Smart Mobility in Cities: GIS Analysis of Solar PV Potential for Lighting in Bus Shelters in the City of Ávila

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Abstract. The reduction of CO_2 emissions in cities implies the generation of clean energy for the supply of the municipal energy demand. In the conversion to Smart Cities, the consumption sources and the generation possibilities should be considered as a whole, in such a way that all the urban elements can be integrated in the energy mix. In this study, bus shelters are evaluated as potential energy generators. The installation of PV panels with the optimal configuration can contribute to the supply of the energy needed in the bus shelter, but also to the generation of surplus energy. The analysis of the possibilities and the definition of the recommendable configuration of PV installations in bus shelters are performed using the city of Ávila (Spain) as case study. In this city, the PV generation reached with the optimal configuration (3500 kWh/year) can cover the energy demand of the bus shelters, including their role as lighting points in the city, and being able to contribute to other energy demands. For this study, geospatial information and a solar radiation model are incorporated in a Geospatial Information System (GIS) tool, specially developed to replicate this study in other cities.

Keywords: Solar energy · Bus shelters · Municipal self-consumption

1 Introduction

The Sustainable Development Goals (SDG) [1], and the goals established by the European Union [2] at urban level regarding the reduction of CO_2 emissions in the automotive sector focus on electrical mobility, mainly applied to cars and buses. In addition, the conversion to a more sustainable society in terms of mobility includes promoting the use of alternative individual transport, such as bicycles and scooters, also electrical, which allow a more agile mobility and a better management to be within the reach of most users [3, 4].

The integration of electrical transport, both public and private, incorporates a new component to the municipal energy demand, which is spatially distributed throughout the city [5]. This transport energy demand is added to others with the same characteristics, such as public lighting demand [6]. Thus, in the context of decarbonization of the municipal energy consumption through its electrification, the reduction of CO_2

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emissions needs the inclusion of clean energies for the energy supply [7]. Among the existing clean energies, solar energy is the energy source more evenly distributed in space and with the more versatile technology to be used at different scales and from different locations [8].

The implementation of self-consumption strategies associated to the use of natural resources implies a reduction in municipal spending on services such as public lighting and transport [9]. This reduction could affect the economy of the citizens through a reduction in public taxes and could expand the supply of public transport [10], more adapted to the real needs and economic resources of the users. Consequently, the gap caused by energy poverty can be minimized thanks to the fact that the facilitation of transport can imply the removal of barriers to employment [11]. In addition, the supply of energy from renewable energy sources, together with the improvement in the public transport service, would lead to an improvement in the habitability of municipalities facing problems of depopulation [12, 13]. In this way, renewable energy for the energy supply of public services would be a solution to the depopulation of rural areas, acting as an incentive for the incorporation of new inhabitants and for the return of the original ones [14].

For a proper planning, distribution and design of solar installations to supply the municipal energy consumption, a prior knowledge of the characteristics of each individual consumption, as well as the possibilities of combined consumption among several components is required.

An example of a combined service is the incorporation of the bus shelters as part of the public lighting, with the dual purpose of increasing the level of lighting with street furniture already in use and the consequent increase in the sense of security for citizens. It has been proved that higher levels of lighting provide a higher sense of security and, consequently, a higher willingness towards mobility [15]. Another example is the equipment of bus shelters as connectivity points, with WiFi stations, USB chargers and Air Control Quality stations, also supplied with solar energy for their contribution to smart cities [16].

For these reasons, the main objective of this work is to analyze the viability of incorporating PV solar installations in bus shelters that serve for the energy supply of municipal services towards their decarbonization. The work is aligned with many SDGs, such as SDG 1 (end of poverty), 7 (clean and affordable energy) and 11 (sustainable cities and communities) [1]. Similar works have been published for the incorporation of the bus shelters as energy providers of an electric system of public transport with PV panels [17], as well as for the combined installation of solar and wind energy systems in the bus shelters in order to maximize their contribution to the supply of municipal services [18].

The analysis of municipal energy demand and the availability of solar energy has an important geospatial component. In addition, the three dimensions of space should be analyzed, provided that the height component is key regarding the intensity of the incoming solar radiation and the shadow projection [19]. Thus, the study is based on the development of a 3D-GIS that, together with numerical analysis of energy needs of the municipal services in terms of public lighting and transport, will be the basis for the design of solar installations in bus shelters.

