IMPACT OF NON-RESIDENTIAL LOAD PROFILES ON THE GRID-INTEGRATION OF BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) SYSTEMS IN TWO DIFFERENT CLIMATE CONDITIONS

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Summary

BIPV systems may satisfy electricity energy consumption of the building on an annual or monthly basis. However, the balance between on-site generation and the building energy consumption requires evaluation with a higher time resolution. One of the main barriers to this evaluation in simulated studies is the lack of building simulation (BES) tools to model the non-stochastic occupant interactions resulting in similar daily consumption profiles throughout a year. This paper investigates the impact of load profiles of a generic office room on the integration of building-integrated photovoltaic (BIPV) electricity generation by taking into account the load fluctuations due to the occupant behavior. Two locations of Seville (Spain) and Munich (Germany) representing two different European climate conditions are considered in the work. The consumption profile encompasses electricity for lighting, office appliances, heating, cooling, and ventilation. The simulation results show for fully electric consumption profile of the model, the annual cover factors change significantly when hourly values of the load matching indicators are considered also illustrating accurate seasonal and daily effects. Taking the average of the hourly values, the building shows a load cover factor of 0.21 and 0.31 for the locations of Munich and Seville, respectively.

Keywords: Load matching, Net zero energy building, BIPV, Stochastic consumption, Office buildings

1. Introduction

Climate change is recognized as a worldwide sustainability issue and requires serious considerations. To mitigate adverse environmental effects of this issue, in the building sector, many efforts towards achieving more energy-efficient and more decarbonized buildings have been made among them Net Zero Energy Building (Net ZEB) has gained growing attention (Berardi, 2015; Gonçalves et al., 2018). A Net ZEB is defined as a building connected to the grid that generates as much energy as it consumes annually (Salom et al., 2014; Sartori et al., 2012). In other words, Net Zero Energy Buildings must provide energy use of their consumers by integrating imported energy from the grid with on-site generation. The on-site generation is dedicated to the generation from available renewable energy sources.

Furthermore, the most viable renewable energy source which can be exploited for buildings is solar energy. Therefore, there is a broad consensus that Building Integrated Photovoltaic (BIPV) technology is the cornerstone of Net ZEBs (Goncalves et al., 2019). Taking into account that Net ZEBs sometimes have excessive generation than their consumption and have energy exported to the grid, their interplay with the grid is not same as typical buildings which are only importing energy from the grid. Therefore, design and evaluation of Net ZEBs integrating BIPV technology require a comprehensive analysis addressing the interplay between the building loads and on-site PV generation that is often called load matching (LM) phenomena (Goncalves et al., 2019).

Load matching analysis provides numeric indicators named cover factors in a yearly basis to study Net ZEBs. However, it has been realized that annual values of the cover factors do not provide a good understanding of the interplay between Net ZEBs and the grid. As a result, studies on Net ZEB concept have moved towards higher time resolution data, e.g. hourly data, either in simulation cases or real monitored cases (Salom et al., 2014; Sartori et al., 2012). Hourly values of the cover factors, namely load cover factor and supply cover factor, illustrate a good picture of the seasonal and daily pattern of the balance between the building demand and on-site generation. In simulated cases, however, non-stochastic occupant interactions modelled within a building simulated by using Building Energy Simulation (BES) tools result in non-stochastic similar daily consumption patterns (Salom et al., 2014). The work aims to study Net ZEB concept in non-residential buildings by

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simulating a representative office room with c-Si BIPV façades while stochastic consumption patterns are taken into account. The most widely used time resolution in building simulation, 1h resolution, is used to provide energy consumption and on-site generation for the representative office room to evaluate load matching phenomena. Two locations of Munich (Germany) and Seville (Spain) are considered as two representative climate conditions in Europe, the former one corresponding to temperate oceanic and the latter one corresponding to hot-summer Mediterranean climate condition.

