ON THE COMPROMISES BETWEEN FORM AND FUNCTION IN GRID-CONNECTED BUILDING-INTEGRATED PHOTOVOLTAICS (BIPV) AT LOW-LATITUDE SITES

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Abstract

The integration of photovoltaic (PV) modules on building façades and rooftops is an ideal application of solar electricity generators in the urban environment. Maximum annual performance of grid-connected PV is usually obtained with modules tilted at an angle equal to the site latitude, facing the equator. The performance of PV systems not tilted or oriented ideally can drop considerably, depending on site latitude. With grid parity - when the cost of solar electricity becomes competitive with conventional electricity – expected in many countries in the present decade, a more widespread application of PV on buildings is expected, and in this context, the main goal of this paper is to show that good compromises between form and function can be reached. In this work we compare the annual energy generation of a curved BIPV system installed as a carport rooftop, with an ideally-oriented and tilted, flat BIPV system installed as a building's rooftop cover at a low-latitude site (27°S). For the one-year period analysed here (Jun/2009 to May/2010), the curved-shaped BIPV annual yield was 12% lower than the reference BIPV system, and, for summer months (Nov/2009 to Feb/2010), the BIPV curved-shaped system presented superior monthly yield (the difference was +15% for Nov/2009). From these results it was possible to show that one can reach a good compromise between form and function in BIPV systems.

Keywords: grid-connected photovoltaics; building-integrated photovoltaics (BIPV); thin-film PV; yield of solar generators.

1. Introduction

Energy generation is one of the central issues of sustainable development all over the world. The direct conversion of sunlight to electricity using solar photovoltaic (PV) devices is one of the most elegant and benign ways of generating electrical power. When PV modules are integrated to a building's skin, as part of the roof or as façade elements, the unique attribute of this power generating technology – the possibility to generate energy where energy is consumed - is put to its most ideal application. Besides, especially in the case of replacing high-priced architectural exterior materials, which are frequently used in recent buildings, the economic efficiency of BIPV systems increases (Miles, 2006). The ability of buildings to supply their own electricity through photovoltaics is receiving concentrated interest (Yoon *et al.*, 2011). When PV generators are constructed as part of a building's envelope, energy transmission infrastructure, and the associated costs and losses are also avoided, and final energy costs can be compared with end-consumer tariffs, instead of with energy costs at the generation plant busbar.

For grid-connected PV systems, annual performance optimization is usually obtained when PV arrays are oriented towards the equator (facing south at sites in the northern hemisphere, and facing north at sites in the southern hemisphere). The tilt angle depends mainly on the position of the sun and, therefore, differs from location to location in the world (Beringer *et al.*, 2011), but commonly it is assumed that the best tilt angles are equal to the site latitude. At low-latitude sites, where the sun is always high in the sky, the integration of PV on vertical façades can lead to considerable performance losses in comparison with the ideal tilt and orientation. Burger and Rüther (2006) have shown, however, that a vertical, north-oriented façade at a 27°S (Florianopolis) site in south Brazil still receives some 30% more solar irradiation over a year than a vertical, south-oriented façade at 48°N (Freiburg) site in Germany. Yoon et al. (2011), analysed a building in order to evaluate the efficiency of the BIPV system under a non-optimized condition for better solar radiation, by considering the effect of shading, especially by the building itself and the direction of the building in terms of azimuth on the electrical energy generation. There are a number of PV systems electrical design and engineering strategies, which try to assess and overcome the intricacies and consequences of the suboptimal position of PV arrays on buildings (Marada *et al.*, 1998; Yoo e Lee, 2002; Ordenes *et al.*, 2007; Song *et al.*, 2008; Chel *et al.*, 2009; Rüther e Braun, 2009; Agrawal e Tiwari, 2010; Corbin e Zhai, 2010; Sun e Yang, 2010).