2 GIS of Bus Shelters in the City of Ávila

Spain is one of the European countries with highest number of solar hours along the year [20], due to its climate conditions and geographic situation. This results in a greater potential of PV solar energy. Within the territory of the Iberian Peninsula, Ávila is the city that receives the second higher solar insolation (2700 h/year) as the highest city (1132 m above sea level) of the Iberian Peninsula [21]. For these reasons, Ávila has been chosen as pilot case study.

The first step for the analysis of the spatial distribution of street furniture and for the incorporation of bus shelters as a solar energy resource is to perform an inventory of the existing urban furniture related to public transport. This inventory includes the geospatial location of each element and information about its connection to the electrical grid. The connection to the electrical grid allows the possibility to exchange energy from the solar installation to the grid in those hours when production is higher than consumption, and vice versa.

The inventory of urban furniture related to public transport resulted in 64 bus shelters and 131 bus stops, respectively (Fig. 1). Among bus shelters, 41 of them are 4 m long, and 23 are 5 m long.

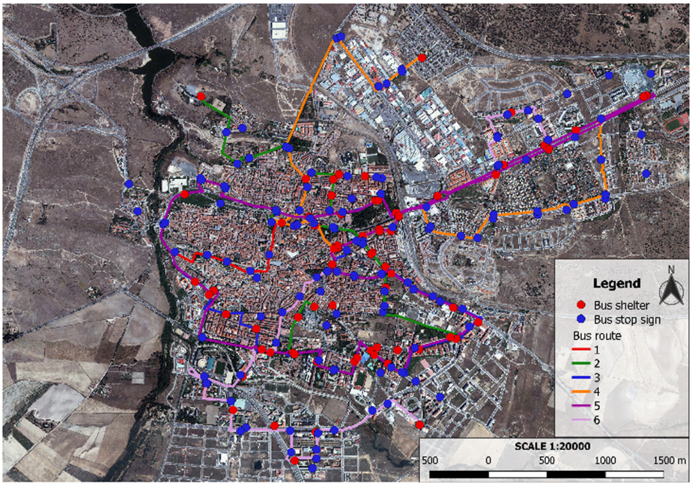

Fig. 1. GIS of the bus shelters (in red) and the bus stops (in blue) of the city of Ávila (plan view). Color lines represent the different bus routes in the city. (Color figure online)

Thus, the GIS for street furniture related to public transport includes the geospatial distribution of the bus shelters and bus stops. This can be associated with the different bus routes to manage the number of passengers in each stretch of the tour and for each tour schedule to size the lighting requirements and the possible energy demand regarding some services of the bus shelters such as the use of interactive screens.

In addition, the environment of the bus shelters is modelled in 3D, so that the tool can provide information on the shadow cast on each bus shelter throughout the year.

The modelling is performed using as a basis the LiDAR data of the city freely offered by the Spanish Geographic Institute (IGN), as in [22]. The 3D modelling includes the buildings that can cast shadows over the bus shelters (those located East, South or West with respect to the bus shelter), as well as the trees that are taller than the shelters in those orientations.

2.1 Energy Demand in Shelters

In order to assess whether the solar potential of bus shelters meets their supply needs, it is key to determine the main consumption sources in bus shelters.

In the context of digitalization and Smart Cities, the objective of giving a double use to bus shelters as furniture for public transport and as public lighting elements determines the sources of energy in bus shelters. Regarding the first condition of Smart Cities, the bus shelter should be equipped with: (i) a LED panel that offers information on the incoming buses and their estimated arrival times, (ii) an interactive screen for the user to obtain information about the city and the public transport, and (iii) a digital advertising panel that minimizes the consumption of paper billboards. These elements should work 24 h a day in order to cover the public transport service hours (mainly during the day) and to reinforce the lighting in the bus shelters during non-service hours, at night. With respect to the integration of the bus shelters as part of the public lighting system, LED lighting would be included with operating hours that match with that of the street lamps, which are adapted to the duration of the night along the year (Table 1). To estimate the total energy demand for lighting, an average operation of 11.8 h has been considered (Table 2).

