. That is not a problem because the ZigZag-cassette can be tuned to specific customer wishes in terms of chosen geometry and decorative panel. In Figure 8, we saw the difference between a white and a grey decorative panel for one day only. Now summing up for all days in May 2016 - which have been measured with a time resolution of about 15 seconds without any system failure (i.e. about 100.000 measurements for each system) – the monthly result is:

Decorative panel	**Monthly AC-yield**	**Monthly PR**
Grey	28.6 kWh	115%
White	30.7 kWh	123%

If striving for maximum yield, the customer will choose for a white decorative panel. However, if the grey colour is more appealing to him (or e.g. a company colour), then the result in the table shows that the effect on system PR is not dramatic: 'just' 8% for this May 2016. Of course yearly PR can deviate from this result as the relative contribution of reflection becomes more important for winter months as we have learned from previous modelling.

In principle, any decorative panel can be chosen by the customer. Real measurements of electrical performance for any decorative panel is very time consuming. But as long as the specular and diffusive (Lambertian) reflection coefficients of the preferred decorative panel are known, we can use the model to predict the yearly irradiance inside the cassette. And assuming that AC yield will closely follow irradiance, this gives predicted kWh per year for a specific designed ZigZag-structure. In this sense we conclude that aesthetics are truly preserved, or even optimized(!), with a very acceptable compromise towards maximum yield that would come out of a ZigZag-cassette with a white decorative panel.

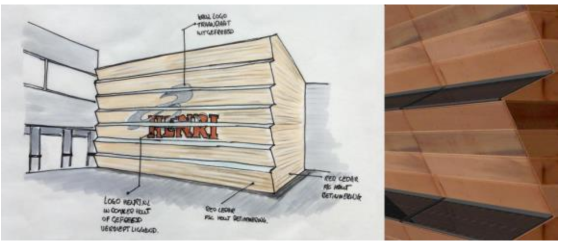

Figure 10: Example of custom-made design for a company that has two preferences: wood-finish appearance of the façade and the company logo printed on the decorative panels.

7 CONCLUSIONS

An improved irradiance model for the ZigZag-structured façade is using the HDKR-model for the diffuse components, and a threefold model for the reflected light based on view factor. For a precise implementation, it has been found necessary to perform this irradiance model on multiple locations at the PV-module, preferably in a grid with a spacing of about 10 cm. The validation of this model with measurements of all minutes of May 2016 looks very promising. Only during low solar altitude, the model has difficulty with nearby objects giving rise to albedo and blockage.

The experimental test façade has been realized in the first quarter of 2016. Analyzing the AC yield of the vertical system, that serves as a kind of reference, shows acceptable daily PRs between 75% and 80%. The PR of the ZigZag-cassettes are understood to be well above 100% because the same vertically installed pyranometer has been used as with the reference system. One should note, that in a ZigZag-structured façade, the complete façade area cannot be cladded by PV-modules only. Therefore, when comparing the total system yield of the vertical system and the ZigZag-system, the presented PR of the ZigZag-system should be divided by a factor calculated from the chosen angles in the cassette.

Finally, regarding the AC yield, it can be observed that the grey reflector produces less than the white reflector. The difference of 8% has only validity for this specific experimental setup in May 2016. The remaining months of the one full year outdoor testing will be studied closely, to be able to draw a more general conclusion.

As suggested by the title of this paper, the customer has the final say in the aesthetics of the façade. In principle he can pick any color and any decorative material (that could come from normal façade panel manufacturers). With the help of the model shown in this paper, an annual yield of a custom-made façade can be predicted and communicated to the customer in order to make the best compromise between maximum yield and aesthetics.

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9 ACKNOWLEDGEMENT

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