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Performance of photovoltaics in non-optimal orientations: An experimental study

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ABSTRACT

Buildings are one of the biggest energy consumers in our world. The concept of zero energy building (ZEB) is an attractive approach in order to reduce the energy requirement of buildings leading to more sustainable cities. Building integrated photovoltaics (BIPV) is one suitable technology for providing electricity to the buildings with a minimum impact. Traditionally, photovoltaics (PV) have been installed looking for maximum yearly energy production.

In this work the feasibility of PV working in non-optimal orientations will be explored by using two experimental setups: a photovoltaic façade with a southwest orientation and an architectural model of a building with the façades in the cardinal points, covered with PV. The results show interesting features, considering yearly and hourly generation profiles. Although the annual energy production for the façades and the roof is between 50% and 76% of an optimum angle installation, the façades have a more stable production along the year: monthly production can vary by a factor 2 vs a variation of factor 4 for irradiance. Moreover, the hourly production profiles are displaced from noon so they can match the demand. With some current net metering proposals, non-optimal orientations could even be more economical than the maximum producing orientation.

1. Introduction

The overuse of resources and especially the increasing energy demand is turning into deeper and serious concerns, leading to initiatives in both efficiency and use of renewable energy sources. One of the biggest energy consumers is the building sector, accounting for about 40% of total energy and 70% of electricity in the United States [1]. In the EU, the European Commission reports that buildings also account for 40% of primary energy consumption and in with a potential 27% reduction in emissions [2]. The EU Directive on energy performance of buildings stipulates that by 31 December 2020, all new buildings must be nearly zero-energy buildings.

These goals can be met using energy efficiency measures and by means of renewable energy sources (RES) produced locally, at building or neighbourhood level. One of the more suitable RES technologies to be used in buildings is photovoltaic technology (PV), which has many potentialities in a ZEB scenario. It has special features: direct sunlight conversion to electricity, easy integration in the building envelope, reduction of CO_2 emissions, as well as a huge decrease in costs in recent years.

PV technology is increasing its share of electricity generation and quickly reaching grid parity, more noticeable in southern European countries [3]. Nowadays, with smaller feed-in tariffs and a rising price for electricity at the consumer point, PV is emerging as a real option for self-consumption. The approval of net-metering schemes for photovoltaic electricity retribution is on the track in several countries. In any case, there are efforts in order to reduce legal-administrative barriers for the development of PV systems in 12 European countries, especially in Spain, aimed to eliminate a disproportionate and unnecessary burden to developers of small PV systems [4]. These regulations, together with simpler and faster administrative procedures are expected to drive a higher use of PV in buildings.

A recent and trendy example on the potentialities of PV for fulfilling the objectives of the ZEB scenario is the so called BIPV strategy (Building Integrated PV) [5,6]. Photovoltaic modules can be easily and smartly integrated into the building envelopes: rooftops, façades, atria, etc., having a structural function as well as sun-shading and cladding function (Fig. 1), and enabling also a construction costs reduction.

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Fig. 1. BIPV system in Historical market in Béjar, Spain.

BIPV enables building owners to save on construction costs of new buildings or retrofitting; while at the same time generating a portion of their own electricity [5]. The potential of electricity obtained by BIPV means is huge; only in the EU-27 countries, it is reported to be 951 GW, with an annual production of 840 TW h [6]. It is estimated that 40% of the total electricity demand in the European Union in 2020 could be met if all suitable roofs and façades were covered with solar panels [7].

However and independently from the PV strategy selected, there is a limit to the amount of energy that can be generated per square meter by a photovoltaic collector, depending mainly on the PV efficiency, the inclination and azimuth angles of the PV generator, the latitude as well as the efficiency of the balance of system (BOS).

For example, in the case of optimal orientation of the PV system (inclination and azimuth angles), a typical energy generation in northern climates such as northern Europe, would be about 100 to 120 kW h/m^2 per year of usable collected energy. In southern climates, such as southern Europe, a typical generation would be around 200–220 kW h/m^2 per year of useful collected energy [8].

