ENERGY PERFORMANCE OF A 1.2 MWP PHOTOVOLTAIC SYSTEM DISTRIBUTED OVER EIGHT BUILDINGS AT UTRECHT UNIVERSITY CAMPUS

Wilfried van Sark[1], Arjen de Waal[1], Jasper Uithol[2], Niekol Dols[2], Fréderique Houben[2], Richard Kuepers[2], Michiel Scherrenburg[3], Benno van Lith[4], Ferry Benjamin[5]

[1]Utrecht University, Copernicus Institute of Sustainable Development, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands, E: w.g.j.h.m.vansark@uu.nl
[2]Utrecht University, Real Estate and Campus, Heidelberglaan 8, 3584 CS Utrecht, the Netherlands
[3]Utrecht University, Programme Team Sustainability, Heidelberglaan 8, 3584 CS Utrecht, the Netherlands
[4]BAM Bouw en Techniek - Regio Midden, Regulierenring 35, 3981 LA Bunnik, the Netherlands
[5]ProfiNRG, Leidsestraatweg 20, 3481 EX Harmelen, the Netherlands

ABSTRACT: A distributed PV system comprising of eight subsystems on separate buildings totaling an installed capacity of 1.2 MWp has been realized at buildings of the Utrecht University campus Utrecht Science Park. A detailed design process was followed taking into account the presence of surrounding buildings. This has lead to a system with modules oriented South, West, East, and even North. Most of the modules are installed at a tilt of 10 degrees. A full year of monitoring results is presented here and shows that the system is performing well, with an average performance ratio of 0.825, thus delivering more than 1 million kWh annually.
Keywords: Energy Performance, PV System, Design, Large Grid-connected PV systems, Education and Training

1 INTRODUCTION

Utrecht University aims to be CO_2-neutral by 2030 with an intermediate aim to generate half of its energy consumption in 2020 in a sustainable way, including thermal storage, the purchase of wind power and the use of solar energy. This has motivated the design and installation of 4,600 PV modules on several buildings in the Utrecht Science Park “De Uithof” in the period May-September 2016. The grid-connected system is designed such that it is predicted to generate one million kWh of electricity annually, which constitutes ~2% of the annual electricity demand. The installation of the PV systems contributes to a reduction of the CO_2 footprint. Moreover, it offers the potential to enhance research and education activities of the faculties involved.

In this contribution we will describe the performance of the system linking that to the specific design and layouts of the systems in detail.

Figure 1: Overview of locations of the eight systems at the UU campus, spanning about 2 km^2. 1: Caroline Bleeker building, 2: Victor J. Koningsberger building, 3: Library, 4: David de Wied building, 5: Jeannette Donker-Voet building, 6: Willem C. Schimmel building, 7: Martinus G. de Bruin building, 8: Waterberging Diergeneeskunde/Jongveestal (Tolakker). The Utrecht Photovoltaic Outdoor Test facility (UPOT, red dot [1]) is used for measured irradiation.

2 SYSTEM DESIGN AND LAYOUT

The design of the system was started by identifying suitable buildings with flat roofs among the many University buildings located at the Utrecht Science Park. Two main criteria were used: 1) roof was strong enough to withstand the additional weight of the PV subsystem, and 2) the building itself would not be renovated nor demolished within the next 25 years. From the remaining selection the suitability with regard to shading from nearby buildings and/or obstacles on the roofs was determined. This has lead to the eight buildings as shown in Figure 1. Several PV systems consist of a combination of East and West oriented modules, others are South oriented, and one is North and South oriented (library building, #3 in Fig. 1), due to surrounding high-rise buildings, see also Fig. 2. This does influence annual yield, however with a tilt of 10 degrees, orientational effects can be considered to be small. Building #8 has a 30-degree tilted roof and is facing South.

Figure 2: Photograph (top) of University Library system, with detail (bottom, © Ivar Pel). The system consists of 860 modules of 270 Wp, and 7 inverters. Total capacity is 232.2 kWp. Half of the modules are oriented towards South and half towards North, at 10-degree tilt.

