ENERGY PERFORMANCE EVALUATION OF A PHOTOVOLTAIC WINDOW

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ABSTRACT: The energy sector is in a process of radical and unstoppable transformation, motivated by two reasons: the fight against climate change and renewable energies. The two factors are decisive and go hand in hand, in line with the social demands and decisions of the European Union to comply with the emission reduction agreements.

The growing increase in energy consumption in developed and developing countries is an important task that must be addressed by the economic policies of these countries. The percentage of energy consumption of buildings relative to the overall energy use has grown in the last years due to the increasing amount of electrical devices.

The photovoltaic windows as an integrated system in the building façades can contribute to generate clean energy to meet needs of the inhabitants of these buildings.

A photovoltaic window specially built by a manufacturer has been studied. An amorphous silicon photovoltaic module encapsulated between two transparent glass sheets, an air chamber and a second double glass sheet with an air chamber forms the photovoltaic window. Everything is framed in a PVC structure. The effective dimensions of the a-Si photovoltaic module are 0.57 m x 1.17 m, equivalent to a standard measurement of 0.60 m x 1.20 m.

To know the electrical characteristics of PV window in standard test conditions, a test in accordance with IEC standard 61646 it was carried out. A peak power of 50.74 W_p was obtained.

Measurements of energy production in real sunlight were carried out. The window was placed vertically facing south on a test bench. Measurements of the energy produced by the photovoltaic window were made in several sunny days of August and September 2016 from sunrise to sunset. On average, the irradiance received on the plane of the photovoltaic window was 4114 Wh/m^2 and the energy produced 71.2 Wh each day. These results match those obtained using the Malaga radiation databases.

For one square meter of the window studied, 79868 Wh/m^2/year are obtained, when an overall efficiency of 0.8 is considered. Integrating this PV window in a building in Malaga (Spain), an annual electric production of 345030 kWh is obtained when a glazing surface of 4320 m^2 is considered. This energy is enough to meet the annual electricity needs of the 68 household of the building. Furthermore, the saving in electricity bill of the houses of the building would be 59279 €/year and the BIPV system would avoid the emission of 240278 kg of CO_2 into the atmosphere per year.

Keywords: PV window, a-Si, Building Integrated PV (BIPV).

1 INTRODUCTION

Modern buildings are built taller and consume more energy, and efforts are being made in various areas to reduce their energy consumption. Building Integrated Photovoltaic (BIPV) is widely used in modern buildings as part of the façade in recent years. Due to its characteristics, its energy production can be combined with other functional features on buildings. This can not only achieve an aesthetic outlook, but also encourage the development of energy efficient buildings. BIPV system does not require extra installation spacing and can be integrated into the building envelope that replaces the traditional building materials. Semi-transparent photovoltaic (STPV) is one of the BIPV applications which becomes more and more popular. A topic about the energy savings of an office building with the use of semi-transparent BIPV modules is analyzed in [1]. The overall energy performance was studied in terms of heating and cooling loads, daylight availability and electricity generation by using EnergyPlus. The thermal performance of semitransparent BIPV modules is studied in [2] and stated that the majority of total heat gain from PV module was solar heat gain. It also evaluated several important design parameters for the design of solar technology, which included orientation, solar cell area ratio, efficiency of solar cells and module thickness. The energy performance and cost of semi-transparent BIPV modules in office building is analyzed in [3]. Thermal and visual properties were the major components of overall energy performance. The results were conducted by manual calculations in order to estimate the reduction of peak cooling load in addition to the annual electricity consumption.

Thin-film technology based on amorphous silicon (a-Si) offers a range of attractive features that are ideally suited for BIPV installations. Solar modules may be assembled to customer-specific BIPV elements for roofs and façades, and thus may combine various functions, namely electricity generation, thermal insulation, shading, and even satisfy aspects of architectural design. Compared to other PV technologies, a-Si modules show only a minor reduction in power output at elevated temperatures, and in efficiency at lower light levels, and thus offer superior energy yields per peak power.

The aim of this work is to evaluate the energy performance of a semi-transparent photovoltaic window of unknown characteristics, specially built, and to estimate the electricity production potential to meet the energy needs of urban buildings in Malaga (Spain).