The electrical design and engineering, as well as the performance forecast of ground-mounted, ideally-tilted and -oriented PV systems is relatively straightforward to perform and assess. With the development and acceptance by architects and builders of PV devices as building elements, tailored for BIPV applications, curved shapes start becoming more common, adding complexity to the estimation of BIPV system performance. Due to the surrounding environment, BIPV systems can quite often be more prone to partial and occasional shading, which lead to performance losses that have to be quantified and minimised at the project stage. Quite often, compromises between the aesthetic appearance (form) and the energy production (function) expected from a PV generator integrated on a building will have to be reached. Knowledge of the concurrent, and sometimes conflicting, consequences between form and function then become of both technical and scientific, as well as of economic interest.

With a more widespread use of this technology, enhancing the performance of BIPV installations will need to be addressed in more detail (Khedari *et al.*, 2002; Yoo e Lee, 2002; Gan e Riffat, 2004; Alnaser e Flanagan, 2007; Tian *et al.*, 2007; Bloem, 2008; Xu e Dessel, 2008; Norton *et al.*, 2010), and output power penalties due to suboptimal PV array tilt or orientation will become a more critical issue. Careful design and the education of architects and engineers can foster the use of PV cogen techniques (Bazilian *et al.*, 2001).

PV solar energy conversion in urban, grid-connected applications is expected to reach grid parity - become cost-competitive with conventional, utility grid supplied electricity – in many parts of the world in the present decade (Byrne *et al.*, 1996; Masini e Frankl, 2003; Yang, 2010). The impressive and ongoing cost and price reductions displayed by this technology in the last ten years were only possible because of the production volumes related to the consistent support of incentive programs, mainly in Germany and the rest of Europe (Neij, 2008; Dusonchet e Telaretti, 2010; Frondel *et al.*, 2010). In Brazil and other low-latitude countries, solar energy scenarios indicate a promising future for grid-connected, building-integrated photovoltaics (Martins *et al.*, 2008), where this technology can have a considerable contribution to the national energy mix in the near future.

In this context, studies that demonstrate, with comparisons, the PV systems performances for different technologies and design concepts, for the same location, are extremely important for support architectural decisions during the project phase.

In this work we present experimental results comparing the seasonal and annual energy generation performance of an aesthetically appealing, but not-ideally-oriented and tilted, curved BIPV system installed as a carport rooftop, with an ideally-oriented and tilted, flat BIPV system installed as a building's rooftop cover using the same commercially available, flexible thin-film amorphous silicon PV module. The BIPV systems are located in close proximity to each other in Florianopolis (48°W, 27°S) - Brazil, and the main goal of this paper is to demonstrate the good compromise that can be reached between form and function in grid-connected, BIPV systems at low latitudes.

2. Method

In order to demonstrate that a good compromise between form and function for a BIPV could be reached, two cases were studied. The first one, considered “ideal system” and called as “UFSC Flat Reference” has the modules on a flat roof north oriented and with tilt angle equal the local latitude (27°). The second one, installed on a curved roof, and labeled as “ELETROSUL Curved System” has half system oriented for northeast and half system oriented for southwest and the tilt angle is, on average, 9°. Both PV generators are very close to each other, with a distance of 600 meters. Besides, both installations have independent data acquisition systems. For this study, a period of one year was analysed, starting on June, 2009 until May, 2010. The two PV generators were compared through their monthly and annual energy yields (kWh/kWp), as this is one of the most relevant performance parameters to compare different photovoltaic systems (Marion *et al.*, 2005).

3. Project description

Both PV generators are installed in Florianopolis, in close proximity to each other. Fig. 1 shows the UFSC Flat Reference System, comprised of a flat, latitude-tilted, north-oriented, 10 kWp building-applied PV generator installed on the rooftop of the Universidade Federal de Santa Catarina (UFSC) theatre’s main building. This PV system uses 80 flexible, 128 Wp each (model PVL-128 from Unisolar), thin-film amorphous silicon (a-Si) laminates, bonded to a flat metal surface, divided in seven subsystems with various electrical configurations designed to allow for experimentation with different inverter types, and inverter vs. PV array sizes (Burger e Rüther, 2006). The subsystem used in this work is comprised of 24 modules (3.072 kWp) connected to a Sunny Boy SB2500 inverter, plus a dedicated data acquisition system that acquires module temperature, solar irradiation and electrical parameters at 5-minute intervals.

