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Energy performance assessment of a semi-integrated PV system in a zero emission building through periodic linear regression method

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Abstract

The ZEB Living Laboratory is a pilot building and experimental facility realized within the Research Centre on Zero Emission Buildings. The building is a single-family house designed to reach the ZEB-OM target – Zero emission Buildings when emissions for operation and building materials are accounted.

The building has a semi-integrated photovoltaic (PV) plant installed over two slopes of the building's roofs. The total installed power (DC) is approximately 12.5 kWP. Each PV roof is connected to a power inverter with a nominal AC rated power output of 4.6 kW, based on a layout that optimize energy conversion, given the fact that shading over the two roof slopes is different.

In this paper, the performance analysis of the PV system is carried out considering the six months in the first year of operation of the system. A graphical analysis based on the linear regression method is presented and the array yield is compared against the reference yield (Performance Ratio). The analysis gives a general overview of the performance of the system, and a focus is then placed on the understanding of the system's output in relation to the undersizing of the PV inverters.

Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: PV; Living Laboratory; Performance ratio; Monitoring; Zero Emission Building

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Nomenclature

ILR	Inverter Loading Ratio [-]
PR	Performance Ratio [-]
PR'	Performance Ratio (calculated without clipping) [-]
Y_{ref}	Reference yield [h]
Y_{sys}	System yield [h]

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1. Introduction

1.1. Background

Photovoltaic (PV) systems are nowadays robust energy conversion technologies that can provide power to a grid-connected building. In many countries PV installation in buildings are becoming more and more common, and they are nowadays planned, installed and operated (almost) without the need of particular consulting services.

In the Nordic context and in Norway in particular, PV market is growing significantly in the last years, but the penetration of this technology is still very limited. This is particularly due to the relatively low annual solar irradiation in this region, compared to other European and world regions, which makes this technology less cost-effective than in other climates. At the end of 2014 [1], the total installed capacity reached in Norway ca. 13 MW, in Sweden ca. 79 MW, in Finland 8 MW. Only Denmark shows a higher figure, with a total of 606 MW connected to the grid by the end of 2014 (accounting thus alone for more than 85% of the capacity installed in the Scandinavia).

Zero Emission Buidings (ZEB) can be realized with very different technologies and systems [2]. However, it is becoming more and more clear that PV systems integrated in the buildings are often a “must” solution in order to reach the ZEB targets. In this perspective, detailed investigations on the performance and optimization of PV systems in the Nordic context are important activities to enable the transition to a world where buildings do not contribute to greenhouse gasses emissions.

The ZEB Living Laboratory is an experimental facility (and a single family house) realized within the activities of the Research Centre on Zero Emission Buildings [3]. The main scope of the building is to test human-technology interaction and to assess the performance of components and systems in a ZEB perspective, being designed to reach the ZEB-OM target [4]. The ZEB Living Laboratory has been equipped with extra-technologies for experimental purpose compared to an equivalent building not used as a laboratory, and it is provided with an advanced monitoring system that records the energy and environmental performance of the building’s sub-systems. Among the others, the semi-integrated PV plant installed on the roof slopes of the house is monitored too.

1.2. Aim of the paper

This paper presents the analysis of the performance of the semi-integrated PV system of the ZEB Living Laboratory. The monitoring system has been in place for roughly one and a half year at the time this paper is written. However, because of frequent operations during the warm-up and calibration phase of the facilities, continuous monitoring is only available for slightly less than one year, with some periods without data because of maintenance. The analysis presented in this paper focuses only on six months (from April 2016 to September 2016). Solar energy converted in these months represents more than 80% of the expected total solar energy converted by the plant in one year. This analysis thus give a good understanding of the performance of the plant in the period of the year when it is expected to contribute to the greatest extent to the zero emission balance of the building, while the performance in the months with the lowest conversion is herewith not presented for the lack of space.

The performance of the PV plan is analyzed through a simple metric, the so-called performance ratio (PR). This metric describes the overall behavior of the system, without detailing the performance of each sub-component and the losses that arise with the operation of the PV plant. The analysis aims at obtaining the PR for different months of the monitored period in order to highlight the change in the performance of the system based on the intrinsic features of the plant. Relevant aspects in this context are the roof’s geometry (which can cause self-shading), and possible shadings from the surroundings.