2 WINDOW PV CHARACTERISTICS

The semi-transparent PV window is shown in Figure 1. An amorphous silicon photovoltaic module encapsulated between two transparent glass sheets, an air chamber and a second double glass sheet with an air chamber form the photovoltaic window. The effective dimensions of the a-Si photovoltaic module are 0.57x1.17 m^2, equivalent to a standard measurement of 0.60x1.20 m^2. The frame of the window is a PVC structure.

The characteristics of the window were not provided by the owner, so the experiments necessary to know them had to be carried out.

Figure 1. Semi-transparent PV window.

Table 1. Climate test conditions and PV characteristics.

T_{max}(ºC)	23,3
T_{min}(ºC)	21,3
RH_{max} (%)	54,3
RH_{min} (%)	51,1
RH_{limit} (%)	<70
I_{sc} (A)	0,71
V_{oc} (V)	113,19
V_{max} (V)	87,18
I_{max} (A)	0,58
Peak power (W_p)	50,74

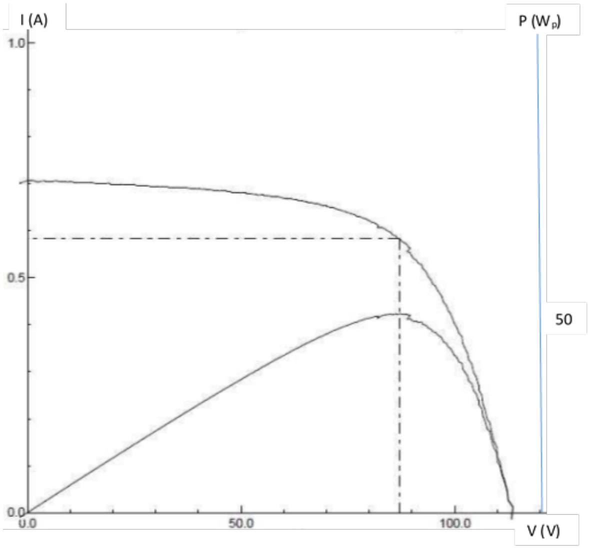

Figure 2. I-V curve of photovoltaic window at standard test conditions obtained in the solar simulator.

The IV characteristic in standard test conditions were determined in a solar simulator according to 61646 IEC standard [4]. The climatic values and the electric results are shown in Table 1. A power uncertainty of ± 6.78% was found. Figure 2 presents the I-V curve of the PV window

Once the window electric characteristics was known, it was placed in a test bench installed on the rooftop of the building of the Andalusian Institute of Renewable Energies, at Málaga (36.73 N, 4.55 W). The PV window was placed on a steel mobile structure. This structure allows an adjustment of both azimuth and inclination. A pyranometer was used to measure the global irradiance on the window plane, and a temperature sensor measures its temperature. The photovoltaic window was placed in vertical position facing South. A protocol for data collection that allows knowing the instantaneous power generated by the photovoltaic window has been developed. The figure 3 shows a scheme of the experimental arrangement.

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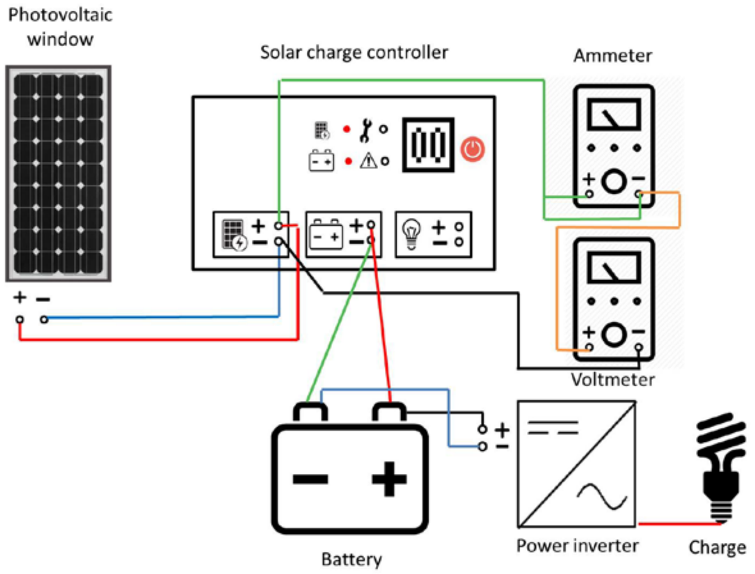

Figure 3. Experimental arrangement.

