URBAN PHOTOVOLTAIC POTENTIAL OF INCLINED ROOFING FOR BUILDINGS IN HERITAGE CENTERS IN EQUATORIAL AREAS

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ABSTRACT

In situ renewable energy production is a favourable alternative for reducing pollution and combating climate change. The research area, Cuenca, Ecuador, is located in the Andes near the equator with optimal conditions for energy self-supply due to its low energy demands and low levels of irradiation variability. In this study, temporary fluctuations in consumption based on 2016 electricity consumption data are characterized. Using GIS, available roofing polygons are obtained, and the amount of usable solar radiation is estimated based on these values. With available surface, orientation, and inclination information, electricity generation based on photovoltaic performance is estimated and compared for monocrystalline silica panels and photovoltaic solar roof tiles, which are architectural alternatives. A potential net supply of 148% is found for monocrystalline silica photovoltaic panels in a typical format, whereas that of photovoltaic tiles is only 61%. In addition, production-demand imbalances are predicted in extreme months and average months and on extreme days due to variations in irradiation and demands.

KEYWORDS

solar energy, photovoltaic on buildings, photovoltaic architectural integration, heritage centres, energy efficiency

1. INTRODUCTION

Cities must be decisive in the face of climate change because they are strategic places of intervention to combat the greenhouse effect (International Energy Agency 2016). Cities account for approximately 70% of energy consumtion, are currently inhabited by more than half of the

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global population and are growing. It is expected that developing countries will increase their emissions, primarily due to the growth in the energy demand, more than will industrialized countries that pollute more but already have alternatives (Liu, Wang, and Zheng 2017). It is therefore necessary to extend mitigation proposals to developing countries, such as Ecuador, that are experiencing considerable growth in energy consumption and emissions (Wegertseder et al. 2016; Winkler 2017).

The alternative is the integration of renewable energies in the cities themselves, where the goal is to minimize energy imports. Smart grids powered by renewable energy integrated into buildings can effectively contribute to urban energy demands (Barragán et al. 2017; Disch 2010). The Paris agreement suggests that those cities with the capacity to supply over 30% of their energy requirements with solar energy should be considered as strategic locations for atmospheric decarbonization. Additionally, the solar potential with respect to urban demands can provide between 8 and 88% of the electricity required in different urban centres (Byrne et al. 2017); however, these cities are located in climates with less and more unstable irradiation than that investigated in this study.

Ecuador is a developing country in which the energy demand of buildings is about 34% (Pelaes Samaniego and Espinoza Abad 2015). The greatest energy consumption, approximately 50%, is associated with transportation, primarily in urban areas; electricity is a potential option to solve both needs if it comes from non-polluting renewable sources. The local electrical grid has achieved a high degree of decarbonization due to the recent installation of large-scale hydroelectric plants. Moreover, the per-capita demand is one-fifth of the population in developed countries, and an immediate increase in consumption is imminent. Contrary to any environmental policy, since 1996, the use of fossil fuels in Ecuador has been encouraged by current subsidies, which create incentives for their consumption. Today, this policy involves considerable expenses associated with the import of derivative products, and the high demand of these sources has exceeded the refining capacity of the country; this issue has become a latent problem. To overcome this contradictory economic and environmental issue, it is necessary to promote and implement alternatives that, for example, incentivize the use of non-polluting energy sources and promote jobs (IEA 2009; Ren21 2013). However, the provision of energy from outside urban limits, renewable or not, impacts the construction of large infrastructures and transport networks (Scognamiglio 2016). It is therefore essential to consider alternatives that encourage the use of endogenous energy resources.

1.1 Study context

Cuenca is an intermediate-sized city with approximately 368,000 inhabitants and is located at an elevation of 2,535 metres above sea level at a latitude close to the equatorial line. Cuenca has climatic conditions that are unusual. The city is characterized by insolation oscillations as a consequence of cloudiness and is minimally affected by seasonality. The ambient temperature is stable and comfortable throughout the year. The thermal fluctuations exhibit minimum seasonal oscillations, with a maximum temperature of 21.8 °C and minimum temperature of 8 °C; however, momentary peaks can occur that can surpass 25 °C or descend below 5 °C (ClimateData-Org 2018). The electrical demands of residential buildings are for the refrigeration of food, appliances, and lighting. Liquefied petroleum gas (LPG) is primarily used to supply the thermal demands for cooking and the heating of domestic water. In addition, energy is consumed by urban requirements, commercial, and industrial requirements. Recently, the Ecuadorian state has introduced policies to reduce the use of fuels at the residential level by promoting the use of electric induction cookers due to the economic losses that LPG use entails (Vizhñay 2013).