Moreover, the analysis has a particular focus on the performance of the system in relation to the undersizing of the inverters, a common practice in PV plant design [5]. This design strategy has several reasons, based primarily on cost-effect considerations in term of installation (considerable reduction of inverter costs with minimal reduction of energy output), in term of operation (maximization of the value of daytime energy and minimization of peak in the conversion output), and should be carried out in light of local solar resource characteristics and temperature [6]. However, in the framework of design of ZEBs, where all the components and systems are optimized, and they are asked to deliver the maximum possible output, the loss of PV conversion due to the undersizing effect of inverter might affect the successful implementation of the ZEB design intentions.

2. Materials and Methods

2.1. The PV plant and the monitoring system

The PV plant of the Living Laboratory [3] is composed by a total of 48 PV modules. Each module has 3 strings of 20 polycrystalline silicone cells with bypass diodes, with a total dimensions: 1,67m x 0,99m. The PV module has a nominal power (values measured at STC) of 260 W (Vmpp: 30.7 V; Impp: 8.5 A), and the efficiency 15.8%. At a low irradiance of 200 W/m^2 (with AM 1.5 and cell temperature 25°C), at least 96% of the STC module efficiency should be achieved, according to technical documentation.

The modules are equally distributed (24 modules each) on the two roof slopes (called north roof and south roof, though both are facing south) of the building (Fig. 1), whose tilt angle is 30°. The modules are grouped in two strings each slope, leading to a total DC installed power for each roof of 6.24 kW_P (12.48kW_P for the whole plant).

Each PV roof is connected to a power inverter with a nominal AC rated power output of 4.6 kW (single-phase, 230 V line). The European weighted efficiency of each inverter is 96.5%. The layout of the system (2 inverters, one for each roof) was designed in order to optimize the total energy conversion, given the fact solar irradiation conditions for the two roof slopes can be different (the northern slope being partially shaded by the southern slope). The inverter loading ratio (ILR) [7], which describes the ratio of the arrays' nameplate DC power to the inverter's peak AC output power, is little less than 1.35 for both the roofs.

The PV plant is equipped with monitoring system based on in-build sensors in the inverter and external sensors connected to the main data acquisition system of the building. Global solar irradiation is measured, both on the horizontal plane and on the PV plane (south-facing, tilted plane with angle 30°), with two thermopiles (accuracy: II class pyranometer). AC output from the inverter is monitored with two electric energy meters (one each inverter), with a resolution of 1 Wh and an accuracy of 2% [3]. The inverters are equipped with a proprietary monitoring system that can be used to investigate more in details the performance of the PV plant's sub-components such as PV modules and inverters. A comparison between inverter output values from the in-built monitoring system of the inverters and the external meters have shown almost perfect agreement between the two readings.

Data are recorded with a variable time-step depending on the source (30 s. data recorded by the main data acquisition system of the building; 5 min. data recorded through the inverter in-built sensors), as a result of sub-minute sampling. Data are then post-processed for data analysis to obtain quantities with a time-step of 5 min. Data recorded by the main acquisition system (sensors not in-built in the inverters) are used in this analysis.

2.2. Performance metric and procedure

The performance of the PV plant in the Living Lab is assessed through the Performance Ratio (PR) metric (Eq. 1). This is defined as the ratio of the actual AC energy output (Y_{sys}), or system yield, over the reference yield (Y_{ref}), i.e. the maximum theoretical yield achievable through the system.