Following this introduction, Section 2 brings the methodology beginning with the description of the representative office room with BIPV façades. Then, the simulation results of the stochastic power loads of the office room are presented. Section 3 provides performance evaluation of the office room in terms of load cover factor and supply cover factor for two selected climate conditions. Finally, the paper is closed with the main conclusions of the work presented in Section 4.

2. Methodology

Representative Office Room with BIPV Façades

An early stage building desing and simulation approach via simulation engines coupled into the CAD tools is adopted in this work (Han et al., 2018). The focus is on a conceptual office room (3 m high, 3 m wide, and 4.4 m deep) with windows towards the south. The architecture design of the representative office room is modelled in Rhinoceros 3D by using the parametric definition approach in Grasshopper environment (plug-in for Rhino) (Rutten, 2015). The construction and materials as well as thermal conditions have been defined to represent an energy-efficient built environment, for more detail information about the envelope properties the reader is referred to (Goncalves et al., 2019). Dynamic simulations of the defined architecture are done using the plug-ins embedded in Grasshopper environment namely Honeybee and Ladybug Tools (M Sadeghipour Roudsari, 2017; Mostapha Sadeghipour Roudsari et al., 2013). The tools connect Rhinoceros 3D to the valid simulation engines such as EnergyPlus and Daysim which are used for the energy simulations in the work presented here. The final definition of the office room in Rhino 3D is shown in Fig. 1.

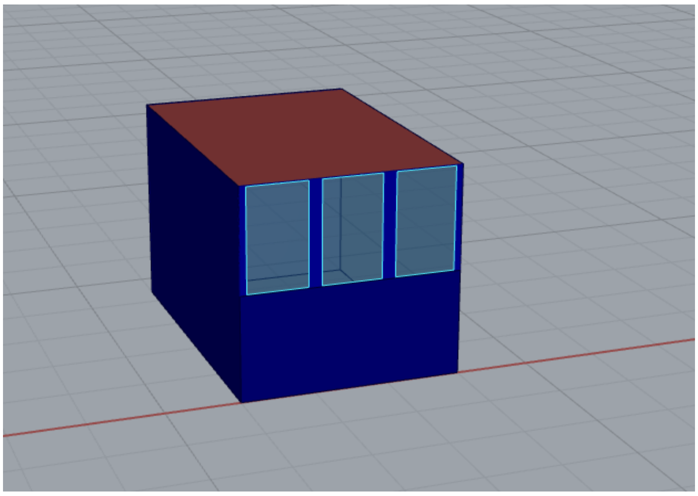


Fig. 1: Preview of the conceptual office room modelled in Rhino 3D

For sake of simplicity, it is assumed that the room is adjacent to the zones with similar thermal conditions on top and bottom, therefore adiabatic conditions are set for ceiling and floor, while the boundary condition for the walls is set to outdoors. All façades are covered by BIPV modules except the upper half of southern façade which is served as windows consisting of triple glazing with a U-value equals to 0.6 W/m-K, a 0.48 solar heat gain coefficient, and a 0.72 visible transmittance. The BIPV module used for the façades is inspired from works presented in (Gonçalves et al., 2018) and the material properties listed in Table 5 of the work presented in (Spiliotis et al., 2020) are used to model the thermal behavior of the BIPV modules. Each module is composed of c-Si cells, with a 14% cell efficiency, a rated power of 244 Wp, and an 80% inverter efficiency. Eastern and western façades are covered by six modules covering 79% of the surface area with the total PV generation of 1464 W. The façade towards north has four modules which generate 976 W in total and covering 77% of the surface. Southern façade has only two modules on the bottom half generating 488 W. Honeybee PV simulation relies on the EnergyPlus Photovoltaic generators, more information can be found in (Photovoltaic Arrays, EnergyPlus 8.0)

Climate Conditions

Using the office model described above, simulations are carried out for the two locations of Munich (Germany) and Seville (Spain) each representing a different climate condition in Europe. Weather data from the International Weather for Energy Calculations (IWEC) which are available in the format of EnergyPlus Weather (.epw) files are used to represent the locations. The main climate characteristics of the considered locations are summarized in Tab. 1.