In seasonal countries, irradiation fluctuations due to seasonality exist to various extents; this instability technically limits the incorporation of photovoltaics (PVs) because there is considerable production in certain months and hourly periods. In most countries, the lower PV production occurs when the demands are greatest (Child, Breyer, and Haukkala 2017; Mikkola et al. 2014; Ramirez Camargo et al. 2015). The stability of solar irradiation available in the context of Cuenca (Delgado O. and Orellana S. 2015) and the stability and reduced demands associated with not needing interior spaces to acclimatize thermally magnifies the solar potential and implies fewer limitations and imbalances in the grid. Furthermore, in such a scenario, there is a reduced need to implement energy storage in a hypothetical scenario of distributed PV generation.

Cuenca is a city with heritage value "because it has preserved its image of a colonial-republican town" and because it has adopted "a dynamic modernization process" (UNESCO 2018). In this type of urban environment, PV panels have a long background in Europe. In England, for example, panels are included in Victorian houses. "The next step for heritage conservation is obvious: align the principles and practice of conservation in the 21st century with the principles of sustainability (…) realigning conservation with today's principles of sustainability is an attractive but challenging contemporary definition" (Cassar 2009). In cities with very high heritage value, such as Florence, the natural events resulting from climate change are leading to the rethinking of positions by authorities and citizens to maintain a state of authenticity in a pragmatic manner. Thus, recent research on the rehabilitation of buildings has considered the incorporation of PVs, including technologies that can be considered invasive, such as large-scale silica plates. Studies conducted in Italy highlighted the need to architecturally integrate PVs to replace or overlap clay tiles, as well as the associated construction implications.

Finally, due to the location of Cuenca, the sun path is at high altitude throughout the year, which means that the sun is only at a low altitude early in the morning and at the end of the afternoon. Thus, the horizontal positioning of PVs is the most theoretically suitable. However, from a cleaning perspective, sloped PV installations are strongly recommended to mitigate 1% losses because of dust accumulation, especially in areas that receive high rainfall amounts, such as Cuenca (Smith et al. 2013). In a recent study, the highest production level was estimated via simulations according to data from 2016. The panels were east oriented and not pointing north, as theory would suggest according to the latitude; however, the difference was only 6% between measures in different orientations with respect to theoretical minimum and maximum performance (Izquierdo and Pacheco 2017). Consequently, the skirt of a sloped roof with any orientation is useful for PV deployment.

1.2 Literature review

Solar energy reaches the land surface in a dispersed manner with relatively low power values, and for approximately half of the day, it is nonexistent or minimal. The global average instantaneous irradiation at day hours on a horizontal surface is approximately 1 kW/m^2. In contrast, urban energy demands, such as that of a car, require a concentrated power of 80 kW in an area of 6 m^2. Additionally, although the consumption of a house is approximately 10 W/m^2 on average, at times, the demand can exceed 200 W/m^2 (Cuchi, Díez, and Orgaz 2002). These imbalances in irradiation and short-term consumption are the primary limitations to achieving energy self-sufficient cities.

A variety of studies and methodologies are used to estimate the solar potential in different urban environments from different perspectives, and the objective is generally to visualize and assess the feasibility of a *solar city* scenario (Byrne et al. 2017). Virtual and computer models have been used to quantify the available radiation. Virtual modelling (3D models) and vectorial representations of irradiation (intensity and directionality) were the first methodologies used to detect the amount of potential urban irradiation (Compagnon 2004); currently, new methodological alternatives are available (Romero Rodríguez et al. 2017). Izquierdo et al. (2008) measured the solar potential on building roofs in Spain and estimated the available irradiation and feasibility of electrical conversion; additionally, the authors determined the amount of usable energy in each municipality and, from that value, the amount on a per-capita basis. Araya-Muñoz et al. (2013) proposed a three-dimensional model of houses in Valparaíso, Chile, combined with a topographic model; from the three-dimensional model, the roof surface area could be determined, and the irradiation conditions and limitations based on the orientation, inclination, and consequent intershading due to the topography and solar pathway were subsequently obtained. Another methodological option is surface scanning via a radar or LIDAR survey. In such cases, radar equipment is required to obtain accurate three-dimensional information regarding the "volumetric texture" of urban centres, and using processing software, irradiation can be estimated in different urban areas through overflights and radar surveys (Lukač and Žalik 2013). Although this approach is a precise methodology; its high cost limits its use in developing countries (Wegertseder et al. 2016). Ko et al. (2015) applied semi-automatic information processing in ArcGIS to estimate available irradiation and investigated the hourly urban effect of shadows.