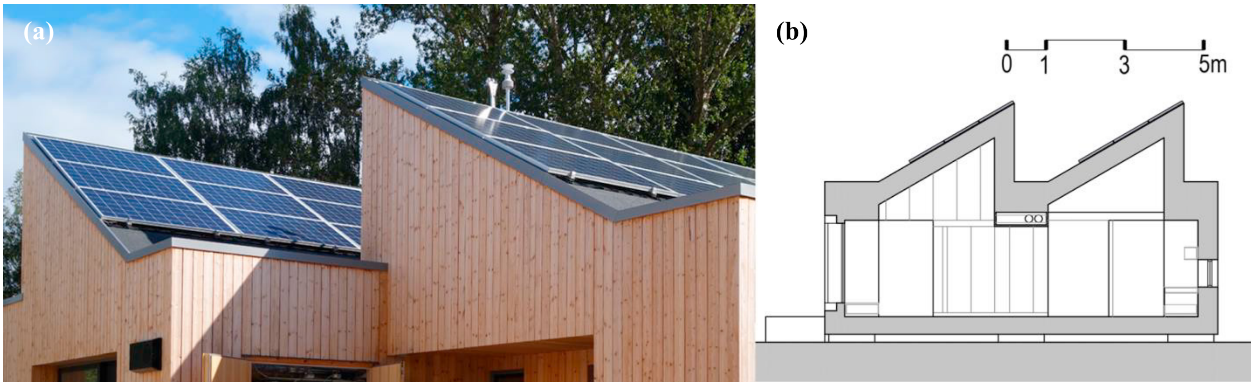

Fig. 1. (a) view of the two roof slopes with semi-integrated PV; (b) vertical section of the ZEB Living Lab with the two roof slopes facing south.

$$PR = \frac{Y_{sys}}{Y_{ref}} \quad (1)$$

The system yield is calculated as the AC energy delivered by the plant normalized over the nominal peak power of the PV plant. The reference yield is obtained as the irradiation measured on the PV plan normalized over the reference irradiance as STC (1 kW/m^2). The PR index can be calculated for different time ranges, and shows the actual performance of the PV plant vs. the maximum theoretical performance of the installed system.

For reference, it is worth mentioning that a high-performance PV plants can easily reach yearly PR values higher than 0.8 (i.e. the PV plants deliver 80% of the maximum theoretical performance of the modules at STC).

In this investigation, the PR value has been calculated for time steps of 5 min. based on electric energy meters readings every 30 s. The linear regression method is then used to assess the monthly PR value, which is also processed through a graphical analysis [8]. The couples of Y_{sys} and Y_{ref} values are plotted as scatter plot in a chart, representing the PR value for each time-step; the average monthly PR value is the slope of the linear regression line for the defined time interval. The use of a linear regression is supported by the (simplified, yet reasonable) assumption that the system yield is proportional to the reference yield. The graphical analysis is then carried out to highlight the differences between one month and the other, as well as between the two roofs' performance.

3. Results and discussion

In Fig. 2 the plots of the system yield (Y_{sys}) valules vs the reference yield (Y_{ref}) values are shown, for the 6 months considered in this analysis. PR values and correspondent linear regression curves (calculated for a two week dataset each month) are also shown for each part of the plant (only north roof, south roof, and the total PV plant).

