PERFORMANCE ANALYSIS OF PV GREEN ROOF SYSTEMS

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ABSTRACT: The common assumption is that plants underneath PV modules will cause a cooling effect resulting in a higher energy yield due to the negative temperature coefficient of PV power. The PV module temperature is measured to verify this thesis on a flat roof PV plant in Winterthur, Switzerland. Thirteen different mounting test field types with two different mechanical PV mounting systems are used, 20° or 15° tilted angles. Each type of mechanical mounting system is combined with planting beneath and with and without irrigation in the different test fields. The difference of the module temperatures, weighted according to the energy production, of all 13 analysed test fields is between ± 1.8 °C. This temperature difference results in a calculated energy yield difference of about ± 0.7 % for the used crystalline silicon modules. This value is in the range of the measurement uncertainty of the power measurement (± 1.2 %). Therefore the green roof has only negligible influence on the temperature reduction of the PV modules on the base of the used system components. However, a combination of PV and green roof is absolutely doable and recommendable provided that the mounting system is optimized for green roofs. Other more powerful benefits of such combination of green roofs and PV are the improvement of water retention in the city.
Keywords: PV System, System Performance, Thermal Performance, Green Roof

1 INTRODUCTION

According to the energy strategy 2050 of the Federal Council and Parliament of Switzerland electricity originated from nuclear power has to be completely covered by electricity from new renewable energies and 21 % attributed to PV power until 2050 [1]. Thereof, the share PV corresponds to twelve square meters PV module area per capita, which is available on the present Swiss roofs.

Cities all over the world are promoting green roofs to reduce further inner city heat generation. Chicago forced to build over half a million square meters green roofs stipulated by law in recent years [2]. The Swiss cities Zurich, Basel, Bern, Winterthur, Lucerne and St. Gallen have some requirements about goals for green roofs. In some cities, the laws are set into force recently and they are not same stringent everywhere [3]. Today, there are nearly no PV installations on the green roofs, yet.

Because of the space requirement conflict between PV on the roof and green roofs, it’s essential to combine these two systems. The goal of this project is to analyse the potential and benefits of PV panels with plants underneath. Outdoor measurements of PV module temperature and power are needed to estimate the potential energy surplus if there is a significant cooling effect observable.

2 APPROACH

2.1 Project goal

A project was set up to verify the PV performance on a flat green building roof in Switzerland. This was achieved with project partners consisting of green roof experts and photovoltaic specialists [4]. One sub goal was to check if the PV panels are cooled caused by the plants on the green roof.

2.2 Setup

A PV plant of 78 kWp was installed on a flat roof (84 m x 16 m, -3° azimuth) located in Winterthur Switzerland and the situation is shown in Figure 1. The roof is divided in 13 test fields. Eight test fields are equipped with 20° tilted commercial ZinCo mounting systems and five are equipped with 15° tilted commercial Hilti mounting systems. The two mounting types are shown in Figure 2.

Figure 1: Aerial photo of the test facility with the installed PV capacity of 78 kWp located in Winterthur, Switzerland. All modules have an azimuth orientation of -3°.

Figure 2: The two used mounting systems on the PV plant. On the left side the 20° tilted ZinCo mounting system for green roofs and on the right side the 15° tilted Hilti mounting system mostly used for flat roofs without greening.

Each test field consists of different soil conditions on the ground including gravel, different substrates and different substrate layer thickness, respectively. The whole green roof part was seeded with the herbs seed mixture “UFA-Kräuter Solardach CH” [5] from the Swiss company “UFA Samen”.

2.3 Measurements

Several module temperature sensors are installed in every test field, total 48 PT100 sensors over the whole PV plant site. The measurement uncertainty of the temperature sensors depends on the actual temperature resulting in ± 0.55 °C (k=1) at 50 °C. The used measurement electronic in the data logger contributes another 0.3 °C to the measurement uncertainty (k=1). The ambient temperature, the wind speed and direction and the power of three PV modules are measured each 10 seconds as well. The measurement accuracy of these three power measurements are ± 1.2 % (k=1). The measurements campaign was started in autumn 2014. The power of the PV modules is also measured and controlled by the SolarEdge module optimizers in approximately 15 minute intervals with a measurement accuracy of ± 5 % (k=1). Additionally three modules were selected and their power was measured with a resolution of 10 second as a reference to the SolarEdge measurement.