Tab. 1: Annual average weather characteristics of the selected locations

Location	Latitude [°N]	Longitude [°E]	Global horizontal radiation [W m^{-2}]	Climate class
Munich (DE)	48.13	11.7	133	temperate oceanic
Seville (ES)	36.9	-2.4	220	hot-summer Mediterranean

Non-residential Power Loads

The representative model of this work is considered as a single-occupant office room. The first step to produce an annual stochastic consumption profile is to determine how stochastically the room is occupied throughout the year. There are different approaches for stochastic occupancy modeling, e.g. using a non-homogeneous Poisson process to simulate time series of occupancy states in a single office room proposed in (D. Wang et al., 2005), homogeneous Markov chain presented in (C. Wang et al., 2011), non-homogeneous two-state Markov chain introduced in (Page et al., 2008a), etc.

To produce the occupancy time series in this work, the non-homogenous Markov chain approach from the work presented in (Page et al., 2008b) is used. Time-varying transition probabilities used in the model are determined by using two inputs, namely a probability of presence over a typical week and a parameter called mobility factor (μ). To provide the inputs of the model, different occupant profiles from LESO-PB database (Zarkadis et al., 2014) corresponding to single-occupant office rooms are used to extract several weekly probabilities of presence. Different values of 0.1, 0.3, and 0.5 are used as μ to calibrate the model. The simulated occupancy time series from the extracted profiles show active occupancy hours with a minimum of 1600 hours and a maximum of 2050 hours during a typical year.

Finally, a time series of 1851 active occupancy hours is used as the "occupancy schedule" to occupy the representative office room in the work presented here. Fig. 2 shows this occupancy schedule assigned to the office model that is simulated in Ladybug tools. The internal gains related to the occupant is taken as 120 W/person, according to ISO 7730 (ISO 7730, 1994), corresponding to an activity level of seating, very light working during active occupancy hours.

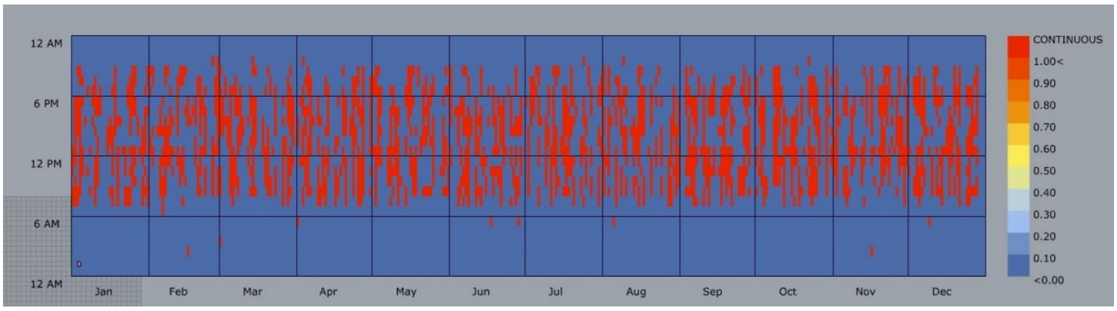


Fig. 2: Stochastic occupancy schedule assigned to the representative office room

After occupancy, the next step is to consider how the occupant interacts with the building systems to quantify the electricity consumption of the office. The most important interaction is the occupant's use of office plug-in appliances. The behavior is also modeled in this work based on the stochastic approaches from the literature. However, there are a few works dedicated to stochastic modeling of this occupant behavior in office buildings. The work presented in (Gunay et al., 2016) provides links between occupancy and use of plug-in loads by developing discrete likelihood distributions for five different time periods consisting of (a) occupancy periods, (b) absences less than 12 hours (intermediate breaks), (c) absences between 12 and 24 hours (nighttime), (d) absences between 24 and 72 hours (weekends), and (e) absences longer than 72 hours (vacations).

