# Investigating the potential for flexible demand in an office building with a vertical BIPV and a PV roof system

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**Abstract:** Building Integrated Photovoltaics (BIPV) are becoming an attractive solution in the context of high penetration of photovoltaics in buildings caused by the strive to achieve net or nearly zero energy status. Besides retrieving solar radiation to produce electricity, BIPV also offers aesthetical advantages because of its architectural feature. However, when integrated into vertical façades, the angle of the PV modules may considerably affect the efficiency of BIPV compared with horizontally oriented modules in the same location and altitude. This paper reports on the electrical energy performance of an office building, Solar XXI, located in Lisbon, Portugal, which was installed on the South façade a BIPV (12 kWp) and an additional photovoltaic roof system in a nearby car park facility (12 kWp) for electricity generation. The purpose of this paper is to investigate the possibilities of introducing a flexible demand side response to satisfy the local energy demand with the energy generated locally. Results are reported regarding *Load Match* for different scenarios which are developed from monitoring data obtained during March 2016 (winter season) and July 2016 (summer season).

## 1. Introduction

### 1.1. Background and motivation

Statistics are showing that buildings are responsible for 40% of energy consumption in the EU and U.S. (Pérez-Lombard et al. 2008). In this context, it is of fundamental importance to identify strategies for the building stock to meet the objectives in terms of energy efficiency and climate change set by different countries (Aelenei et al., 2013a).

Unlocking the potential of energy efficiency in the buildings sector is a priority for EU countries. One of the most important legislative instruments aiming at this is the directive 2010/31/EU (EUD, 2010) which require MS to draw up national plans for increasing the number of nearly zero-energy buildings (nZEBs). A nZEB refers to a high energy performance building of which annual primary energy consumption is covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (Aelenei et al. 2013). One such building is Solar XXI, located in Lisbon, Portugal (Gonçalves et al., 2012). Solar XXI is an office building which integrates a variety of energy efficiency measures and strategies and has installed on the South façade a BIPV (12 kWp) and an additional photovoltaic roof system in a nearby car park facility (12 kWp) for electricity generation. Because BIPV serve dual functions, they are very attractive because of their ability to meet both the energy and the users comfort requirements at the same time.

The main aspect investigated in this study is the potential for energy flexible demand in an office building which integrates two different PV technologies, a façade BIPV and a photovoltaic roof system in a nearby car park facility. Solar XXI has a proven record of high performance with respect of zero energy concept. However, because the supply from renewable sources is governed by the availability of the respective primary energy source, there is often no correlation between production and consumption (Montuori et al., 2014). This mismatch is approached with the adoption Demand Response (DR) measures and the results reported in terms of *Load Match* indices for different scenarios which are developed from monitoring data obtained during winter and summer season.

## 1.2 BIPV in ZEB context

Integrating renewable energy sources in nZEBs is the key factor to achieve the desired level of zero energy performance, but there is a global consensus that a consistent approach should first explore the available energy efficient measures (Aelenei et al. 2013b). Regarding the integration of renewable sources, BIPV represent an attractive solution if designed to generate electricity, generate heat to improve comfort of occupants during heating season and improve the aesthetics of the building if installed on the façade. However, there are some important variables to consider in the case of BIPV systems integrated on the façade. One of them is related with the sub-optimal angle of irradiation which, together with the shading posed by surrounding obstacles, may significantly affect the performance of the system and in turn, the zero energy expected balance. Thus, one way to counteract this disadvantage is to use BIPV in conjunction with a roof system in a nearby car park facility.

## 1.3 ZEB Balance and Boundaries

While the approach followed by Solar XXI, which combines a BIPV system on the South façade together with a PV roof system in a nearby car park facility, appears to be suitable, it may raise concerns regarding the definition of nZEB in terms of boundaries. If the boundary in terms of energy flow is limited at the building footprint, the energy generation of the roof system is not part of the energy balance calculus. However, if the boundary is drawn around the building site (Torcellini et al., 2006) then the PV located on-site in the park nearby is part of the energy balance calculus. Additional concerns regarding grids and conversion factors could also be considered in the case of community-based infrastructures where all buildings are part of a cooperative net zero energy community (Amaral et al., 2016), but this approach is out the scope of this work. In the context of this work, the energy balance of the building is calculated with delivered energy (*DE*) supplied by the grid to the building and with the energy generated but not used in the building energy balance, feed-in energy (*FE*), at building site, as (Salom et al., 2011), (Sartori et al., 2012):