3 INNOVATION AND RELEVANCE

Sealed floor surfaces in cities, waste heat of vehicles and houses which build heat islands enhance the warming of the air during the day and decrease the cooling of the air during night. Thus, summer nights are four to five degrees warmer in cities compared to rural regions [3]. The economic and ecological advantage of green roofs is undisputed. Today, the decision between PV and green roof is often made on flat roofs. If it’s decided to install PV, about 16 % of heating power is converted into electricity and then bitumen or gravel is used regularly under the PV panels. The green roof has several advantages like water retention, reduction of peak water runoff, protection of the roof seal, additional insulation, cooling and air humidification of the ambient atmosphere, habitat for animals especially insects, filtering air pollutant etc [6]. With PV on green roofs, the symbiosis of these two components can be combined. In this project, the advantages and disadvantages of this symbiosis is analysed with focus on the cooling effect on the PV panels caused by the plants.

4 ANALYSES AND MEASUREMENT RESULTS

The energy weighted module temperatures were analysed at the different test fields from 01.10.2014 to 31.05.2016. The days were classified into seven classes according to the operating hours. In each of these classes, the differences in the energy weighted module temperatures between the test fields were analysed.

4.1 Data availability

Some days of data were missing due to a hardware failure of the module temperature measurement system in summer 2015. Furthermore, the days taken into account are those that have every 10 second one measurement between 08:30 in the morning and 16:00 in the afternoon available. Thus, 527 days of measurement data are analysed in the period from 01.10.2014 to 31.05.2016 resulting in an electricity production of 99 MWh for the whole PV plant according to the SolarEdge web portal data for these 527 days. Thus a specific AC yield of 974 kWh/kWp results for the annual period starting in June 2015.

4.2 Calculation of the energy weighted module temperatures

The temperature measurements are available in a resolution of 10 seconds as well as three PV module power measurements. The SolarEdge module power measurements are available for all installed modules. Unfortunately, the SolarEdge power measurements, exported from the online monitoring portal, have no constant time interval. The calculation of the energy weighted module temperatures according to Formula 1 needs a synchronised data set between the SolarEdge data and the temperature data.

$$T_{m,w} = \frac{\sum(T_m \cdot P_{m,DC})}{\sum P_{m,DC}} \quad [°C] \qquad (1)$$

Three methods are analysed by calculating the energy weighted module temperature using the SolarEdge power data. The results is compared to the the energy weighted module temperature of one module that has power and temperature measurements with 10 seconds resolution available. The methods are applied on to the SolarEdge data set using different time periods.

- Method A “Linear interpolation”: The interpolated value at a query point is based on linear interpolation of the values at neighbouring grid points in each respective dimension. The time resolution of the received values is 10 seconds.
- Method B “Nearest neighbour interpolation”: The interpolated value at a query point is the value at the nearest sample grid point. The time resolution of the received values is 10 seconds.
- Method C “closest own measurement point”: For each SolarEdge point the closest own measurement point is searched in a range of ± 10 seconds around the SolarEdge point. The time resolution of the received values is the same at the SolarEdge values.

Table 1 Energy weighted module temperature for one module with 10 second power measurement (Ref) compared with the three methods linear interpolation (A), nearest interpolation (B) and closest own measurement (C) calculated over different time periods.

Calculation Method / Time period	Energy weighted module temperature for 1 Module			
	Ref [°C]	A [°C]	B [°C]	C [°C]
2 days (08-09.11.2014)	21.08	21.20	21.20	21.22
1 month (September 2015)	32.32	32.39	32.41	32.48
Whole analyse period 01.10.2014 to 31.05.2016	31.65	31.67	31.68	31.72

Table 1 shows the results for these three methods compared to the values calculated with the 10 second data (Ref). The linear interpolation method A provides the most accurate result with a deviation of + 0.07 % compared to the Ref value.

Figure 3 illustrates the result for the 4th August 2015.

The green graph corresponds to the 10 second power measurement, the SolarEdge power measurements are indicated by black x-markers and the blue graph shows the linear interpolated SolarEdge power measurements.

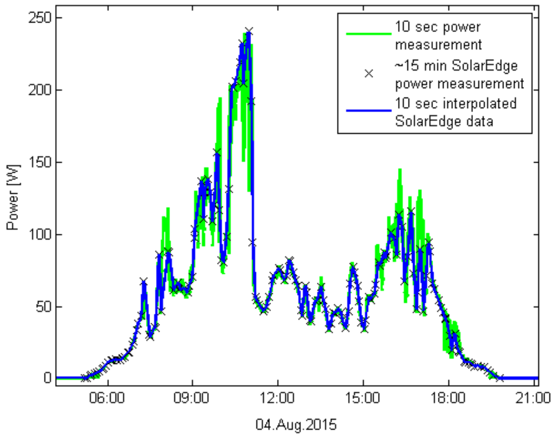

Figure 3: The power measurements for the 4th August 2015 are shown for the 10 second power measurement (green), the SolarEdge power measurement (x) and the linear interpolated SolarEdge measurement (blue).