3 ENERGY PRODUCTION OF PV WINDOW

To know the energy produced by the window in vertical position, the voltage and current generated by the photovoltaic window in sunny days as well as the solar irradiance, module temperature and ambient temperature are collected every ten minutes from sunrise to sunset. The measurements of the energy supplied by the photovoltaic window have been compared with those obtained with an IV photovoltaic meter.

To carry out the measurements, the following devices have been used:

● Fluke model 8842A multimeter: one to measure the voltage and another to measure the current of the photovoltaic window at every moment.

●Fluke Hydra model 2620A (Hydra Data Acquisition Unit) to collect the radiation, the ambient temperature and the temperature of the photovoltaic module by:

  ○ CM11 pyranometer from Kipp-Zonen located in the same plane of the photovoltaic window.

  ○ Temperature probe (thermocouple) that is placed on the back of the cell.

  ○ Temperature probe (thermocouple) for the ambient temperature.

● Fluke-1735 power logger to measure the voltage, current and power consumed by the test load.

● Digital meter for measuring the voltage at the terminals of the photovoltaic battery.

● I-V400 solar I-V meter to verify the instantaneous measurements of the power generated by the photovoltaic window.

In addition, a solar FS-155 battery, a pure sine wave inverter 800W/1600W, a MMPT solar charge controller and a variable charge, form the experimental arrangement to simulate a stand-alone PV system as is shown in Figure 3.

The result obtained for solar radiation and the instantaneous power produced by the photovoltaic window on a sunny day of measurement is shown in Figure 4. The irradiance received on the plane of the photovoltaic window at daytime was 4114 Wh/m^2 and the energy produced was 71.2 Wh. These values are consistent with radiation data obtained from databases [5] and the power value obtained from PV window under standard test conditions.

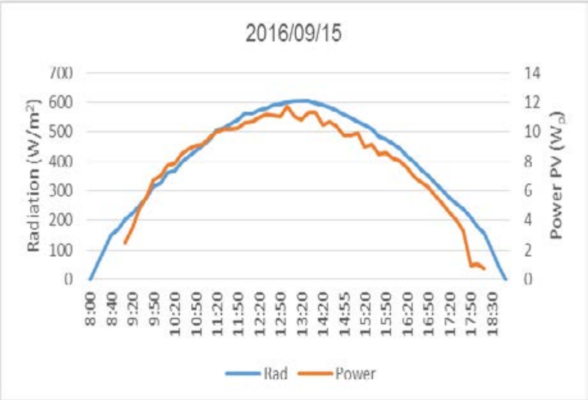

Figure 4. Solar radiation and instantaneous power of PV window in a sunny day.

Considering that the power generated by the photovoltaic window is proportional to the surface, the photovoltaic power of a window of one square meter of useful surface will be 76.1 W/m$^2_{\text{window}}$.

The energy yield of a photovoltaic system depends on the power of the system under standard test conditions, on the normalized solar radiation received on the plane of the module and on the efficiency of the system [6]. That efficiency takes into account the total losses that occur in the photovoltaic system like the dispersion of parameters, the actual temperature of the modules, the wiring, the effect of the angle of incidence of the sun on the plane of the module, the performance of the devices of power conditioning (regulator and inverter) and the battery performance. Its value for commercial systems varies between 0.75 and 0.85 usually.

With the PV window placed in vertical position, the monthly yield production for one year has been obtained. Efficiency values of 0.75, 0.80 and 0.85 and radiation data from the Energy Agency of the Junta de Andalucia for Malaga are considered [5]. Figure 5 graphically compares these results.