Moreover, assessments of urban potential must consider the detection of the space-time oscillations of irradiation and the energy production demanded. Such data are essential for the calibration of the electric grid, and/or storage systems (Lund 2012) and for temporal and spatial modelling (Mikkola and Lund 2014). It has been demonstrated that the configuration of grids and electrical distribution systems limits the capacity of self-supply to a fraction of the potential supply that exists in catchment areas. For example, it has been shown that despite the existence of an important solar potential in an urban area, as in the case of Concepción, Chile, where 87% of the total demand could be reached (Zalamea and García Alvarado 2014), the potential is reduced to 15% to 27% due to seasonal oscillations and grid restrictions (Wegertseder et al. 2016).

A third aspect is the social acceptance and architectural implications when integrating active solar collection systems. The possibilities, criteria, and limitations of PV architectural integration have been theorized and discussed (IEA SHC Task 41 2012; Jelle 2016; Kaan and Reijenga 2004). The emergence of thin-film PV provides the potential for technology to mimic real materials and is a particularly useful strategy in architecturally sensitive areas. However, these products do not perform as well as typical products, require complex installation and are expensive (Cinnamon 2016).

This paper presents a methodology to estimate the PV potential considering temporary fluctuations in the demand and energy production. Hourly oscillations are observed from net irradiated surfaces, and the geometry of collectors versus roof geometry is considered. Occupancy indices are obtained by considering local parameters associated with variations in collector inclination and shading indices, which are factors that have been identified as relevant and influential in temporal imbalances. Additionally, a comparison of performance among PV potential technologies is presented considering the potential efficiency of products for architectural integration. The proposed methodology is robust and based on actual consumption data from the study area and hourly measurements of photovoltaic performance, which are used to validate the estimation model. Izquierdo et al. (2008) noted the need to analyse three factors to determine the feasibility of large-scale PV integration: the solar potential, conversion and network technologies, and social implications. This study investigates the first factors and addresses the second and third factors, because in addition to estimating production and the imbalances in grid design, the architectural implications of choosing one alternative over another are considered (social implication). Additionally, energy shortage and surplus scenarios are assessed (conversion end network technologies). The novelty of the proposed methodology is to jointly consider parameters, such as the roof geometry, hourly consumption, irradiation, and shading, and to compare PV technologies. These parameters have not been considered in previous studies.

2. MATERIALS AND METHODS

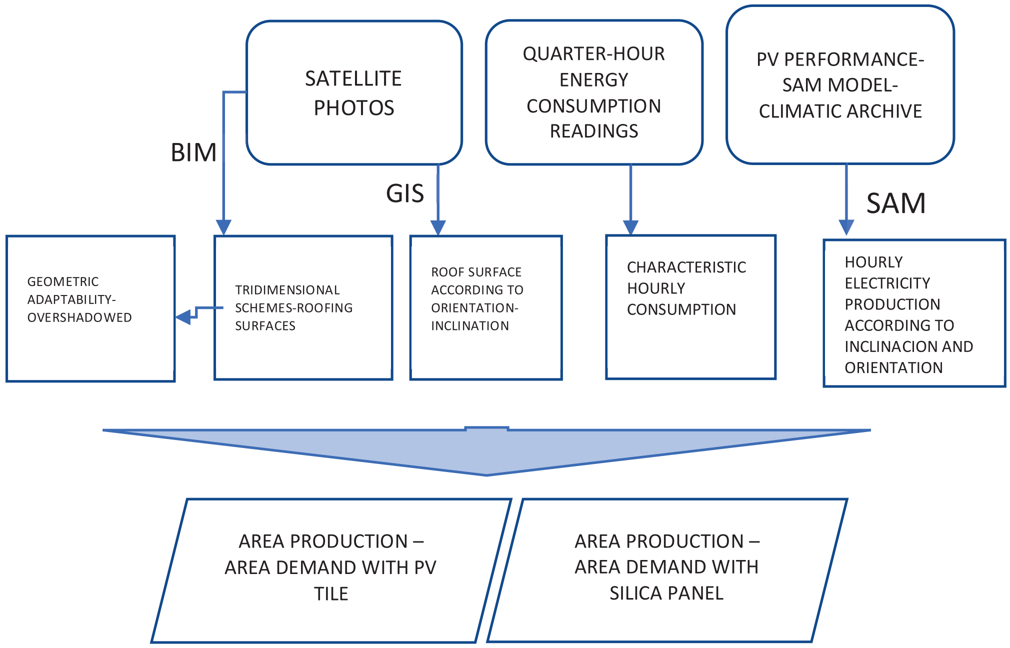
The local electrical company records the sale by distribution sectors in quarter-hour readings. Consumptions are taken from four of these constituent sectors in the central core of the city of Cuenca from 2016. The study area contains approximately 80 blocks. From the general data, urban demands are characterized via hourly, daily, monthly, and annual curves. Seasonal, average, and extreme conditions are detected.