Fig. 1: Flat, latitude-tilted (27°), north-oriented, 10.24 kWp building-applied PV generator installed on the rooftop of the Universidade Federal de Santa Catarina (UFSC) theatre main building.

Fig. 2 shows the ELETROSUL Curved System, a curved surface 12 kWp PV array integrated as a car port roof cover at the utility company ELETROSUL headquarter’s building, which is some 600 metres away from the UFSC’s PV installation. This BIPV installation is comprised of 88 flexible, 136 Wp each (model PVL-136 from Unisolar), thin-film a-Si laminates, bonded to a curved metal structure, and divided in three subsystems, each connected to an individual Sunny Boy SB4000 inverter, plus data acquisition system that acquires module temperature, solar irradiation and electrical parameters at 5-minute intervals. Fig. 3 shows a schematic diagram of the three subsystems PV modules' layout. Because the car parking lots at the ELETROSUL headquarters building complex were already defined, the PV system orientation followed the existing pattern, and was not aligned with the north orientation, as shown in Fig. 3. Subsystem 1 (yellow) presents half of the modules facing NE, and the other half facing SW; this layout has consequences in the electrical design of the installation, since the NE and SW portions of the PV array are subjected to different irradiance conditions. In subsystem 2 (green), all modules face SW and are subjected to the same irradiance level; and in subsystem 3 (red) all modules face NE, receiving the largest amount of sunshine over the year.

Fig. 2. Curved surface 11.97 kWp PV array integrated as a car port roof cover at the utility company ELETROSUL headquarter's building.

Fig. 3. Schematic diagram of the three subsystems PV modules' layout.

The irradiation values used in this paper were obtained through a pyranometer of photovoltaic cell model Sensor Sunny of SMA, installed in the reference system, with inclination of 27° and north-oriented (same plan of the photovoltaic array). These values correspond to the global irradiation, because they involve the components direct and diffuse of the incident radiation. Fig. 4 shows the evolution of the monthly irradiation in the analyzed period.

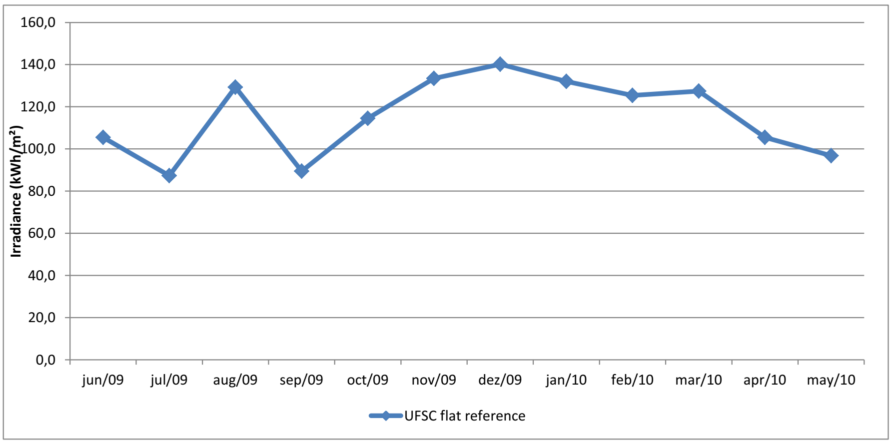

Fig 4. Evolution of the monthly irradiation (kWh/m²) of the UFSC flat reference.