The installation of the various subsystems has taken place between May and September 2016, a video can be found here [2]. In this video UU's chair of the University Board stresses the importance of this system for UU research and education and how it supports UU's ambition regarding sustainability.

The layout of the system is optimized using separate inverters per orientation. In total 4,474 modules of 270 Wp and 126 of 265 Wp are installed and 37 inverters of different nominal AC capacity (12, 20, 23, and 30 kW). The average ratio of AC inverter capacity to PV DC capacity is 0.825. Details of the subsystems are listed in Table I.

Table I: Subsystem details. Inverter/PV ratio is defined as AC inverter nominal capacity divided by DC PV rated capacity. Building number refer to Fig. 1. Total DC PV rated capacity is 1218 kWp.

building	size (kWp)	orientation	inverter/PV ratio
1: Bleeker	132.3	W-E	0.81
2: Koningsberger	22.4	S	0.90
3: Library	232.2	N-S	0.85
4: Wied	121.1	W-E-S	0.80
5: Donker-Voet	46.4	W-E	0.73
6: Schimmel	233.3	W-E	0.85
7: Bruijn	285.7	W-E	0.81
8: Jongveestal	131.2	S	0.81

Monitoring of performance is executed using inverter-based monitoring at 5-minute time resolution, while calibrated kWh meters are installed per building that measure at 15-minute time resolution. The latter is required in order to receive SDE+ subsidy (Stimulation of Sustainable Energy Production [3]) per generated kWh. In addition, for every orientation and building pyranometers will be installed (in total 15), and temperature sensors will be mounted to ~50 modules. This allows to link the energy yield with solar irradiation and to determine the performance ratio for every system and orientation. A web-based platform is under development in which measured power, irradiance, and module temperatures are collected, stored and visualized. Irradiation data is measured at the Utrecht Photovoltaic Outdoor Test facility [1]. In this paper we will show monthly averaged performance data.

3 PERFORMANCE EVALUATION

3.1 Data analysis

The monthly averaged irradiation data measured at UPOT is depicted in Fig. 3. The summer of 2017 clearly peaked in May in the Netherlands. The 12-month (September 2016 – August 2017) global horizontal irradiation sum is 1035 kWh/m^2.

Figure 4 shows the generated amount of energy for all subsystems for all months, as taken from inverter readings. The maximum amount of energy is generated in May 2017, i.e., 161 MWh adding all subsystems, while a minimum of 15 MWh is found for December 2016. The total amount over the full period is 1007 MWh.

The specific energy yield in kWh/kWp is depicted in Figure 5. We conclude that most systems show similar specific energy yield, however, the Donker-Voet and the Bleeker system clearly do not, especially in the months

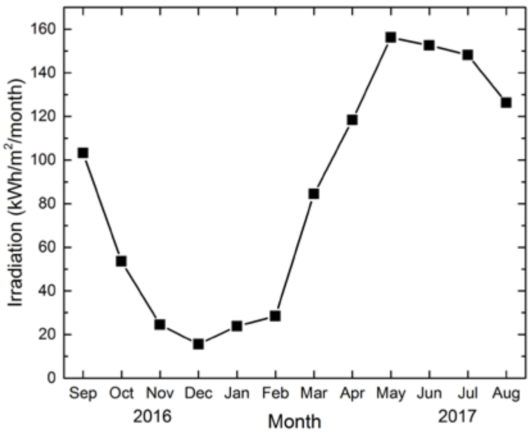

Figure 3: Monthly averaged global horizontal irradiation in kWh/m^2 for the full monitoring period, measured at UPOT.