With GIS, shapes are extracted from the roof surfaces available for solar radiation collection, which are discriminated by orientation towards the cardinal axes. Only inclined roofs are used, and terraces are not considered because terraces can potentially be used for alternative uses, such as for occupancy and cultivation or as a green roof. The study area is developed in an urban layout on a Spanish grid with streets that run north-south and east-west with a deviation of 9°. This implies that the roof skirts are also arranged close to these four orientations. The skirts are dimensioned by classifying them based on orientation to estimate the irradiation and hourly feasible production. The occupancy index of typical 60-cell silica solar panels is obtained, and this format is the most common on the market (Cinnamon 2017b). The PV roof occupancy index is also determined; it proportionally measures losses due to geometric adaptability. A sample of one hundred houses and their respective roofs was taken at random, and the sample was representative of the textures of silica PV panels and roof tile geometries. Typical indices are used to quantify a feasible catchment surface or correct values due to geometric conditions.

For the same hundred houses, in thirty-four cases, shading is significant. Thus, shadow indices are determined through simplified 3D models generated in BIM (Building Information Modelling) software, and hourly analyses of the blocks themselves and their adjacent volumetric measurements are performed.

The PV yield is based on readings obtained in a previous study that investigated the performance of monocrystalline silica panels arranged at different inclinations according to those typically considered for local roofs (Izquierdo and Pacheco 2017). Based on this production capacity and the climatic archive that records local irradiation, the PV yield is calibrated in a model for PV simulation in a System Advisor Model (SAM; NREL 2017). With this procedure, an estimated hourly yield of production for the year 2016 is obtained in m^2 in accordance with inclination and orientation. In a similar manner, the potential yield of PV roof tiles is estimated. Such technology has become commercially available in recent years in both Europe (Farkas

FIGURE 1. Methodological diagram.



2013) and the United States (Tesla 2017). Despite the low efficiency compared to some other panel options, this approach provides better geometric adaptability and a better occupancy rate.

The absolute total annual, monthly, hourly, and daily production values are compared to demands. Peak productions and demands are identified and compared on days of maximum irradiation, minimum irradiation, and average irradiation, as well as days of maximum, minimum, and average demand. This method can be used to identify the requirements and oscillations in the grid required for an eventual massive PV installation.

Figure1 shows the methodological scheme used in this work.