The flat 10 kWp PV installation at the UFSC theatre faces true north, and is never shaded, representing an ideal and real, but not always possible, situation in terms of PV array tilt and orientation. PV array performance optimization (function) was the priority in this system's design. The 12 kWp PV system at ELETROSUL, on the other hand, represents an effort in the compromise between performance and aesthetics. This installation also presents some elements around it (trees, advertising billboard, and the main ELETROSUL headquarters building itself) that can project a certain amount of shade over parts of the PV system in the early morning and late afternoon depending on the season.

In order to be able to assess the effects of shading on the ELETROSUL PV generator, we have used the software ECOTECT. Fig. 5 shows a diagram with the PV system and the surrounding volumes that can project shade on its surface. The simulation shown in this figure corresponds to 11:00 on a typical mid-August day.

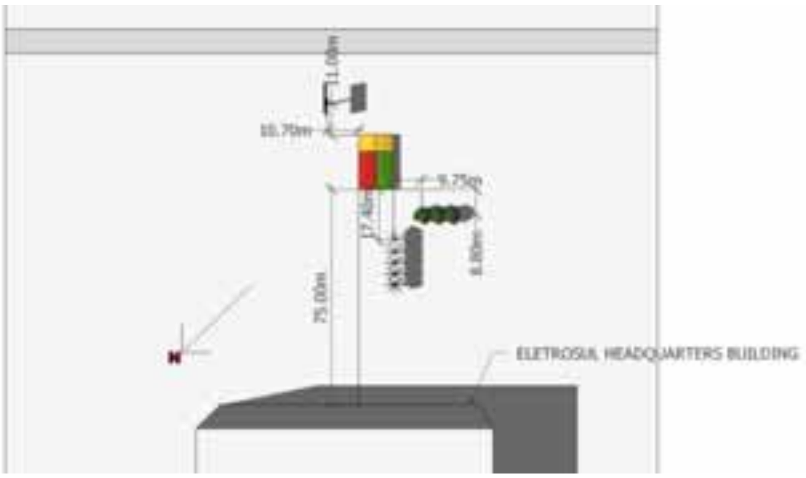

Fig.5: Diagram with the PV system and the surrounding elements that might project shade on its surface. The simulation shown corresponds to 11:00 on a typical mid-August day.

One subsystem representative of the flat-surface UFSC PV generator, and the three ELETROSUL curved-surface subsystems subjected to different degrees of solar irradiation due to their various tilts and orientations were compared in terms of monthly and annual energy production (energy yield). In the next section we present and discuss these results, in the light of the compromises between form and function for these two solar PV generators.

4. Results and discussion

With the aim to ascertain whether the aesthetic compromise reached in the ELETROSUL PV installation resulted in an acceptable annual energy loss, we compared the output performance of the two installations previously described. Table 1 shows the total annual energy yield for each PV array, for the period June 2009 to May 2010. In all cases, in order to account for PV system and subsystem nominal power differences, and to facilitate direct comparison, we have presented output performance (kWh) normalised to nominal (rated) power (kWp).

Tab. 1: Annual yield of the UFSC flat reference and the ELETROSUL photovoltaic subsystems and full system (kWh/kWp).

	UFSC flat reference	**ELETROSUL curved # 1**	**ELETROSUL curved # 2**	**ELETROSUL curved # 3**	**ELETROSUL full system**
Yield (kWh/kWp)	1265	1080	1081	1173	1110
%	100	85	85	93	88

The ideally tilted and oriented flat reference UFSC system yielded 1265 kWh/kWp over the 12 months period, while for the ELETROSUL full system, the annual energy yield was 1110 kWh/kWp (87.7% of the UFSC reference system's yield). Looking at the three ELETROSUL installation's subsystems individually, annual yields were 1080 kWh/kWp (85.4% of the UFSC reference system's annual yield), 1081 kWh/kWp (85.5% of the UFSC reference system's annual yield), and 1173 kWh/kWp (92.7% of the UFSC reference system's annual yield), for subsystems #1, #2, and #3 respectively. Fig. 6 shows the evolution of the monthly yield for the two systems. A smaller annual variability in output for the UFSC installation, which is designed for maximum output throughout the year, with the PV array tilted at 27° (latitude tilt). The good performance of thin-film amorphous silicon PV systems operating in warm climates, is the result of the intrinsic characteristics of this photovoltaic material, and these issues have been discussed elsewhere (Rüther e Livingstone, 1995; Rüther, 1998; Rüther e Dacoregio, 2000; Rüther *et al.*, 2003).