$$NZEB = \sum_{i} FE_i \times fe,i - \sum_{i} DE_i \times fd,i \qquad [1]$$

where *f* are factors which are used to convert the physical units into other metrics, such as primary energy or equivalent carbon emission. Because there are no specific requirements for nZEBs in Portugal, the framework here follows the common rule according to which, if the annual energy balance is neutral (i.e. $NZEB = 0$), the building is commonly referred as a Net Zero-Energy Building or NZEB. If the building falls short of the neutral balance then it can be referred to as a nearly Zero Energy Building or nZEB. In the scenario where the balance is positive ($NZEB > 0$) the building is referred as a plus energy building.

Regarding the balance period, a yearly balance is suitable to cover all the operation settings concerning the meteorological conditions in most cases.

## 1.4 Energy Flexibility in ZEB context

With the high penetration of photovoltaics in buildings caused by the strive to achieve net or nZEB status, grows the amount of intermittent energy that flows to the grid, causing occasional periods of overproduction (Montuori et al. 2014). This mismatch caused by the lack of correlation between production and consumption, can be addressed with three categories of measures: Supply-side management, which is the adaptation of the electricity generation to demand through (flexible) conventional capacities, demand-supply management, which reflects the spatial or temporal decoupling of supply and demand by extending electricity grids or energy storage capacities and demand-side which can be defined as changes in electric use by demand-side resources from their normal consumption patterns in response to load price and/or high renewable generation periods (Boßmann and Eser, 2016). In the ZEB context, investments and studies on energy flexibility measures based on DR are getting more relevant and in this respect, two main approaches, *Thermal Energy Storage* (TES) and *Load Shifting*, are frequently used to deviate the electricity consumption of a particular building from the typical plan (Amaral, 2016). The approach followed in this work is based on *Load Shifting* which shifts the electricity demand to later times through the control of electrical devices to periods of high renewable energy generation.

## **1.5 Energy Matching**

Many recent studies have focused on the energy matching analysis of the NZEB (Mohamed and Hasan, 2016). One of the most common ways to capture the energy flexibility features is through the dynamic interplay between the on-site energy generation and the building loads, often called *Load Matching* (*LM*):

$$f_{load,T} = \min\left(1, \frac{G(i) - L_o(i)}{L(i)}\right) \qquad [2]$$

where $T$ is the period of evaluation, $G$ the PV generation and $L$ the building load (Salom et al. 2011). The higher the LM, the lower the seasonal unbalance of energy exchanged with the grid [9]. For individual buildings with on-site generation, LM determines how the building interacts with the distribution grid, describing the degree of utilization of on-site energy generation related to the local energy demand, which may have impacts on the value of the electricity generated on-site if bought and sold electricity are valued differently (Salom et al., 2014a). In this context, other two indicators are suggested to describe the LM; *Load Cover Factor* (*γ load*) and *Supply Cover Factor* (*γ supply*) (Salom et al., 2014b):

$$\gamma_{load,T} = \frac{\sum_{i}^{N+1} \min\left[G(i) - l(i), L(i)\right]}{\sum_{i}^{N+1} L(i)}\ ;\ \gamma_{supply,T} = \frac{\sum_{i}^{N+1} \min\left[G(i) - l(i), L(i)\right]}{\sum_{i}^{N+1} G(i)} \qquad [3]$$

where $l$ stands for the energy losses. *γ load* factor represents the percentage of electrical demand covered by on-site electricity generation whereas the *γ supply* factor, also known as *Self-Consumption Factor*, is defined representing the percentage of the on-site generation which is used by the building. Generally speaking, the high *γ load* and *γ supply* values mean better energy matching, the best scenario of 100% load cover and supply cover factors being indicated by values of 1.0 (Mohamed and Hasan, 2016). The smaller the period of evaluation (time step) the more accurate energy matching analyses. However, small periods in minutes or seconds needs a fine resolution of the load and generation powers. In this study, the energy matching analysis is based on *γ load* and *γ supply* cover factors using 15 minute resolution data from a monitoring campaign. As shown by Salom et al. (2014b), *γ load* is a good indicator of when and how much of the on-site supply is self-consumed. In addition, the losses-of load probability factor (*LOLP*) shows how often the on-site supply does not cover the on-site demand, and thus how often energy must be supplied from the grid. *LOLP* is defined by Equation 5:

$$LOLP = \frac{time_{L(i) > \left[G(i) - l(i)\right]}}{T} \qquad [4]$$

## 2. Case study description

### 2.1 Building description

As mentioned above, this study reports on the electrical energy performance of an office building located in the campus of the National Laboratory of Energy and Geology, in Lisbon, Portugal. Solar XXI is three story demonstration building which combine wisely a wide range of energy efficiency measures and strategies with a BIPV system integrated on the main building façade (South oriented) together with a PV roof system in a nearby car park facility to reach a Net Zero Energy performance (Aelenei and Gonçalves, 2014). The BIPV system integrated into the south façade includes about 100 m$^2$ of photovoltaic modules of multi crystalline silicon, producing an average of 12 kWp directly used by the building. The PV CIS system installed in the PV roof of the car park, also 12 kWp, provides electricity to Solar XXI and the remaining buildings of the campus. The building relies on South oriented large windows and on the BIPV system to meet the comfort requirements during heating season. South oriented windows are outfitted with external shading devices to prevent overheating as the building is not equipped with any means of active cooling. Also, the BIPV modules are mount at a distance of 10 cm away from the insulated masonry wall to allow airflow. This allows the building the lower PV operating temperatures and improve the thermal comfort during the heating season in the adjacent rooms with heat recovery which serve as air pre-heating system. Detailed information regarding the thermal performance of the BIPV of Solar XXI is presented in Aelenei et al. (2014). The building has no HVAC system and relies on natural ventilation and on buried pipe to provide fresh air to the occupants and cooling during summer nights, respectively.

### 2.2. Building monitoring

Solar XXI monthly data regarding energy load and generation is collected on a regular basis. The corresponding data collected during 2016 allows for a preliminary assessment of the building in the ZEB context. Fig. 1 shows the energy load versus the energy generated by the BIPV and PV roof together, on a monthly basis.

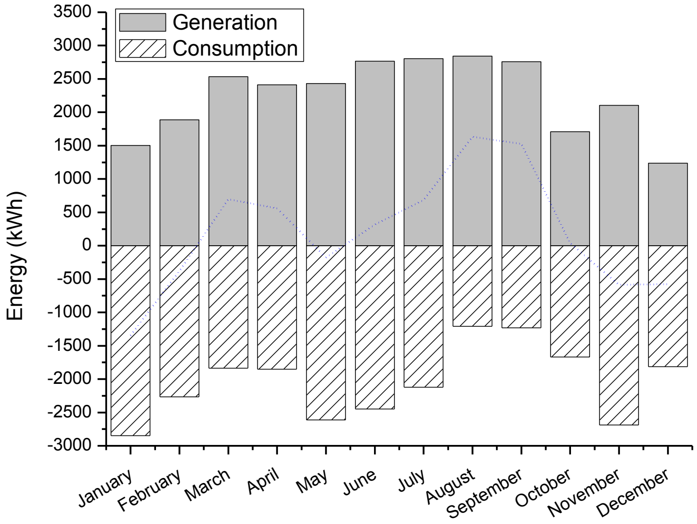

Fig. 1. Monthly energy consumption and energy generation from PV of Solar XXI during 2016

Analyzing Fig. 1 one can note that the months during the winter period are characterized by a negative balance (blue line) whereas the rest of the period is characterized by a positive balance. The only exception to this pattern is represented by May, when an unexpected negative balance was recorded due to excessive energy consumption. A considerable energy consumption was also recorded in January when the consumption almost doubled the production. Despite of these, the data recorded is in line with the expected seasonal balance where energy production during the winter season is lower due to fewer daylight hours and the significant amount of cloudy days when compared with summer season in Portugal. Fewer daylight hours is also responsible for higher electricity use for artificial lighting. Regarding the yearly balance, one can note that, based on electricity generation and load recorded during 2016, Solar XXI is a plus energy building in terms of zero energy performance.