Two simplified and probabilistic approaches to predict the use of plug-in appliances in office buildings are presented in (Mahdavi et al., 2016). The work defines load fraction, the ratio between actual load and installed load at each time-step, as a function of occupancy. In the probabilistic approach, load fractions are formulated into three specific Weibull distributions corresponding to three different time periods. This probabilistic approach is adopted in the work presented here to produce the stochastic profile of the electricity consumed by the office appliances. The occupancy time series generated previously are used to map the active occupancy hours into three Weibull distributions corresponding to (a) occupied periods or intermediate absences shorter than one hour, (b) intermediate absences longer than one hour, or (c) outside working hours. The generated load fraction time series (Fig. 3) are used to calculate the energy consumption of the appliances by assuming 10 W/m^2 power density, as a conservative estimation (Mahdavi et al., 2016), for the representative office room. As in Fig. 3 can be seen between 7:00 to 19:00 load fraction is mainly greater than 0.6 and outside this period, the load fraction is mainly less than 0.3.

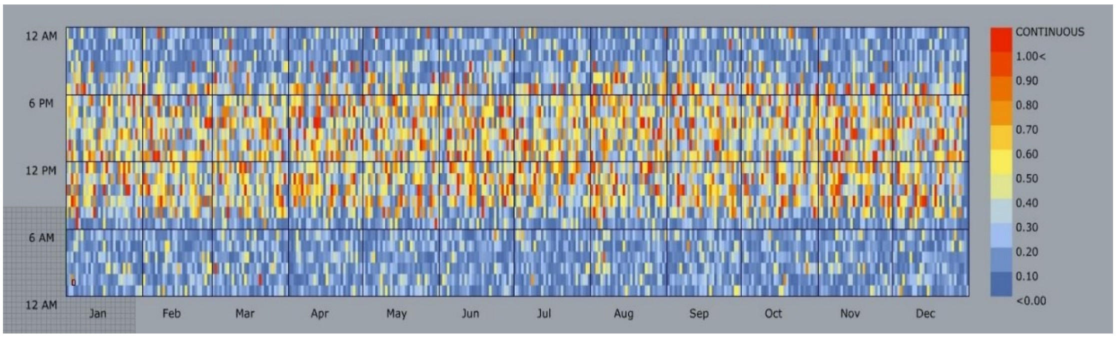


Fig. 3: Stochastic load fraction time series to calculate the energy consumption of the office appliances

To calculate the energy consumption due to the lighting, the amount of daylight inside the office room is simulated by using Daysim simulator integrated into Ladybug tools. The lighting schedule is linked to the stochastic occupancy schedule to always maintain 500 lux for a test surface 1 m above the floor area contributing to add 5 W/m^2 during active hours. Fig. 4 shows the simulated lighting schedule for the representative office room located in Munich. As it can be seen, during summer compared to winter, energy consumption due to the lighting is lower which is because of more available daylight and longer days during summer.

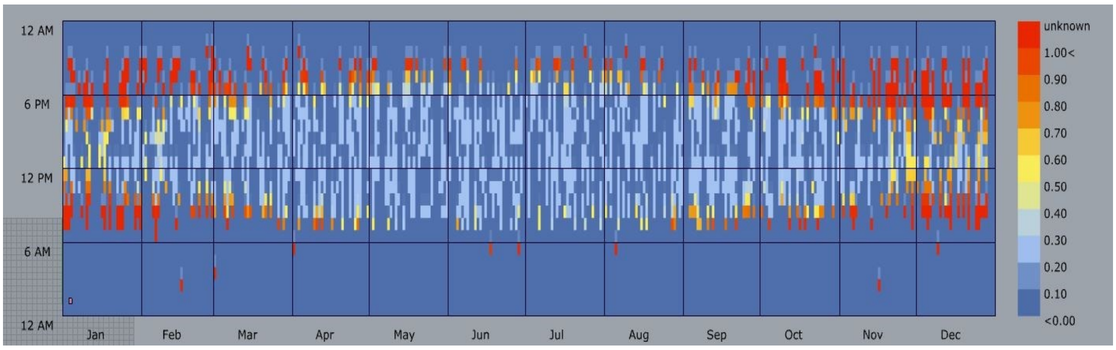


Fig. 4: Simulated lighting schedule (linked to the stochastic occupancy schedule) for the representative office room