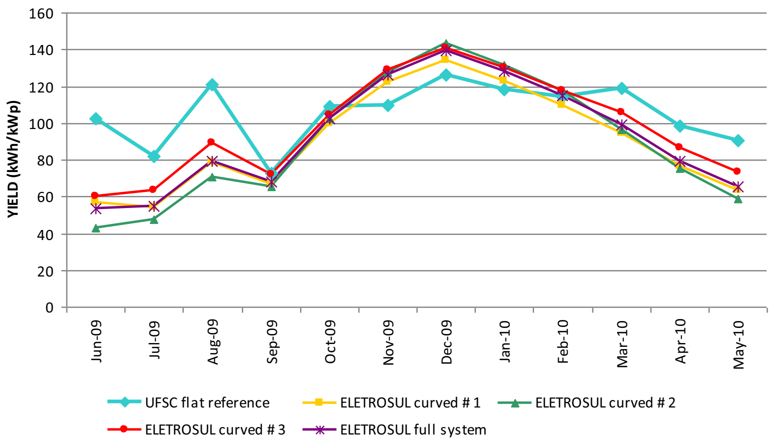

Fig. 6: Evolution of the monthly energy yield (kWh/kWp) of the UFSC flat reference and the ELETROSUL curved PV arrays.

It is noteworthy that on an annual basis, performance losses due to non-ideally tilted and oriented PV arrays at the ELETROSUL PV installations were relatively small, when taking into account the more aesthetically pleasing result of PV integration achieved at the ELETROSUL generator. Considering the full ELETROSUL generator, total annual losses were just over 10% on average, in comparison with the ideal tilt and orientation that leads to the maximum possible output. These results can be considered fairly satisfactory, revealing that on an annual basis at low latitudes the integration of PV modules on curved surfaces leads to a good compromise between form and function.

These results are also presented in Fig. 7 as monthly fractions (%) of the output performance of the reference UFSC system, considered the optimum (100%), or baseline, system in terms of annual performance. On an annual basis all of the ELETROSUL subsystems output performance levels were below that of the UFSC PV installation. However, on a monthly basis, the more horizontally-mounted and curved modules at the ELETROSUL installation outperformed the UFSC PV system in the months around the southern hemisphere's summer solstice (November, December, January and February), when the sun is high in the sky. Due to higher air-conditioning loads in summer, these are the three months with the highest energy demand at the ELETROSUL headquarters (Zomer, 2010). In November 2009 the curved PV generator produced 15% more energy than the flat PV system.

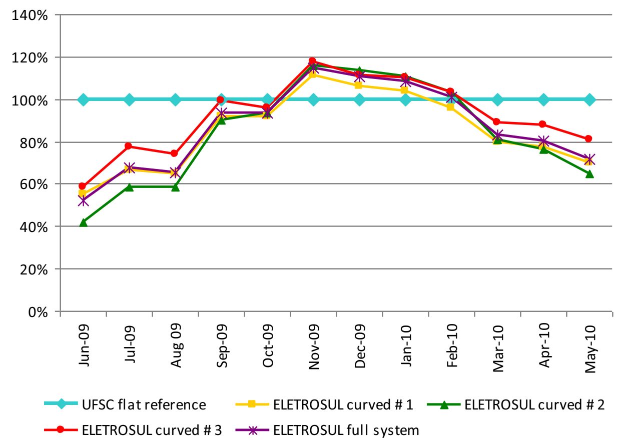

Fig. 7: Percentage of the UFSC system's monthly output performance, showing the strong seasonal variation of the curved PV subsystems.