## 2.3 Assessing the potential for energy flexibility

The data shown in Fig. 1 above does not allow to perform an accurate energy matching analysis. For this reason, an additional data collection of electricity generation and load was performed with the help of power energy analyzers installed in different electrical panels of the building. Electricity generation and load measurements were performed in a 15-minute resolution during the first week on March (winter season) and first week of July (summer season). With respect to the choice of the first week of March as winter season one should note that the recorded outdoor temperature was in line with the winter typical temperature in Lisbon and, as it can be seen in Fig. 1, the building electricity load is similar with the load recorded during December. Fig. 2 shows the electricity power load and generation for the March and July as average daily values. The typical winter day depicted on the left-hand side of Fig. 2 shows a constant electricity power load of around 1kW outside the building occupancy period and 3kW peak loads one hour before and after the working office hours. This pattern is also noticed in the case of summer period (right-hand side), but the difference between occupancy period and non-occupancy periods is less pronounced due to a constant electricity power load recorded of 4kW, well above the corresponding values recorded during March. After careful investigation it was found that the power load during July was affected by the permanent working of the ventilation system (fume hood) designed to limit exposure to hazardous fumes in one of the laboratories of the building. Also, the peaks of power load recorded in the vicinity of the working hours are caused during the cleaning operations when vacuum cleaners and artificial lighting are used. With regard to the electrical power generated, BIPV shows significant higher values in winter when compared with summer due to vertical position of the PV panels which improve their performance when solar radiation is at its lowest.

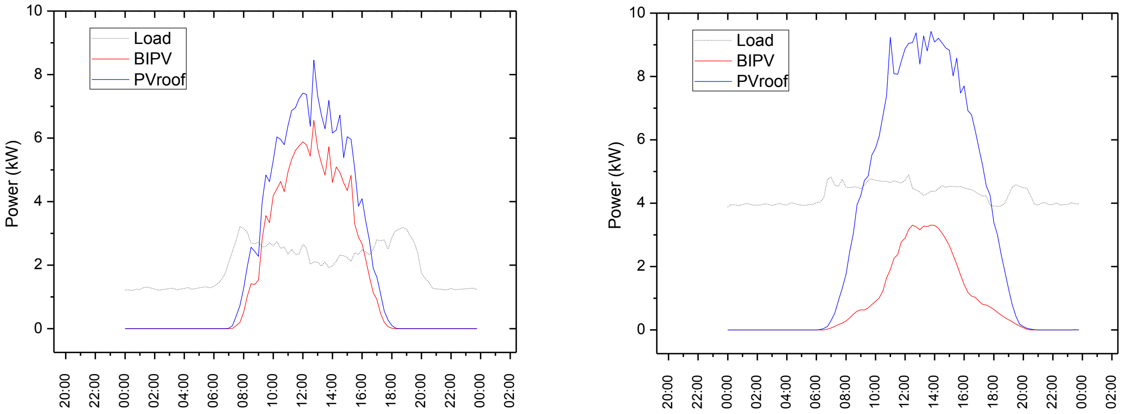

Fig. 2. Average load and energy generation from BIPV and PV roof during March (left-hand side) and July (right-hand side) 2016

## 2.4 Load shifting design approach

Based on the results shown in Fig. 2 it is evident that one of the possible strategies to increase the energy matching of Solar XXI is through a *Load Shifting* approach. The implementation of

an energy flexibility measures based on *Thermal Energy Storage* was not considered due to lack of programmable devices (e.g. air conditioner, electrical water tank or heat pump) which are normally required to anticipate the energy consumption later.
To this end, a study was designed with the objective to shift the power loads of cleaning operations and charging of laptop computers from low generation periods to the period between 12 AM and 2 PM when there is high renewable generation. This period of time, does not only offer a high renewable generation but is also characterized by a slight decrease of power load due to lunchtime (see Fig. 2).

The total shiftable load *TSL* due to cleaning operations and laptop computers was calculates as:

$$TSL = (ALCC \times 11) + LV(i) - RAV \quad [5]$$

where ALCC is the *Average of Laptop Charging Consumption, LV* is the load during the period under analysis and *RAV* is the residual average value. To estimate the consumption and charging periods of the laptop computers, an analysis was carried out with power energy analyzers. At the time when this study was designed, there were 11 computers in Solar XXI, 6 of which were laptops. To enhance the energy flexibility, the value of the TSL was calculated assuming the replacement of the 5 desktop computers with laptops.