To simulate the power consumed for heating, cooling, and ventilation, VAV with PFP boxes (ASHRAE Baseline Systems #8), recommended for non-residential buildings, is set as the HVAC of the office room. The cooling system is allowed to turn on when the indoor temperature is above 24°C during occupied hours, and during unoccupied hours, the indoor temperature is kept at 28°C. Similarly, the heating system is allowed to be activated when the indoor temperature is below 21°C during occupied hours, and the room space is kept at 17°C temperature during unoccupied hours. The room is ventilated at a rate of 0.0007 m^3/(s-m^2) and 0.007 m^3/(s-person) corresponding to the low-polluting buildings according to EN 15251 (CEN, 2007).

3. Results and Discussion

In this paper, the effect of the building integrated photovoltaic system on reducing the electricity consumption imported from the grid is quantified by the load factors. The cover factors include the load cover factor γ_l, the ratio to which the electrical demand is covered by the on-site electricity generation of the BIPV systems, and the supply cover factor γ_{PV} that is defined as the ratio to which the BIPV generation is used by the building represented in eq. 1 and eq. 2, respectively (system losses and storage are not considered in this work).

$$\gamma_l^{[t_1,t_2]} = \frac{\int_{t_1}^{t_2} \min(PV(t), l(t))dt}{\int_{t_1}^{t_2} l(t)dt} \quad \text{(eq. 1)}$$

$$\gamma_{PV}^{[t_1,t_2]} = \frac{\int_{t_1}^{t_2} \min(PV(t), l(t))dt}{\int_{t_1}^{t_2} PV(t)dt} \quad \text{(eq. 2)}$$

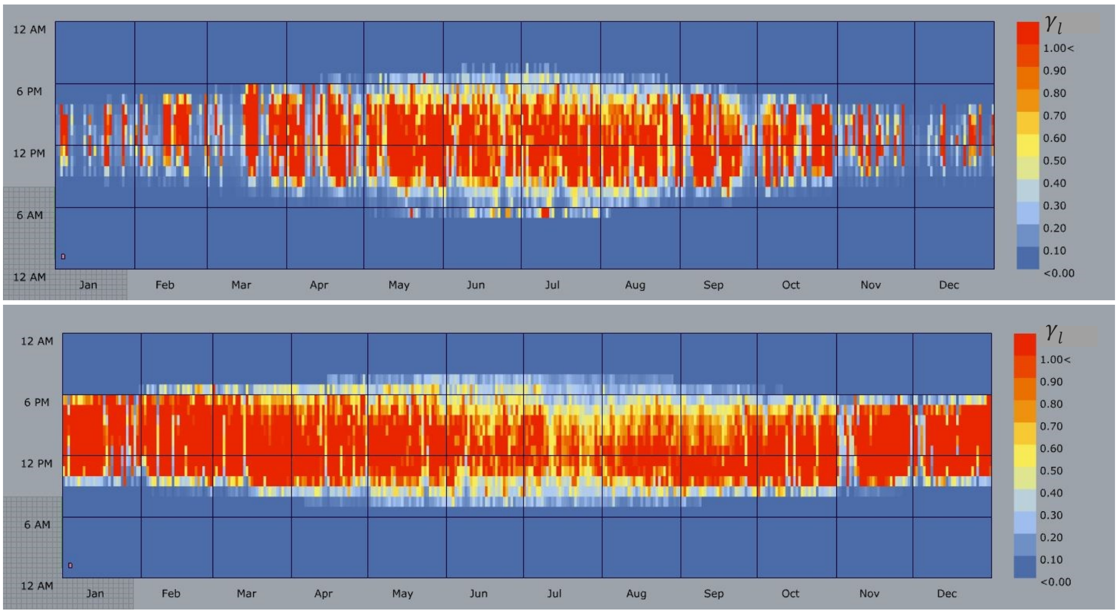


Fig. 5: Annual load cover factor with 1h resolution time for the representative office room located in Munich (up) and Seville (bottom)