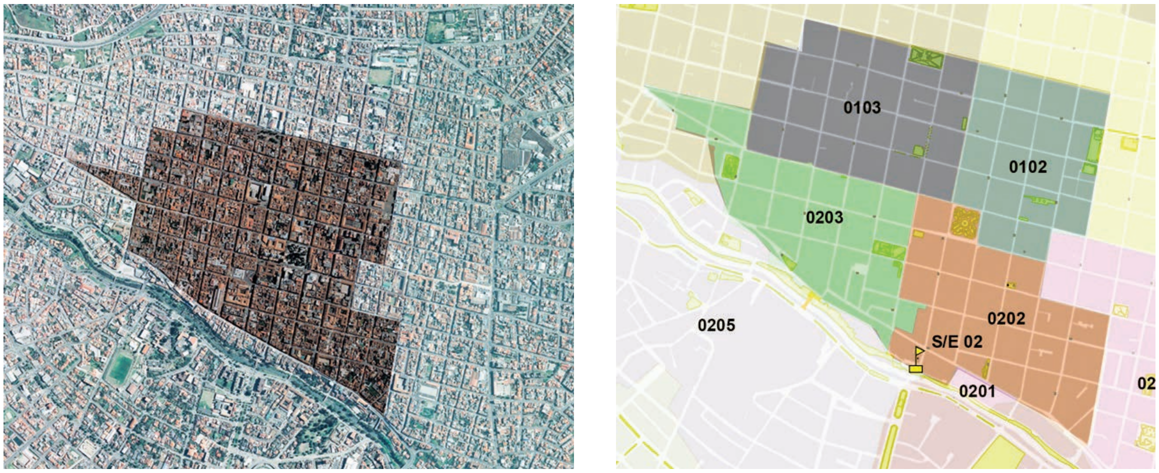
3. RESULTS

3.1 Study area and characterization of the energy demands

The study area, which is composed of four sectors of power distribution, is shown in Figure 2. These data are hourly time records provided by the distribution company Centrosur for 2016 and consist of approximately eighty blocks that cover a total area of 1,073,876 m^2. There are approximately 2800 buildings with typical sloping roofs in this area. The buildings typically have between one and three floors, and most have a typical "Spanish" clay tile roof covering; however, there are a number of buildings with alternative roof materials, such as fibre cement or zinc sheets.

Using the GIS tool, all the roof skirts are selected and dimensioned; among them, inclined roof skirts are extracted and grouped according to orientation. The total dimensioned inclined roof surface area is 339,227 m^2, and the characteristic inclination angle is 18°, although roofs vary between 14° and 26°. Thus, the net sloping roof index is 0.32 m^2 per m^2 of city.

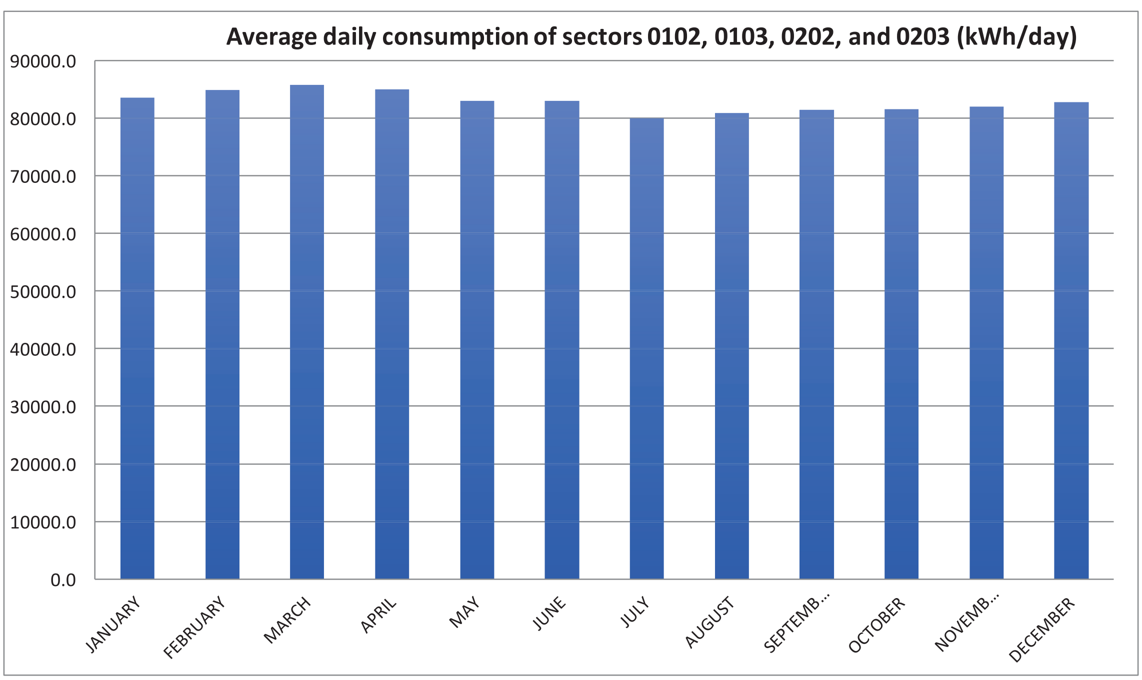
FIGURE 2. Aerial image of study area and electrical connection of sectors 102, 103, 202, and 203.