When comparing subsystems #1 and #2, it should be noted that due to the fact that the NE- and SW-oriented fractions of subsystem #1 are subjected to different irradiance conditions, the whole subsystem was led to perform under the worst case irradiance levels, as expected. Both subsystems #1 and #2 performed at 85% of the optimum on the annual basis, and the fraction of subsystem #1 that was under the same irradiance conditions as subsystem #3 (93% of the optimum expected output), performed as if the irradiance at that portion of the PV array were the same as that reaching subsystem #2. In any case, all these losses can be considered acceptable in the present discussion on tradeoffs between form and function. Furthermore, the small difference in output performance among the three subsystems of the ELETROSUL array indicates that even a negative tilt (the SW-oriented subsystem #2) leads to acceptable losses in output performance. The subdivision of subsystem #1 in two further smaller PV arrays connected to smaller individual inverters, would further optimise output performance, but at the expense of increasing total system complexity and cost. With the introduction of multi string inverter technology, different PV subsystem tilt and orientations can also be addressed satisfactorily, but system design remains bound to limitations in commercial availability of inverter sizes. Fig. 7 also shows that during winter months, output performance of the curved PV installation can drop considerably, reaching a low between around 40 and 60% of optimum, both due to the sub-optimal tilt and orientation, and also as a result of the partial shading shown in Fig. 8. This figure shows the monthly evolution of the shading caused by the surrounding obstacles at the ELETROSUL headquarters complex at hourly intervals shown by the shade projections.