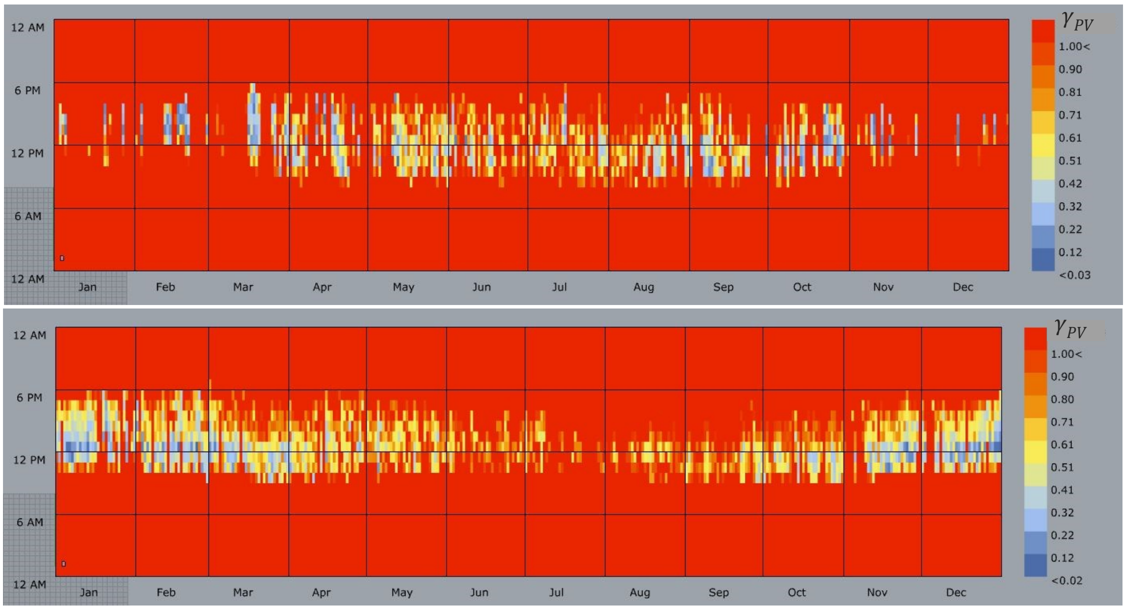
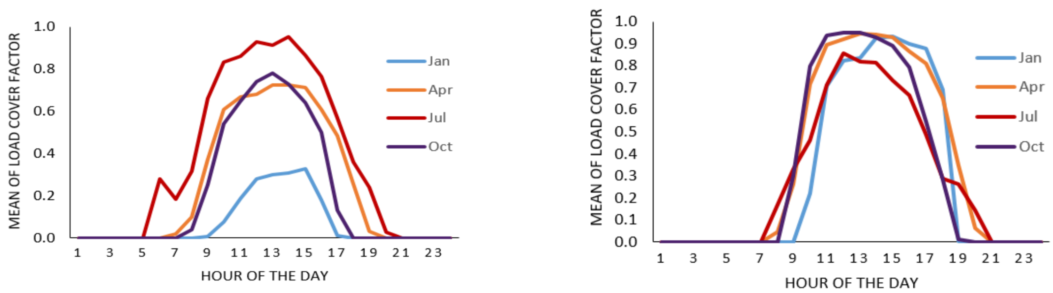


Fig. 6: Annual supply cover factor with 1h resolution time for the representative office room located in Munich (up) and Seville (bottom)

Simulation results of the load cover factor (γ_l) and the supply cover factor (γ_{PV}) for the office room with BIPV façades are illustrated in Fig. 5 and Fig. 6, respectively. In each figure, the upper profile shows the result of the simulation of Munich, and the bottom profile results from the simulation of the office room located in Seville. The cover factor takes a value between 0 (dark blue) to 1 (red). As can be seen in Fig. 5, comparing the profiles of Munich and Seville together, for Seville, greater load cover factor occurs from September to May and during May, June, July, and August, load cover factor decreases. The reason is because of the cooling loads during these months that increase the electricity demand, therefore the power generated by the BIPV systems is not sufficient to cover the building demand.