4.3 Results

In Table 2 and Figure 4, the resulting energy weighted module temperatures calculated according to Formula 1 are shown for the whole analysed period and for each test field. The average energy weighted module temperature over all test fields is 31.7 °C. Table 2 shows also the configuration of all test fields.

Table 2 Overview over the test fields data with name, characteristics and energy weighted module temperature analysed from the 1st October 2014 to the 31th Mai 2016. Two different mounting systems are used, 8 test fields from ZinCo and 5 test fields from Hilti, respectively. At each type of mounting system, there is one field without planting and there are fields with and without irrigation (* = raincover).

Test field	Energy weighted module temperature [°C]	Deviation from the average [°C]	Mounting system	Irrigation	Planting	Vegetation layers [mm]	Vegetation material
Z50K	31.6	-0.1	ZinCo	No	No	50	Gravel
Z70R	30.4	-1.3	ZinCo	No	Yes	70 (60+10)	RieFa/ZinCo
Z70	30.3	-1.4	ZinCo	No	Yes	70	ZinCo
Z100VA	31.8	0.2	ZinCo	No	Yes*	70/100/130	ZinCo
Z100V	30.5	-1.2	ZinCo	No	Yes	70/100/130	ZinCo
Z70B	33.3	1.6	ZinCo	Yes	Yes	70	ZinCo
Z70BR	31.3	-0.4	ZinCo	Yes	Yes	70 (60+10)	RieFa/ZinCo
Z100VB	30.6	-1.1	ZinCo	Yes	Yes	70/100/130	ZinCo
H70	33.5	1.8	Hilti	No	Yes	70	ZinCo
H100V	32.1	0.5	Hilti	No	Yes	70/100/130	ZinCo
H70R	32.7	1.0	Hilti	Yes	Yes	70 (60+10)	RieFa/ZinCo
H70Ro	30.8	-0.9	Hilti	No	Yes	70 (60+10)	RieFa/ZinCo
H50K	32.9	1.2	Hilti	No	No	50	Gravel
average	31.7						

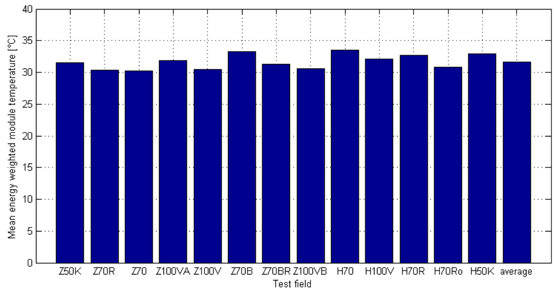

Figure 4: Average energy weighted module temperatures in °C of each test field during the measurement period from the 1st October 2014 to the 31th May 2016. The overall averaged energy weighted module temperature is shown in the last bar and corresponds to 31.7 °C.

The temperature differences result in a lower or higher energy yield because of the negative temperature coefficient (-0.39 %/K according to the module datasheet). Figure 5 shows these energy yield differences relative to the overall average.

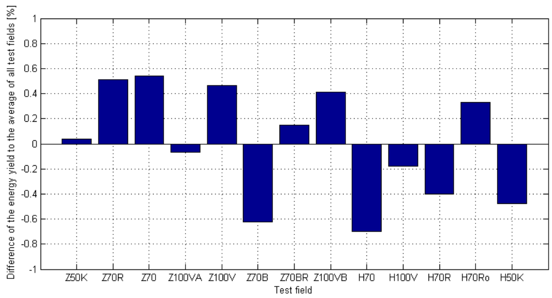

Figure 5: Differences of the energy yield relative to the average of all test fields in % calculated with the power temperature coefficient (-0.39 %/K) and the energy weighted module temperatures during the measurement period from the 1st October 2014 to the 31th May 2016.

4.4 Distribution of the resulting energy weighted module temperatures according to the operating hours of all test fields

For each day, the nominal operating hours are calculated resulting in 1356 hours over the 527 days. The distribution of the number of days according to the nominal operating hours is build and illustrated in Figure 6.