## 3. Results and Discussion

### 3.1 Load Matching factors before load shifting

In this section, the results of load matching factors for winter and summer periods, before shifting are presented and discussed. Table 1 shows the values of the load matching *LM*, the load cover factor (*γ load*), the supply cover factor (*γ supply*) and the loss of load probability (*LOLP*) at different time resolutions, before load shifting.

Table 1. Load Matching factors before load shifting

| | BIPV (%) | | PVroof (%) | | BIPV + PVroof (%) | |
|---|---|---|---|---|---|---|
| Factor | March | July | March | July | March | July |
| *γ load* | 32 | 18 | 36 | 44 | 38 | 45 |
| *γ supply* | 32 | 18 | 36 | 44 | 38 | 45 |
| *LOLP* | 74 | 100 | 70 | 65 | 67 | 63 |
| *LM* – 15 minutes | 32 | 18 | 36 | 44 | 38 | 45 |
| *LM* – Daily | 82 | 21 | 90 | 68 | 96 | 92 |
| *LM* – Weekly | 76 | 19 | 100 | 72 | 100 | 91 |
| *LM* – Monthly | 44 | 44 | 69 | 69 | 90 | 90 |
| *LM* – Yearly | 40 | 40 | 73 | 73 | 100 | 100 |

Analyzing BIPV individually, it can be noticed that *γ load* and *γ supply* have a higher percentage during the winter season, which leads to a higher rate of *LOLP* in the summer period. The reason for this is a large amount of energy consumption in the summer period. Analyzing the PV roof of car park facility data, the opposite tendency is observed, because the energy generation is much higher than the energy consumption in some periods. The reason for similar values of *γ load* and *γ supply* is the lack of any battery system in this case study. Also, the *LOLP* has high values since it includes night values where residual consumption and no energy generation exists. Accounting for the BIPV system only, the monthly and annually values are lower than expected, both in winter and summer. Also, none of the system individually is able to reach a 100% degree of matching on a yearly basis. However, when BIPV and PV roof systems are working together, a LM of 90% and 100% is reached at monthly and yearly resolution, respectively. With regard to *LM* values, interesting features can be found in Fig. 3

representing the corresponding cumulative distribution of load and generation, which allows the visualization of the evolution of the energy matching on the daily level, based on the values averaged during each week.

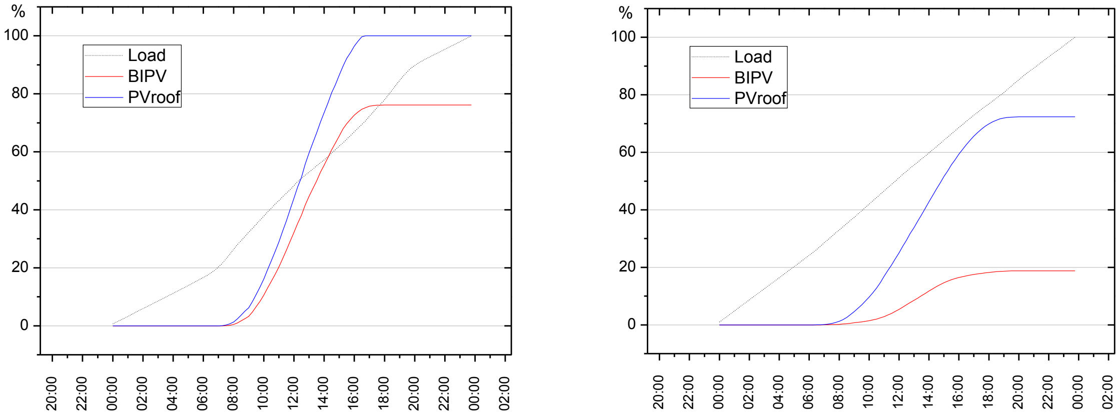

Fig. 3. Cumulative weekly data of load and generation from BIPV and PV roof during March (left-hand side) and July (right-hand side) 2016

Analyzing the energy matching at the weekly level, one can note that the PV roof cumulative generation exceeds the cumulative load alone (100% matching) during winter season, although BIPV does not fall far behind with almost 80% matching during the same period. In the summer season, the systems are not able to reach 100% of matching neither when taking alone, nor when working together (Table 1). Based on 15 min data resolution (Table 1), the maximum energy matching is reached when both systems are working together. However, the degree of matching of energy generation to local energy demand does not go above 38% and 45% during winter and summer season, respectively.