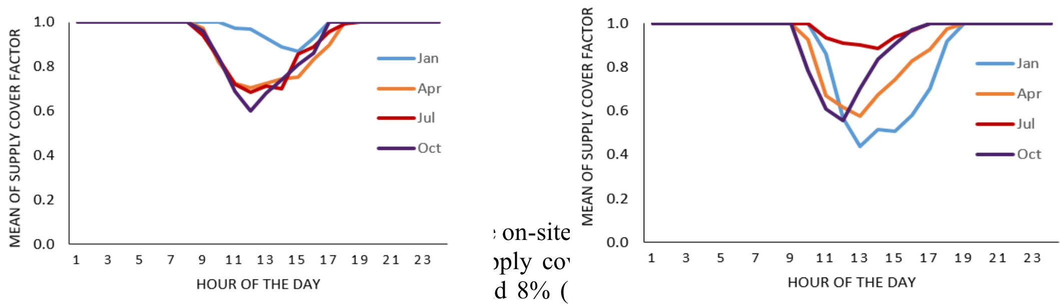
Conversely, for Munich as the upper profile in Fig. 5 shows, BIPV can cover the building demand for longer periods during the months of May, June, July, and August, while during September to April, the reduction of the load cover factor is evident. The reason is that during these months, not only the amount of solar energy is reduced due to shorter days and azimuth angle, but also heating loads due to the oceanic climate condition increase the building demand which results in low cover factors for that time period. In addition, the profiles of the supply cover factor shown in Fig. 6 represent the hours of the year during which the generation of the BIPV is more than the building demand and can be exported to the grid. The majority of the profiles are in red color which refers to the supply cover factor of 1 indicating either no generation by the BIPV systems (during the night) or the times that on-site generation is completely consumed by the building.

In general, it can be concluded that the load cover factor provides more useful information for evaluating the Net ZEB concept. The average of the hourly values indicates a load cover factor of 0.21 and 0.31 for Munich and Seville, respectively. While considering the yearly basis this indicator changes to 0.15 for Munich and to 0.5 for Seville. The daily effect of the building loads on the load cover factor can be seen in Fig. 7. In this figure, mean hourly values of load cover factors averaged over 4 months (January, April, July, and October), which are selected representing 4 seasons, are shown for each of the considered locations. It can be seen that Seville has smoother annual distributions, while there is a significant seasonal variation for Munich. For example, γ_l at 14:00 varies from 0.3 to 0.9, while at the same time, Seville has a variation from 0.81 to 0.95.



(a) **(b)**

Fig. 7: Mean daily load cover factor for four selected months; (a) Munich, (b) Seville



(a) **(b)**

Fig. 8: Mean daily supply cover factor for four selected months; (a) Munich, (b) Seville

annually. In Munich, the building exports up to 3% of on-site generation in January at noon and in Seville, the lowest degree of export occurs during July for which the building exports up to 10% of the BIPV generation at 14:00. However, during the hours of maximum solar radiation, $\boldsymbol{\gamma_{PV}}$ varies between 0.68-0.93 and 0.44-0.9 for Munich and Seville, respectively.

4. Conclusion

In this paper, hourly values of the load matching indicators (namely, the load cover factor and the supply cover factor) were discussed for a conceptual office model for two different climate conditions. Stochastic consumption profiles were simulated by using the results of stochastic occupant behavior modelling implemented from the literature. Munich and Seville showed an annual cover factor of 0.21 and 0.31, respectively.

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