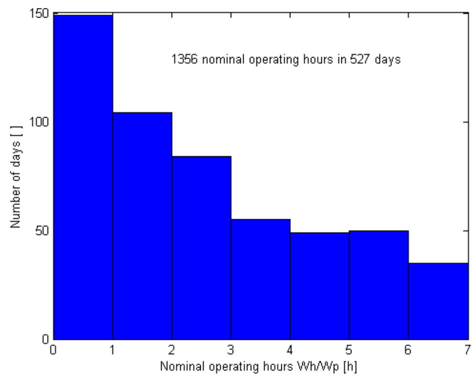

Figure 6: Distribution of the number of days according to the nominal operating hours.

Next, the daily average energy weighted temperature is calculated for each group of daily measurements that have the same nominal operating hour. This is shown in Figure 7.

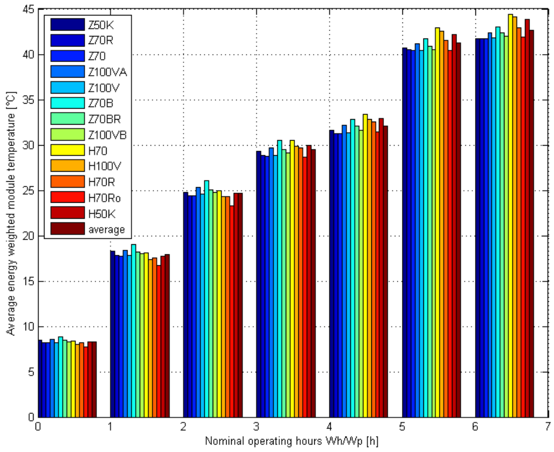

Figure 7: Distribution of average energy weighted module temperatures according to the nominal operating hours of all test fields during the measurement period from the 1st October 2014 to the 31th Mai 2016.

Figure 8 illustrates the distribution of the energy yield difference compared to the average of each range with the same nominal operating hour. This is calculated by building the differences between the energy weighted module temperatures and its corresponding average values in the same nominal operating hour range and by multiplying with the power temperature coefficient of - 0.39 %/K.

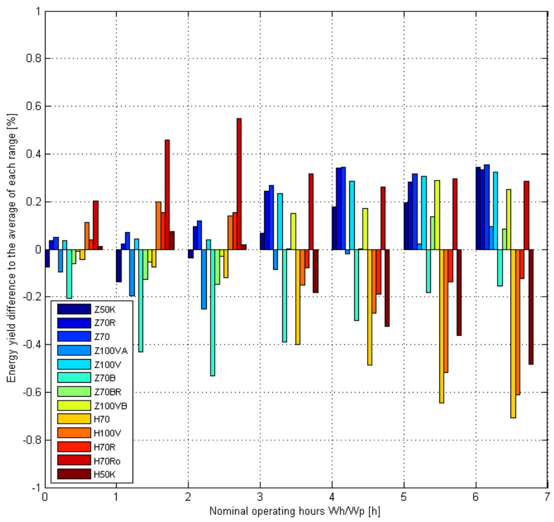

Figure 8: The distribution of the energy yield difference in % is calculated using the power temperature coefficient and the energy weighted module temperatures and it is compared to the average yield of each range with the same nominal operating hours from the 1st October 2014 to the 31th May 2016.

5 CONCLUSION

The main result of the analyses during the first one and a half year is that the difference of the energy weighted module temperatures between all the thirteen test fields is below ± 1.8 °C. Therefore, the energy yield difference is below ± 0.7 % calculated with the standard temperature coefficient for crystalline silicon modules. This difference is in the range of the measurement uncertainty of a power measurement of ± 1.2 %. It's relevant that the mounting system is optimised for green roofs in order that the plants do not cause shades on the PV modules and thus leading to expensive maintenance [7].

Because of the space requirement conflict between PV on the roof and green roofs, it's essential to combine these two systems. Due to the fact that the green roof has a negligible influence on the temperature reduction of the PV modules on the base of the used system components a new follow-up project with Solarspar was startet. The vertical East-West facing bifacial modules shown in Figure 9 combine PV and green roof and allow a cost-effective maintenance of the green roof.

Figure 9: The PV power plant "Seniorenzentrum Wiesengrund" a) with vertical East-West facing bifacial modules before module mounting b) schematic of mounted bifacial PV modules and picture of the PV powered lawnmower working autonomously beneath the PV modules, located in Winterthur, Switzerland is a follow-up project of ZHAW with Solarspar and will be start operation on July 11th, 2016.

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