3.2 Characterization of demands

The energy requirements of a city are highly dependent on climate, among other factors; in this case, weather conditions are particularly stable throughout the year. For characterization, the average daily electricity consumption is determined for each month. Figure 3 clearly shows the annual stability. The minimum daily average demand occurs in July (vacation month) at 80.0 MWh/day, and the maximum average is observed in March at 85.7 MWh/day. The absolute

FIGURE 3. Average daily consumption in each month.



average is 82.8 MWh/day with variations on the order of +/– 3.5%. Due to the location of the city at latitude 2.5° south, there are seasonal variations, although extremely slight, with less irradiation in June and July. The most irradiated months are November and December. The average electric demand index in urban areas is 77 Wh per m^2.

However, the weekly analysis reveals oscillations between days. On weekends and especially on Sundays, there is substantially less consumption compared with that on working days. On Saturdays and Sundays, consumption is reduced by 15.5% and 31.0% on average, respectively, compared with that on the average working day. Figure 4 shows the typical weekly consumption and fluctuations.

The consumption time characterization is shown in Figure 5, which shows the daily average in extreme months according to the maximum demand (March) and minimum demand (July). Despite being maximum and minimum extremes, these values are extremely similar, and this trend is radically different from that in countries with moderate seasonality, such as the city of Concepción, Chile (García et al. 2014), and marked seasonality, such as Helsinki, Finland (Salpakari, Mikkola, and Lund 2016). A comparison of the hourly demand shows that there is 2.5 times more consumption during the day than at night. During the weekend, the demand during working hours is consistently low, but this is not the case during late-night hours when it is essentially the same every day.

3.3 Energy supply capacity with integration of monocrystalline collectors and PV roof tiles

3.3.1 Geometric occupancy and shadows on skirts

To estimate PV production on roofs, it is necessary to establish the loss associated with shadows and the geometric adaptability of the catchment surface of both PV silica panels and PV roof tiles.

To estimate the influence of shadows, thirty-four cases are identified in which shadows occur among a sample of one hundred. The cases are three-dimensionally plotted with the

FIGURE 4. Characteristic consumption during the week.

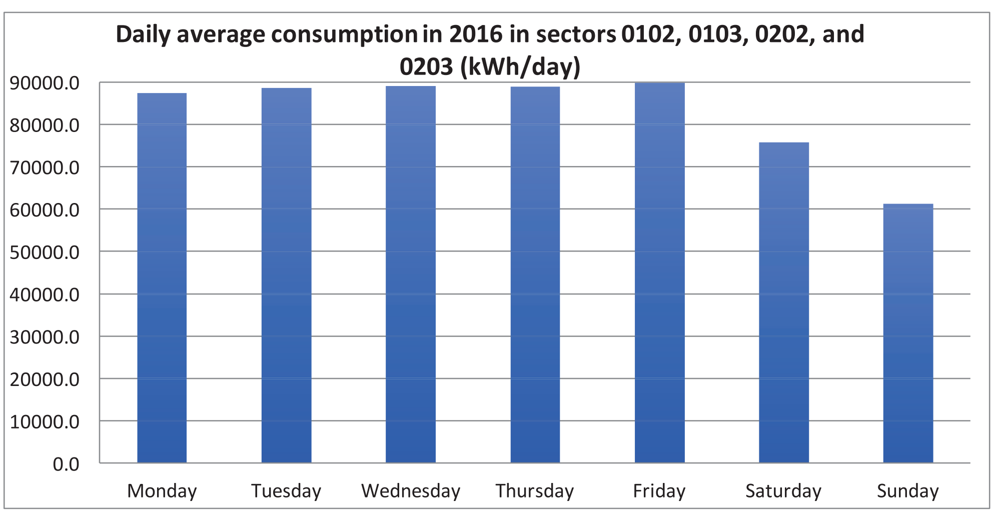
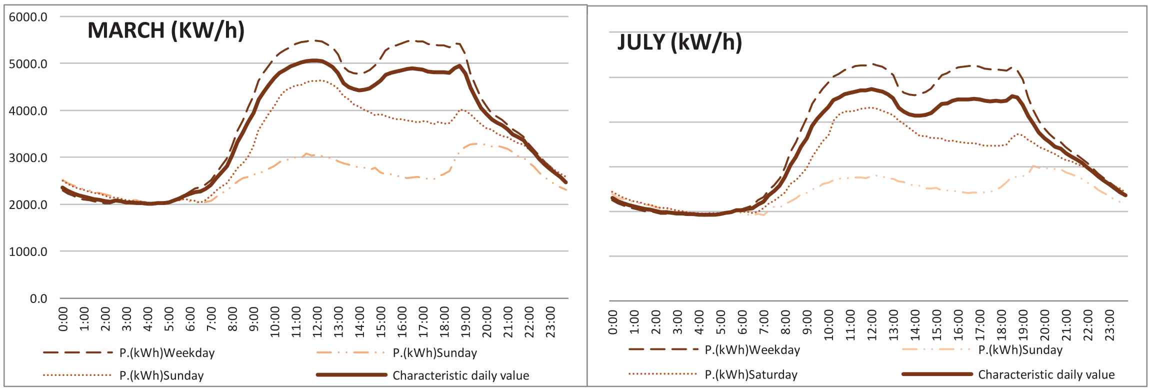