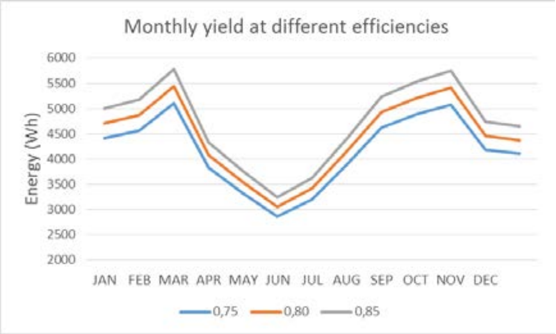

Figure 5. Monthly yield at different efficiencies.

From the analysis of the results, it is observed that when the window is vertically placed (usual position) the energy production in the months from April to September is significantly affected.

The annual production can be improved if instead of using the photovoltaic module as a vertical window, the same semi-transparent photovoltaic module is used as an enclosure element in a building, for example as a skylight for the covering of a courtyard or an atrium. This application would increase the solar energy captured and, therefore, the annual production [7, 8].

To analyze the influence of the photovoltaic window position in a building, the annual yield for 0.85 efficiency has been obtained when the PV window is placed in vertical position, and tilted 60º or 30º. Figure 6 shows the monthly result of one square meter of PV window.

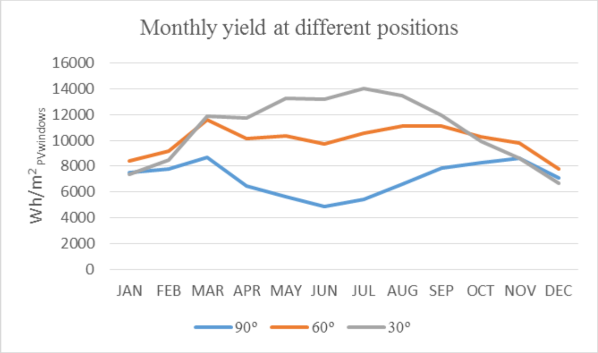

Figure 6. Monthly yield of window at different positions.

As can be seen on Figure 6, the tilt angle affects the yearly energy production of PV window. The bigger production correspond to a tilt of 30º, so the best use of this window in BIPV is as a part of an atrium [9]. Also, the 60º inclination presents a more homogeneous behaviour throughout the year, although the annual production is greater for 30º tilting. This is recommended to obtain maximum production in a photovoltaic system connected to the grid when the installation is placed in a latitude like that of Malaga.

In Figure 7 are presented the annual yield for different efficiencies and different tilting position of the PV window.

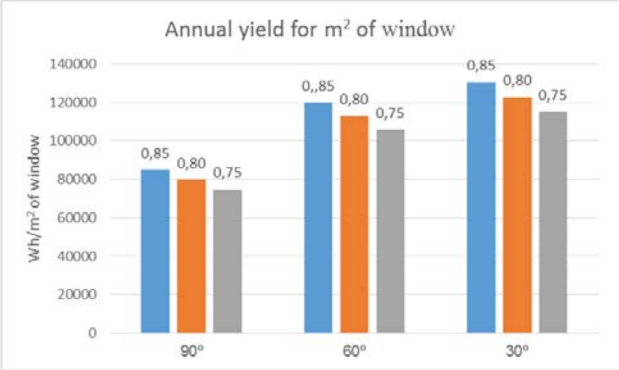

Figure 7. Annual yield for one square meter of window.

4 DISCUSSION

The integration of the photovoltaic window in a building has several advantages over conventional systems: energy saving, economic savings and environmental advantages. In the previous sections, we have analyzed the energy produced per square meter of photovoltaic window. In this section, the production of electricity, the economic savings, and CO_2 emissions avoided will be analyzed if PV semi-transparent windows were installed in an apartment building located in Málaga (Spain).

Energy saving

An apartment building with the following characteristics is considered:

Residential building with 17 floors with 4 apartments per floor (68 apartments):

- 2 apartments of 60 m^2
- 1 apartment of 75 m^2
- 1 apartment of 100 m^2

The glazed surface of the building facing south is supposed to be 4320 m^2. All apartments are equipped with appliances, air conditioning and electric stove.