Table 1. Summary of possible sources of energy consumption in bus shelters.

Element	Power (W)	Average daily usage time (h)	Daily demand (W)
LED panel	18	24	432
Interactive screen	7	24	168
Digital advertising panel	350	24	8400
Lighting	40	11.8	473

According to the average value of hours of sun per month, the total energy demand required per bus shelter in the City of Ávila would be that detailed in Table 2. This table distinguishes between the energy demand required if the complete equipment is installed and if only the basic equipment (information LED panel, interactive screen and lighting) is installed. This distinction is made because the high consumption of the digital advertising panels can limit the efficiency of the PV solar installation, and also because of the commercial value of the panels, which makes their energy supply with municipal services arguable.

The main source of variability on consumption shelters is lighting. Therefore, the energy demand decreases in summer, when the length of the day is longer, and increases gradually until winter, when there is a greater need for lighting.

Table 2. Daily energy demand on the bus shelters.

Month	Street lighting daily usage time (h)	Demand with a complete equipment (W)	Demand without digital advertising panels (W)
Jan.	14.21	9568	1168
Feb.	13.41	9536	1136
Mar.	12.02	9481	1081
Apr.	10.65	9426	1026
May	9.54	9382	982
June	8.98	9359	959
July	9.39	9376	976
Aug.	10.22	9409	1009
Sep.	11.55	9462	1062
Oct.	12.93	9517	1117
Nov.	14.11	9564	1164
Dec.	14.77	9591	1191

3 Analysis of PV Solar Potential in Bus Shelters

3.1 Shadow Analysis

The analysis of shadows cast on the bus shelters has been performed using the NOAA Solar Calculator [23] and the 3D modelling and geospatial information from the GIS created for the street furniture related to public transport (and presented in Sect. 2).

The NOAA Solar Calculator determines the azimuth and altitude coordinates of the Sun for specific times, considering the position under study. With these azimuth and altitude values, the NOAA Solar Calculator determines the Sun position for each hour, and consequently the sunrise, sunset, and solar noon through the year. The calculations of solar position and incoming solar radiation are based on [24], including the computation of the refraction effect on the incoming solar radiation, increasing the precision of the results.

The shadow analysis is based on the tracing of rays from the Sun to the position of the bus shelter, and the determination of an obstacle (building, tree) within the path of the rays. If an obstacle is present, it would cast a shadow on the bus shelter, consequently reducing the generation of energy of the solar installation on the shelter. The size of the obstacle determines the size of the shadow projected on the bus shelter.

In order to include the loss of energy generation caused by the shadows cast on each bus shelter, the hourly position of the Sun was calculated for one representative day of each month. In this pilot case study, the day 15th of each month was considered.

In addition to the visual analysis shown in Fig. 2, which shows the results of the presence of obstacles (shadow projectors) within the rays between the Sun position and the bus shelter, a summary table has been created for each bus shelter (Fig. 3). The summary table shows in which hours the bus shelter is covered by shadows, and therefore for what times the total PV solar production initially calculated is minimized. As a criterion established for this pilot case study, a bus shelter is considered as "overshadowed" if more than 50% of its surface is covered by shade. In the GIS tool developed, this percentage can be adapted to the characteristics of each case also, the reduction in production can be proportional to the percentage of surface in the shade.

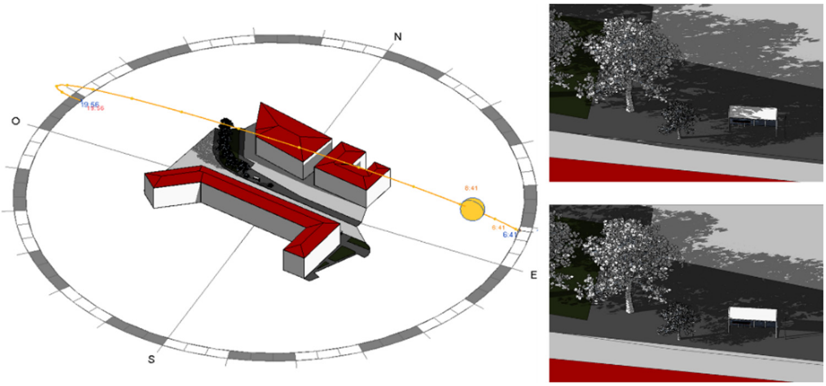

Fig. 2. Example of the simulation of shadow projection on a bus shelter, 4 m long. Left: Sun path; right: detail of shadow projected at two different times.