Several investigations have studied the solar potential of buildings in urban landscapes [9,10], In particular, the first referenced work concludes that, "the annual irradiation on vertical facades is lower than that of more favourable surfaces (roofs) but that, due to their very large areas, the solar potential of façades is relevant for the overall solar potential of a building and/or an urban area". In addition, roofs are not always suitable for PV due to building infrastructure deployed on them (chimneys, ventilation, elevators, antennas, etc.). For these reasons, it is important to have a good knowledge of the properties of PV in façades for helping in an adequate planning of PV deployment.

Regarding to research focused in BIPV generation properties, in ref [11] an extensive simulation study is presented for several orientations, including southwest. This study is focused on total energy production, finding that the more favourable options are roof and southwest. The main difference in the results of these researches [9–11] is the latitude of the locations: at higher latitudes the energy production of the roof is lower but the production of the vertical surfaces is higher than at lower latitudes.

The use of solar energy in façades can be made by thermal and/or photovoltaics technologies. There are references of using solar thermal for passive heating in winter and hot water production in summer [12]. In particular, windows are very influential on energy demand: artificial lighting and heating/cooling load. Semi-transparent PV glasses based on thin film technology has been object of some research, for example PV ventilated window properties were numerically investigated in [13] and PV see-through glasses were experimentally characterized in [14].

One of the preferred options for using the vertical planes of buildings is the use of double skin façade systems [15]. This is one of the best choices in managing the interaction between the outdoors and the internal spaces, while providing some architectural flexibility to the design. Using PV as part of the façades also has interesting thermal features, as it is shown in [16]. In fact, using PV on a multilayer wall leads to significant reductions both in heat losses in winter and heat gain in summer. This allows a better energetic performance of the PV systems, by using solar modules as shading/insulating devices, or making use of the heat at the backplane of the modules: greenhouse, heaters, solar chimneys, etc. [17]. In terms of exergy efficiency, this is higher when the residual heat from PV is used for other purposes thus leading to PV/T systems. Extensive work has been done in modelling both PV/T air systems [18,19] and PV/T water systems [20,21]. Making use of the exergy analysis, it is possible to determine the optimum parameters for PV/T systems depending on several factors, in particular local latitude and climate. This is due to the different quality of the two kinds of energy present in PV/T systems: electricity and heat.

Stepping backwards in order to get a better view, the use of PV in ZEBs has to be related on the one hand to the energy needs of the building (ZEB balance) in the absence of other energy generation systems. Therefore, the PV performance should tend to balance the energy demand of the building. On the other hand, it is possible that the low energy density in PV makes the building envelope not to be sufficient to generate all the energy the building needs. This leads to the possibility of using PV in the proximity of the building when the surfaces available for PV are not large enough to reach equilibrium ZEB.

There is also the possibility to connect a ZEB (Network ZEB) to the grid to obtain a fully adapted annual energy balance, but in the case of PV, the matching load (fraction of the electricity consumed directly) is in the range of 30% or less. For this reason, it might be interesting to create a smaller network with other nearby buildings in order to increase the matching load.

In short, to know how to properly use the PV energy in a ZEB building, it is necessary to have information about the boundary conditions of the building and thus compare different ways of using the PV energy, leading to Network ZEBS (zero energy buildings network). These boundary conditions can be, for example: the type of construction (offices, education, housing, etc.), climate (Dominated cooling, heating, Dominated heating and cooling), occupation (people/m^2)) [22–24]. It is important not only to get the maximum power from every photovoltaic installation but also to get that power in the right time when it is expected to be consumed [25].

From the foregoing, it seems necessary to know in detail how the generation profiles and energy consumption can be fitted in accordance with the requirements and typology of the building. In many cases, the optimal orientation and inclination of the PV modules do not comply at all with consumer profiles; however non-optimal situations could be very efficient for self-consumption.

The work presented here is an experimental study of PV generation in non-optimal orientations. There are several investigations concerning this topic at the building [26] and neighbourhood level [27] but they are based on analytical and simulation methodologies. Few installations in these conditions are reported [28]. For this reason, two experimental set-ups have been monitored for more than a year. Results show interesting features regarding the daily and seasonal generation profiles. These properties are very useful in order to match the generation with the consumption.

2. Experimental setup

The experimental setups are intended to demonstrate the viability of PV installations with non optimal orientations, like those in