## 3.2 Load Matching factors after load shifting

Figure 4 shows the average load and energy generation from BIPV and PV roof in the car park before and after load shifting.

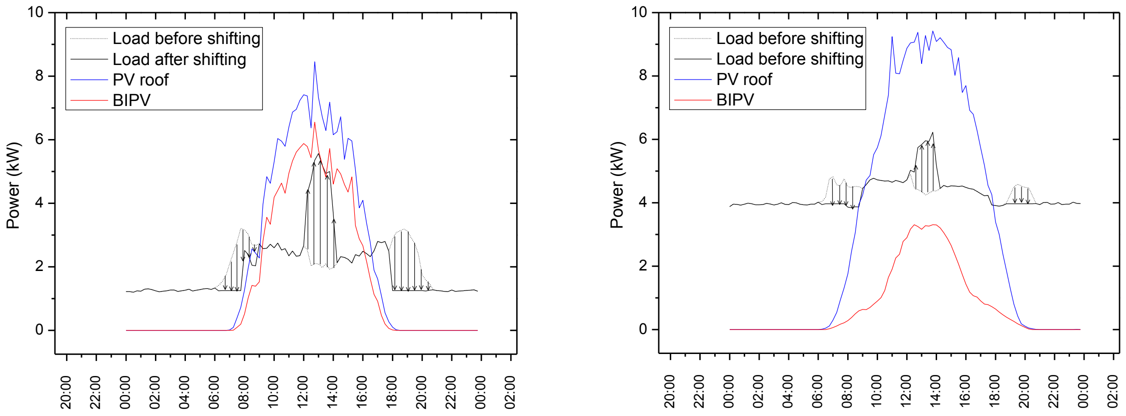

Fig. 4. Average load and energy generation from BIPV and PV roof before and after load shifting for March (left-hand side) and July (right-hand side) 2016

As it can be observed in Fig. 4, load matching is enforced during the period of time when the PV production is maximum, with better results during winter season when the shifted load values are reaching the values of the power generated by the BIPV system. Indeed, the load shifted during winter and summer periods were respectively 22.06 kW and 9.44 kW.

The impact of load shifting on load matching is shown in Table 2. As it can be seen from Table 2, the potential for improving the energy matching based on load shifting of cleaning operations and charging of laptop computers is higher in winter than in summer season, although likely limited to marginal increase from 38% to 41%.

Table 2. Load Matching factors after load shifting

| March | BIPV (%) | PV roof (%) | BIPV + PV roof (%) |
|---|---|---|---|
| LM before load shifting | 32 | 36 | 38 |
| LM after Load shifting | 35 | 39 | 41 |
| July | | | |
| LM before load shifting | 18 | 44 | 45 |
| LM after load shifting | 18 | 45 | 46 |

## 4. Conclusions

This work bring into focus the electrical energy performance of an office building located in Lisbon, Portugal, which was installed on the South façade a BIPV and an additional photovoltaic roof system in a nearby car park facility for electricity generation. Unlike other studies, this investigation examines the possibilities of introducing DR measures based on data obtained from measurements of load and generation rather than numerical modelling. The potential of increasing the energy matching between load and generation is studied through a load shifting approach which consisted in shifting the power loads of cleaning operations and charging of laptop computers from low generation periods to a period when there is high renewable generation for winter and summer season. The load match reported values have shown the importance of the time resolution in the study of the potential for increasing the energy matching and how different strategies can influence the zero energy performance of the building.

Results show that load shifting is able to improve the energy matching, although the potential in this case study is limited, mostly because of lack of programmable devices, which are not part of an office building designed with passive strategies. The present work proved that a BIPV system works better when used in combination with a horizontal mounted PV system and that, in future work, the presence of on-site battery storage could be further investigated as a mean to improve the energy matching of the building.

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