The average annual electricity consumption for a residential utility consumer in the Mediterranean area, estimated by the IDAE (Institute for Diversification and Energy Saving) according to the study carried out with real data for the years 2010 to 2016, is 3487 kWh/household/year [10]. Therefore, the annual consumption of the dwellings of the building will be 237116 kWh/year.

The PV window provides a peak power per square meter of 76.1 W_p/m^2. If the entire glazed surface of the building is covered by the PV window, a peak power of 328.8 kW_p would be available.

The annual electric production per square meter in Malaga (located in the Mediterranean area) of the window facing South was 79.868 kWh/m^2/year, considering a global coefficient of losses of 0.20 as shown in Figure 7. Therefore, the yield obtained for the BIPV system would be 345030 kWh/year.

As the electric consumption of the apartments is 237116 kWh/year, an electric excess of 107914 kWh/year is obtained that represents an energy surplus of 46%. This surplus of energy could cover the building's common electricity needs, such as elevators, lighting in common areas, pumps for water supply and car park doors, which can be estimated at 6700 kWh/year. The rest of the energy could be sold to the network or to other users, if the legislation allows it.

Economic savings

In March 2014 the Spanish Government introduced a new way of calculating the price of electric energy that consumers must pay: the Voluntary Price for Small Consumers (PVPC in Spanish acronym). The PVPC is the system for fixing the price of electricity for customers on the regulated market (customers who have their contract with a Reference Seller), with a contracted capacity of no more than 10 kW.

Currently, consumers have digital meters so billing is based on the consumption of electricity that occurs every hour, applying the prices established at that time by the energy market. That is, today the price of electricity changes every hour of the day and every day.

However, the small consumer can take advantage of tariffs with a fixed price of electricity, which can be revised annually. They can also choose among different market traders.

On the other hand, the bill of the electric company consists of three concepts: a) the power contracted, b) the energy billed and c) taxes, both the tax on electricity and VAT.

The energy extreme prices of the first week in September 2016, ranged from a minimum of 0.096 €/kWh, corresponding to a Saturday at 5 pm, to a maximum of 0.162 €/kWh which corresponds to a Wednesday at 9:00 p.m. Similar values have been found in other weeks with an uncertainty of 0.005 €/kWh. When taxes are considered a daily average price of 0.25 €/kWh is obtained.

Under these conditions, if an efficiency of 0.80 is considered, the saving in electricity bill of the houses of the building would be 59279 €/year. If the energy surplus produced by the BIPV system is sold to the network at 50 €/MWh, an additional profit of 5396 € would be obtained.

With this type of windows another benefit in relation to the consumption in air conditioning is reached. It is saved not only by the energy generated by the BIPV system but also by the lower energy consumption required by the home when using windows that significantly increase thermal insulation and decrease solar radiation loads, reducing the consumption of air conditioning systems in up to 30% according to the sources consulted [10].

CO_2 emissions avoided

The photovoltaic window not only saves money but also prevents the emission of harmful gases to the environment by generating electricity from renewable sources and, therefore, non-polluting.

If a conversion factor of 0.30 kg of CO_2 emitted per each electric kWh consumed is considered, the BIPV system avoids the emission of 240278 kg of CO_2 into the atmosphere per year.

5 CONCLUSIONS

A PV window has been studied with the aim of being integrated in a building in Malaga (southern Mediterranean area). A peak power of 50.74 W_p was obtained from measurement made in a solar simulator at standard test conditions.

An experimental arrangement was built to obtain the daily production at real sun conditions. A value of 71.2 Wh was obtained when the window is placed in vertically facing south. The production depends on the overall efficiency of the system and on the inclination of the window.

The integration of the PV window in a building allows to obtain energy, economic and environmental advantages.

Considering an apartment building with a surface of photovoltaic windows of 4320 m^2, the BIPV system provides enough energy to cover the annual electric demand of the dwellings of the building, producing an excess of energy that can be sold to the grid and avoiding the emission of 240 tons of CO_2 to the atmosphere annually.

The use of semi-transparent BIPV elements will become more and more popular to combine various functions, namely electricity generation, thermal insulation, shading, and even satisfy aspects of architectural design.

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