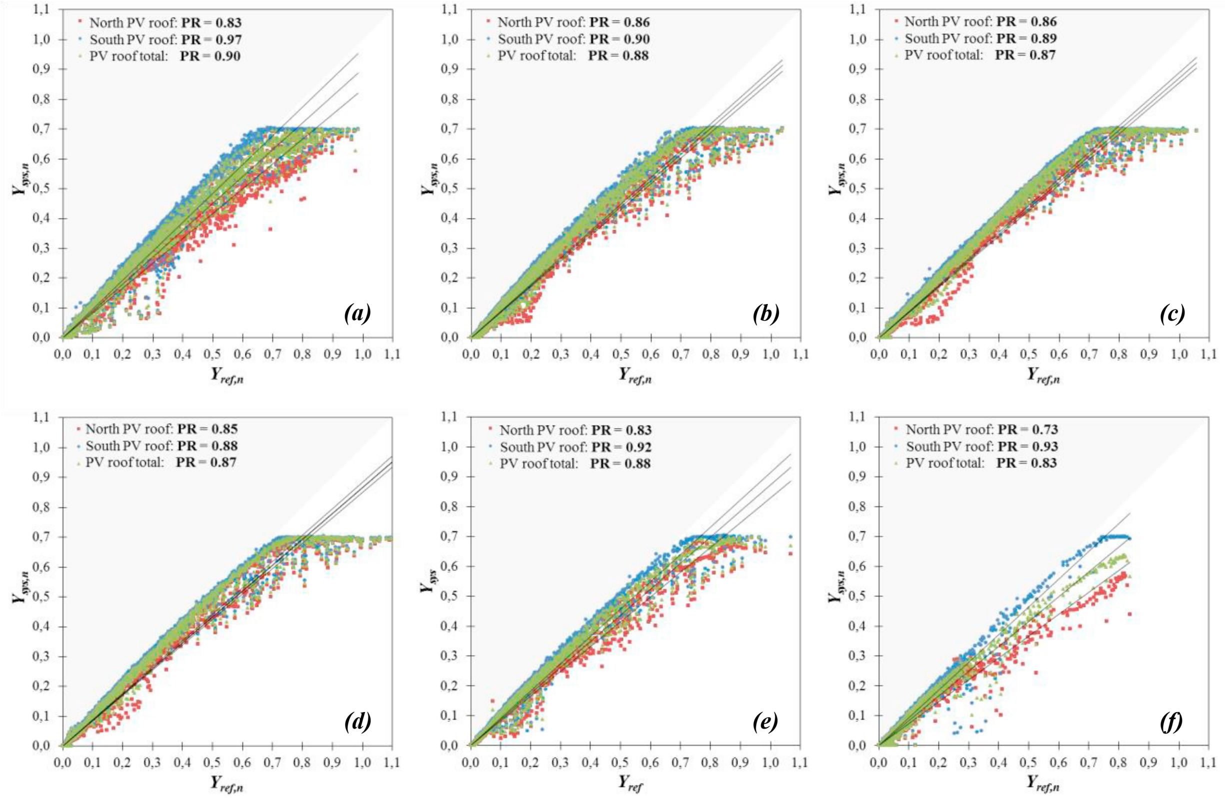

Fig. 2. Plots of the Y_{sys} vs. *Y*ref and PR values for different parts of the plan (north roof, south roof, and total), during 6 months in 2016: (a) April; (b) May; (c) June; (d) July; (e) August; (f) September – two weeks data each period, 5 min. time-step.

The analysis shows that for the selected periods the PV plant reaches a satisfactory performance, in line with the state-of-the-art technologies installed. The PR values for the whole plant are always higher than 0.8 and reach very high values around 0.9, even if one of the two roofs (the north roof) is partially shadowed by the other roof. This phenomenon is particularly evident when the performance of the two different roof slopes is assessed. In the central part of the summer (June and July), due to the sun altitude, the self-shading effect is minimal and the PR for the two roof slopes is very close (e.g. 0.86 and 0.89 in June; 0.85 and 0.88 in July, for the north and the south roof, respectively). Conversely, a larger difference between the PR values is registered when moving away from the central part of the summer: in September, the PR of the north roof is 0.73, while the south roof (the one fully exposed to solar irradiation without self-shading) still shows a PR of 0.93.

A more scattered distribution of the values (red squares in Fig. 2) of the north roof compared to a more grouped distribution (along the linear regression slope) of the values correspondent to the south roof (blue dots in Fig. 2) is also an evidence of the less stable performance of the north roof due to shading by the south roof. It is worth mentioning that values of the reference yield (Y_{ref}) higher than 1.0 are not meaningless, but occur whenever the solar irradiance over the PV plan is higher than the solar irradiance at STC (1.0 kW/m^2). On the other hand, values of system yield (Y_{sys}) substantially higher than 1.0 should be interpreted as measurement.

Even though the performance of the south roof seems extremely close to the maximum theoretical limit (PR = 1), the calculated PR values are always around 0.9 (still a remarkable value). This result can be explained considering the so-called “clipping” effect, i.e. the fact that not all the delivered DC power is converted by the inverter to AC power because of inverter undersizing. This phenomenon is particularly evident in the graphical method, where it is possible to see that the system yield (Y_{sys}) values are limited to approximately 0.70 *h* (to be more precise, 0.68 *h*). This value corresponds to a DC output from the 24 modules of approximately 4.3 kW, i.e. the inverter cannot convert the part of the power from the solar generator that exceeds 4.3 kW.