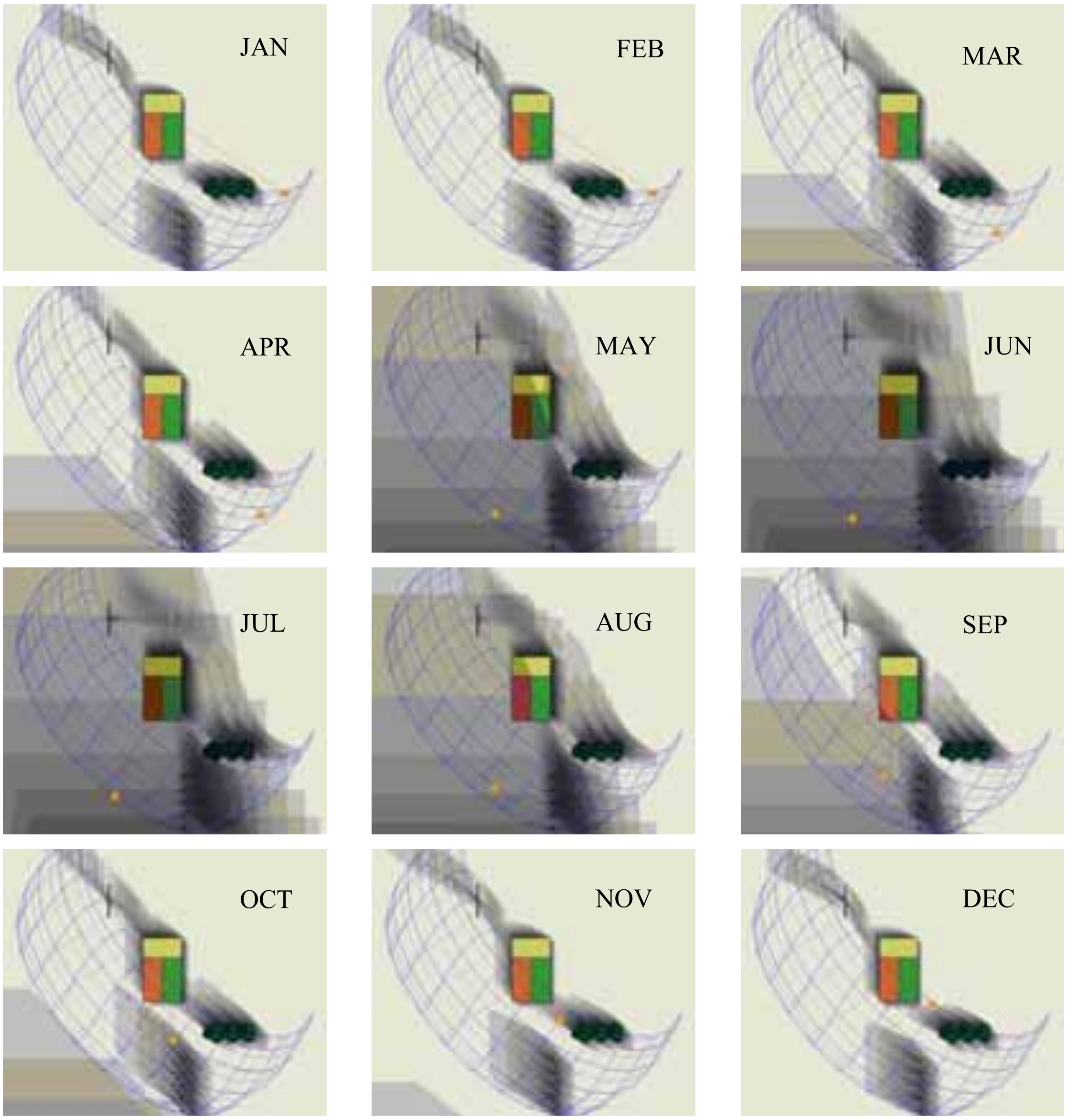

Fig. 8: Monthly evolution of the shading caused by the surrounding obstacles at the ELETROSUL headquarters complex at hourly intervals shown by the shade projections, simulated at the ECOTECT® software.

After a careful examination of the images, it was possible to note that in almost every month, during the period from 8 am to 9 am, the roof was partially shaded. At 6 pm, the roof was partially shaded in all months and from April to September the roof was completely shaded at that time. In the afternoon, the shadow began to take place from 3 pm, and the period from 10 am to 2 pm, there was no shade on the roof. As expected, the effects of shading are more pronounced in winter months and more so in the early morning and late afternoon hours, when irradiance levels are typically low. The most affected subsystem for shadowing was Subsytem #2.

5. Conclusions

The integration of PV on buildings is a worldwide trend, and as PV module prices decline as a result of economies of scale, it is expected that the use of these on-site generators will become more widespread. The adoption of PV modules as building elements by architects and builders is dependent on compromises between aesthetics and performance. It is therefore important to assess to which extent these aspects might conflict with each other.

We have presented results on the monthly and annual performance of two BIPV systems where a compromise between form (aesthetics) and function (annual energy yield) was reached. The ideally tilted and oriented flat PV system resulted in the maximum annual generation, while the average annual output of the curved PV installation was some 88% of that maximum. It can thus be concluded that a good compromise between form and function has been reached in the more aesthetically appealing building-integrated PV generator, with low associated energy losses on an annual basis. On a monthly basis, the curved and more horizontally-tilted PV array showed a more pronounced energy yield variability throughout the year, with a lower minimum in winter and a higher maximum in summer, in comparison with the flat, latitude-tilted generator. Especially in urban BIPV systems, the match between the PV array's solar energy generation profile and the building's energy demand profile should also be taken into account in the design of PV generators. There is a growing trend in distributed energy policies worldwide towards self-consumption by buildings equipped with PV.

As architects and builders become more acquainted with the integration of the different PV technologies on building envelopes, the assessment of energy losses associated with curved and suboptimal orientation and tilt of PV modules becomes a matter of both scientific and technological, as well as of economic importance.

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