Hour	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
6.00					YES	YES	YES					
7.00				YES	YES	YES	YES	YES	YES			
8.00		YES	NO	NO	NO	NO	NO	NO	NO	YES	YES	
9.00	YES	YES	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
10.00	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
11.00	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
12.00	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
13.00	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
14.00	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
15.00	YES	YES	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES
16.00	YES	YES	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES
17.00	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES
18.00	NO	NO	NO	YES	YES	YES	YES	YES	NO	YES		
19.00				YES	YES	YES	YES	YES	YES			
20.00					YES	YES	YES	YES				

NO The bus shelter is **NOT** overshadowed YES The bus shelter **IS** overshadowed

Fig. 3. Summary of the presence of shadows in the bus shelter of Fig. 2, for each month and with hourly resolution.

3.2 Optimal PV Panels Design

The bus shelters are structures that can be open to different designs for PV solar installations. The key to an optimal design is to analyze the different options available, calculate the total energy production for each option and decide which production regime is best suited to each case. In turn, there is a criterion of generating the maximum amount of energy or generating energy for the longest possible time each day.

In the case of Spain, the energy production in bus shelters can benefit from the possibility of discharging the surplus of energy to the electricity grid and proportionally reduce the cost of the energy consumed from the grid when there is no generation. In other countries, where discharging the surplus of energy to the electricity grid is not possible, there is the possibility of installing batteries to store the surplus of energy and make it available in non-generation hours.

Among the design possibilities contemplated in the study, the following are included: (i) maximum annual production, consisting on panels oriented to the south (northern hemisphere) and optimal inclination (35º for the city of Ávila); (ii) energy production for the longest period per day, which consists on the horizontal position of the panels that guarantees that the panels receive solar radiation from the sunrise to the sunset; and (iii) highest level of geometrical integration of the panels, with flexible panels following the curved shape of the shelter.

For the three possibilities, the computation of energy production includes the subtraction of the energy that is not generated due to the presence of shadows cast over the shelter. For this reason, in the case study of Ávila, the months with zero energy production are those in which the bus shelter is in the shade during the entire day.

PV Panels with South Orientation and Optimal Inclination

The installation of PV panels on orientable supports is a common strategy in order to adapt the position of the panels to the desired design of the PV installation. In the case of cities located in the northern hemisphere, the panels must be oriented towards the south in order to receive the incoming solar radiation from the most perpendicular angle. The opposite orientation (north) is recommended in the south hemisphere. In the case of Ávila, the optimal inclination of the panels is 35º. This is the inclination that guarantees the capture of Sun rays as perpendicular as possible throughout the year, allowing the generation of the maximum energy possible.

Table 3 shows the estimated energy production of the bus shelter of Fig. 2 with PV panels facing south and inclined 35º. As shown in Fig. 3, there is only one hour in which the shelter is not covered by shadows for the months of January and November, while the solar radiation never reaches the bus shelter in December. This is the reason why low or no energy generation is obtained during those months.

Table 3. Daily maximum power production per month, in watts, for the bus shelter of Fig. 2 with a PV installation facing south and inclined 35º.

Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
60	3038	5264	5462	6021	6493	7077	6966	6366	4436	199	0

By analyzing the energy demands, the percentages of self-consumption and the possible energy surplus can be computed. Table 4 shows an example of the self-consumption level achieved for the example shown in Fig. 2.

In addition to the energy production, another criterion to be considered is the structural and visual integration of the panels on the bus shelter. In the case of establishing a design with south orientation and 35º inclination, the panels would require the installation of an additional support to facilitate the installation in this position. This support would imply: (i) an additional weight for the shelter, which may have not been designed to support such load and that caused by the resistance offered against the wind; and (ii) an over-height that would not favor either the visual integration nor the conservation of the panels (possibility of vandalism).

Table 4. Daily percentage of self-consumption and energy surplus for solar panels facing south and with an inclination of 35º on bus shelters in Ávila.