Clipping is evident in all the six months analyzed, with September being the only month when this effect is of little relevance. In particular, it is possible to see that the PR of the south roof in September is higher than that in May-August. This behavior could be explained considering the dependency of the modules’ performance on the module’s temperature (and September is characterized by a lower air temperature, which may affect positively the performance of the module, compared to June and July). However, it is also part of the explanation that the clipping reduces the PR calculated over the entire dataset, since PR values correspondent to Y_{sys} values higher than 0.68 *h* is lower than that theoretically achievable if the inverter DC input were larger enough to convert the whole DC output from the PV strips into AC power.

A precise assessment of the effect of clipping on the total harvested solar energy is not a trivial task, but a preliminary evaluation of this phenomenon can be carried out again by means of the linear regression method applied to the PR. By filtering out vales of the dataset characterized by a system yield (Y_{sys}) higher than 0.68 *h*., a new PR index (PR’) is calculated without the clipping phenomenon. The obtained values are rather stable for all the months (PR’ = 0.96 for all the months but April, which reaches a value PR’ = 0.99, in case of the south roof; PR’ = 0.90 in May-July, and slightly different values in the other months, in the case of the north roof) and testify also the robustness of both the system and of the analysis. By applying this PR to the reference yield (Y_{ref}) in correspondence of the values of the system yield that exceed 0.68 *h*, it is possible to calculate a new system yield that neglects the effect of the undersized inverter. A new total energy output can be then calculated and referenced to the original, monitored energy output from the PV plant. The energy output loss due to clipping is summarized in Tab. 1.

The energy output loss reaches the highest value in July, with a missing 4% of the total potential output of the system due to the undersized inverter, while in September (and presumably in the other months outside the analysis) the missing energy output is less than 1 % (i.e. well within the experimental accuracy). These results are in line with the literature (e.g. [7]), where optimal ILR around 1.25 determines minimal losses due to clipping (in the range of few percent).

Table 1. Calculated energy output loss due to clipping.

April	May	June	July	August	September
2%	3%	3%	4%	2%	< 1%

4. Conclusion

In this paper, the energy performance of the semi-integrated PV plant of the ZEB Living Laboratory has been presented. The analysis is limited to the six most productive months of the year, and reveals a satisfactory performance of the system. The analysis has been conducted using the linear regression method to calculate and visualize the Performance Ratio, i.e. the obtained energy output referenced to the solar energy input to the PV plant.

The PV system presents PR values in high ranges (close to 0.9 for most of the analyzed months, and however well above 0.8 in the worst month of the six considered). The geometrical features of the PV plant (on two roofs, both facing south, with potential self-shading) has an impact on the output of the system only outside the summer season, when most of the PV converted energy is obtained by the plant. In September and in April, the PR of the northernmost roof is lower than that of the southernmost roof, showing that the latter shadows the former, and that the geometrical features of the roof thus affect the total output of the system.

The analysis also highlights the effect of undersized inverters (with an ILR of approximately 1.35), that constitutes a bottleneck in the solar energy conversion flow (from DC to AC). Because of this configuration, which is very common and has its ground in cost-effectivity of the plant and predictability of PV output under peak conditions, there is a potential loss of convertible DC energy. These value is relatively small (maximum 4% of the actual converted energy) and in line with systems current best practice for PV plant design.

If on the one hand, clipping losses are acceptable from a cost perspective and give stability of the energy flow from renewable energy sources, on the other hand these represent a non-optimal use of components in a system. In particular, PV modules are, from an embodied emission perspective, elements of the construction with a high impact, and their use should be therefore optimized in order to facilitate the achievement of the zero emission building target. Furthermore, an oversized DC input to inverter may reduce their life-time, and thus increase emissions associated to their maintenance/substitution.

In the context of zero emission buildings, where all the components of the construction need to find the right balance between performance and embodied emission, it is therefore interesting to investigate if conventional guidelines for design of PV systems integrated in the building need to be revised. This question is definitely too ambitious to be treated in this paper, which instead focuses on monitoring the performance of the system as realized. Future activities will instead focus on finding the optimal PV plant configuration given the geometry of the building, the exact site insolation and the embodied emissions of the system's components.

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