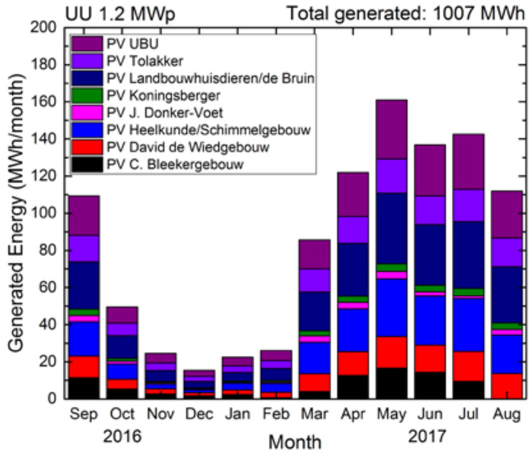

Figure 4: Monthly generated energy in MWh for the full monitoring period for all subsystems.

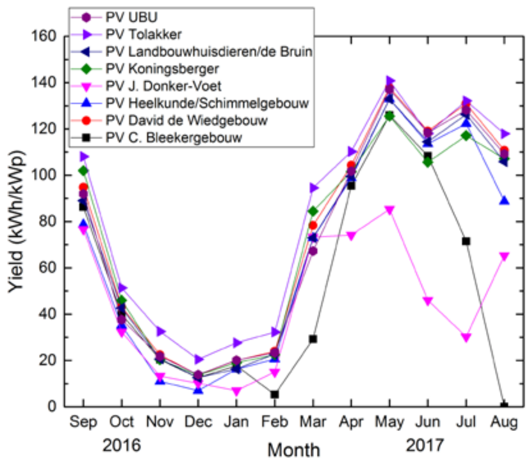

Figure 5: Monthly specific energy yield in kWh/kWp for the full monitoring period for all subsystems.

from February 2017 onwards. As the Jongveestal (Tolakker) system has a tilt of 30 degrees and is facing South, the yield is higher than other systems. The annual performance data, i.e., annual generated amount of energy, specific yield and performance ratio (*PR*) is summarized in Table II.

Table II: Subsystem annual generated energy, specific yield and performance ratio. Note, the Jongveestal is a 30-degree tilt system.

building	energy (MWh)	yield (kWh/kWp)	PR
1: Bleeker	81.0	613	0.592
2: Koningsberger	28.9	865	0.835
3: Library	202.1	871	0.841
4: Wied	110.7	899	0.868
5: Donker-Voet	24.6	529	0.511
6: Schimmel	186.1	798	0.771
7: Bruijn	244.6	856	0.827
8: Jongveestal	129.4	986	0.857

Interestingly, most systems show a good to very good performance ratio value of 0.8 or higher [4], demonstrating that the systems operate as designed. However, using the inverter data to calculate performance ratio may lead to the conclusion that two systems (Donker-Voet and Bleeker building) are not performing well, as is also obvious from looking at the annual yield. Inspection of the data on a daily level revealed that for some days, and even for the Bleeker building a full month, data from the inverter were not transmitted correctly. We can conclude this, and excluding system malfunction, as the data from the calibrated kWh meters for the Donker-Voet and Bleeker building showed that the monthly energy yields for these buildings are similar to the other buildings. If we use the energy measured from these calibrated kWh meters, an additional amount of 11.9 and 20.6 MWh for the Donker-Voet and Bleeker building system respectively can be added to the generated amount of energy of 1007 MWh. We thus find that the performance ratio of the complete system is PR = 0.825, which can be considered an excellent value taking into account the many high-rise buildings at the campus that cause shading losses.

3.2 Educational activities.

We have developed practical assignments for master students allowing them to get acquainted with analysis of various parts of the data, as part of the master course Photovoltaic Solar Energy Physics and Technology [5], in which we use a recent textbook [6]. Students were given irradiation data from UPOT (1-min time resolution) as well as inverter readings for four systems (5-min time resolution), differing in capacity but foremost in orientation. The sequence of assignments is designed such that students start analyzing PV systems that are optimized for yield (South oriented, 30 degree tilt), followed by more complex systems (mix of East and West orientations).