	Self-consumption (%) with all sources of consumption (Table 1)	Self-consumption (%) with no digital advertising panels	Energy discharged to the electricity grid with no digital advertising panels (Wh/day)
Jan.	1	5	0
Feb.	32	267	1902
Mar.	56	487	4183
Apr.	58	532	4436
May	64	613	5040
June	69	677	5534
July	75	725	6102
Aug.	74	691	5958
Sep.	67	599	5304
Oct.	47	397	3322
Nov.	2	17	0
Dec.	0	0	0

Horizontal PV Panels

The PV panels can be installed horizontally directly on the top of the bus shelters or using a support in case the shelter has a pronounced curvy design. Table 5 shows an example of the energy production of horizontal panels for the bus shelter of Fig. 2.

Table 5. Daily maximum production per month, in watts, for the bus shelter of Fig. 2 when installing PV panels horizontally.

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
30	2126	4217	5037	6064	6813	6813	6529	4592	3165	107	0

As in the case of south orientation and 35º inclination panels, the percentages of self-consumption and the generation of surplus energy can be computed in the case of horizontal panels. Table 6 shows an example of the self-consumption level achieved for the example of Fig. 2.

Regarding the analysis of integration of horizontal panels and the need of supports for the panels, both depend on the specific design of the bus shelters. In the case of the bus shelters of the city of Ávila, these have a curved shape of 30º (angle formed by the horizontal plane and the shelter), in such a way that supports would be necessary to stabilize the panels in a horizontal position. This position, closer to the shelter, implies a reduction of the wind loads regarding the load caused by the 35º panels. A higher level of integration also decreases the risk of damage caused by vandalism. On the other hand, horizontal panels are easily damaged by natural causes such as snow or hail, which are typical in Ávila in winter and summer. In addition, the panels are more susceptible to accumulating dust, reducing their performance.

Table 6. Daily percentage of self-consumption and energy surplus for bus shelters with a horizontal PV panel configuration.

	Self-consumption (%) with all sources of consumption (Table 1)	Self-consumption (%) with no digital advertising panels	Energy discharged to the electricity grid with no digital advertising panels (Wh/day)
Jan.	0.3	3	0
Feb.	22	187	989
Mar.	44	390	3136
Apr.	53	491	4011
May	65	618	5082
June	73	710	5854
July	73	698	5838
Aug.	69	647	5520
Sep.	49	432	3529
Oct.	33	283	2048
Nov.	1	9	0
Dec.	0	0	0

Flexible PV Panels Integrated on the Shelter

The latest advances in adaptable materials have allowed the generation of flexible PV panels. The position of these panels can be adjusted to the geometry of the bus shelters, which mostly present curved shelters. The main limitation of flexible panels is that their curvature must not exceed 30º.

The average curvature value of the shelters in Ávila is 30º, which is exceeded in some parts of the shelters. Therefore, and in order to satisfy the curvature requirement, the proposal was to install flexible panels in the middle of the shelter, in such a way that each panel had half of its surface facing towards one orientation and half towards the opposite orientation.

For the bus shelter in Fig. 2, 50% of the panel faces south and 50% of the panel faces north. With this configuration, the average degree of curvature is 25º, which is within the technical requirements of the flexible panels. The maximum monthly production obtained with this PV solar design is shown in Table 7.

Table 7. Daily maximum production per month, in watts, for the bus shelter of Fig. 2 when installing flexible PV panels.

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
14	715	1526	1825	2190	2453	2601	2341	1901	1142	45	0

Again, the percentages of self-consumption and the generation of surplus energy were computed as shown in Table 8.

Table 8. Daily percentage of self-consumption and energy surplus for bus shelters with flexible PV panels.

	Self-consumption (%) with all sources of consumption (Table 1)	Self-consumption (%) with no digital advertising panels	Energy discharged to the electricity grid with no digital advertising panels (Wh/day)
Jan.	0.2	1	0
Feb.	7	63	0
Mar.	16	141	445
Apr.	19	178	799
May	23	223	1208
Jun.	26	256	1493
Jul.	28	267	1625
Aug.	25	232	1333
Sep.	20	179	839
Oct.	12	102	25
Nov.	0.5	4	0
Dec.	0	0	0

In terms of structural and visual integration, flexible PV panels are the best configuration. On the one hand, their position, parallel to the bus shelter, eliminates the need for additional support and reduces the visual impact. On the other hand, the lightness of the flexible material reduces the additional weight on the shelter, also reducing the structural demand and possibility of being damaged by the wind or other meteorological phenomena. In addition to minimizing the visual impact, the integrated panels reduce the possibility of vandalism due to the unawareness of their presence.

4 Discussion

Applying the methodology proposed in Sect. 3 and making use of the GIS of bus shelters, it is possible to know the PV solar potential in all the bus shelters of the city of Ávila. The average annual production for the different PV designs considering all the bus shelters in Avila (and their different dimensions) is shown in Table 9.

Table 9. Annual average production, in gigawatts-hour, for the city of Ávila and the different configurations of the panels.

	Conventional PV panels		Flexible PV panels
Inclination	0º	35º	25º
Annual average production for the bus shelters in Ávila (GWh)	122	132	52

For all the configurations, the highest production was obtained for PV panels with the optimal inclination (35º), followed by the configuration with a 0º inclination.

Although the flexible panels have an inclination (25º) closer to the optimal in this pilot case study, the energy production was reduced by half for two reasons:

– Maximum power. Conventional solar panels can reach high production power (330 W has been used for computation of this work) while flexible solar panels are currently limited to 200 W (for the computations of this work, 170 W panels have been considered).
– Available radiation. Although the incident radiation on solar panels with an inclination of 25º is greater than on a horizontal surface, the available radiation is practically the same. This is due to the limitation of the curvature of the flexible panels on the shelter, which means that the entire panel cannot be oriented optimally.

Table 10 sums up the percentage of self-consumption considering (i) all consumption sources considered in Table 1, and (ii) without considering the digital advertising panels. For the first case, with conventional PV panels, the self-consumption percentages were between 55% and 59% while for flexible panels the self-consumption did not reach 25%. For the second case, without the digital advertising panels, the percentage of self-consumption was always more than 100%. Specifically, for conventional panels with 35º inclination, self-consumption reaches 527%, while 487% of the demand was covered with the energy generated with horizontal panels (0º inclination). For flexible panels, the percentage was reduced in a half (208%). As a result, the energy discharged to the electricity grid was 107 GWh/year, 97 GWh/year and 27 kWh/year when using a 35º, 0º and 25º inclination, respectively. With the current average price of the energy in Spain (0.09 €/kWh), savings will be around 9630 €, 8730 € and 2430 €, respectively.

Table 10. Annual percentage of self-consumption and energy surplus for bus shelters depending on the inclination of the solar PV panels.

	Self-consumption (%) with all sources of consumption (Table 1)	Self-consumption (%) with no digital advertising panels	Energy discharged to the electricity grid with no digital advertising panels (GW)
0º	55	487	97
25º	24	208	27
35º	60	527	107

5 Conclusions

This work presents the development of a tool based on geospatial data with the aim of analyzing the PV potential of bus shelters. With this tool, bus shelters could play a dual role: (i) serve as street furniture, and (ii) contribute to the energy supply of the municipal demand with clean resources. In addition, the analysis of energy capabilities of bus shelters has been performed seeking the integration of the bus shelters in the street lighting, and in the public transport system.

Taking this into account, an analysis of the solar PV potential in bus shelters has been performed with two combined approaches: the presence of shadows, and the configuration of the panels.

The presence of shadows in the bus shelters reduces energy production during certain months and depend on the location of the bus shelters. Due to the greater intensity of solar radiation in summer, if shadows cannot be avoided, it is possible to reduce their influence in the annual energy production if their presence occurs mainly in winter.

The results of the analysis of the configuration of the panels have shown that the maximum production occurred when the panels are installed on the shelters with their optimal inclination (determined by the location of the city under study, 35º in the city of Ávila). A 7% reduction of the production was obtained when the panels are horizontally installed, while the installation of flexible panels resulted in a 60% loss of energy production. Thus, considering other criteria such as the visual and structural integration level as well as the safety of the panels, the most recommended configuration for the panels would be that with horizontal position.

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