The following assignments were given to the students:

a) Koningsberger system**:** Make graphs of the time-series of this system. What is the maximum power generated? The PV/inverter ratio is about 1; could a smaller inverter capacity have been chosen smaller?
b) Show the variation of daily performance ratio of the Koningsberger system.
c) Jongveestal system**:** Make graphs of the time-series of this system. What is the maximum power generated for each inverter? Do you see effects of the different PV/inverter ratio values? Does the daily performance ratio differ per inverter?
d) Bleeker system: Make graphs of the time-series of this system. What is the maximum power generated? The PV/inverter ratio is about 1; could a smaller inverter capacity have been chosen smaller?
e) Wied system: Compare time-series of this system and explain differences in relation to the four inverters and the number of West, East, and South oriented panels. What is the maximum power generated? Why is the PV/inverter ratio lower than 1.
f) Show the variation of daily performance ratio for the West, East, and South oriented panels for the Wied system. Explain your results.

An example of a student's answer is shown in Figure 6, in which the student shows a daily power profile illustrating that the system combines East, West and South oriented modules. In fact, the Wied system combines four inverters and three orientations: inverter #1 and #2 serve a capacity of 30.51 kWp PV modules, inverter #3 37.36 kWp, and inverter #4 24.84 kWp, see Table III, with inverter AC capacity of 20, 20, 30, and 20 kW, respectively. The student realized that a combination of several orientations makes it possible to lower the inverter capacity below the DC PV capacity as maximum power per inverter will never be reached. However, around midday inverters clip shortly at 100 kWp.

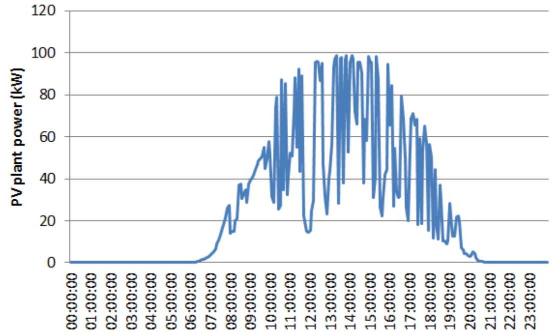

Figure 6: PV power generated on 28 April 2017 as a function of time for the Wied system.

In Figure 7 the student graphed the generated amount of energy for a period of four weeks roughly covering the month of May 2017. Variations are obviously due to variations in irradiance, while also differences in inverters can be discerned. The calculated average PR per inverter is given in Table III. The student concluded based on the data that "when the south-oriented PV capacity becomes higher (inverter #3), the performance ratio will be improved". However, the differences in PR values are not statistically significant. An MSc student will further investigate the performance of the system.

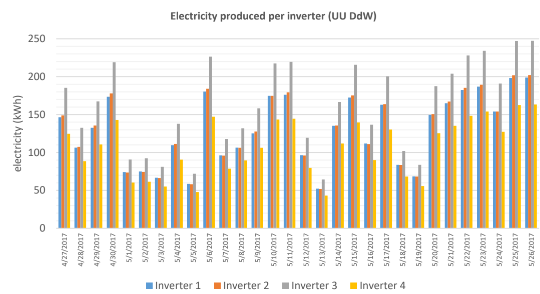

Figure 7: Daily energy yield in kWh for the Wied system showing differences per inverter for the period 27 April 2017 to 26 May 2017.

Table III: Inverter analysis for the Wied system.

inverter	PV capacity (kWp)			*PR*
	W	E	S	
1	12.42	12.42	5.67	0.899
2	12.42	12.42	5.67	0.903
3	12.42	12.42	12.42	0.911
4	12.42	12.42	0	0.907

4 CONCLUSION

In this paper we have described the design and realization of a 1.2 MWp distributed PV system on eight different buildings at the Utrecht University campus Utrecht Science Park. A combination of East, West, South, and North oriented PV subsystems is shown to perform well, with annual yield of over 1000 MWh and an average performance ratio of 0.825. Detailed performance analysis is presently part of a Master level course on photovoltaics.

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