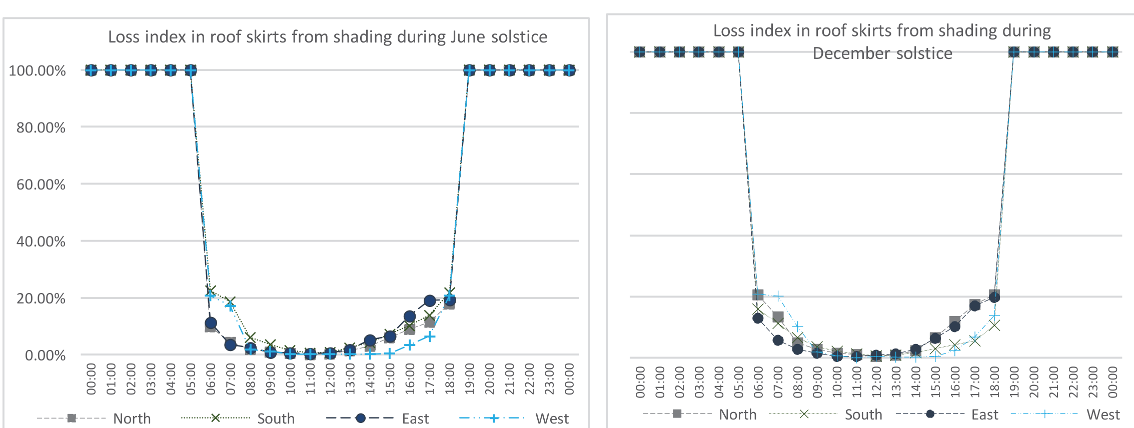
FIGURE 5. Daily characteristic consumption in extreme months of minimum and maximum consumption.



schematic volumes of neighbouring constructions. In this process, the potential losses of direct incident irradiation are detected. Figure 6 plots the percentage of hourly shadows detected, and this percentage is markedly less than that noted in study cases in southern latitudes, which can be explained by a lower solar path at those locations (Pelland and Poissant 2006). The determined indices are used in the modelling software SAM, which is a tool that integrates a shading penalty as an input. Shaded areas can greatly affect PV sensors. When direct irradiation does not occur on a portion of the collectors or a series of sensors, the entire group that shares a converter is affected. Thus, PV panels subjected to this adverse effect should be installed with microinverters and/or optimizers to avoid this type of effect (Luque and Hegedus 2011).

The percentages of shadows on the skirts oriented in each direction and in each month are shown in Figure 6. The extreme months are analysed, but the difference between these months is minimal. After 8:00 and before 16:00, shading does not exceed 7%, and between 10:00 and 14:00, shading does not exceed 2%. These periods coincide with periods of high direct irradiation.

FIGURE 6. Daily characteristic consumption in extreme months of minimum and maximum consumption.



To determine production, the performance of monocrystalline silica panels measured in a previous study (Izquierdo and Pacheco 2017) is applied. The yield is approximately 14% with respect to irradiation. In the case of PV tiles, with recent developments in amorphous silica thin-film PV technology, the expected efficiency according to the manufacturer is 30% lower compared with that of typical crystalline silica technologies (Energysage 2017); however, the occupancy rate of a solar cell on an individual tile is 30% less because a thin-film panel does not cover an entire tile and the panels can be installed overlapping multiple tiles (Cinnamon 2016). From these data, a yield of 4.5% of the irradiation is assumed for the estimations; however, verification of the actual performance is still pending. With these data, SAM is calibrated (NREL 2017). By simulating the annual production, the hourly fluctuations per m^2 of PV can be obtained. The results of this study, based on calibrated models and verified on-site yields, are more reliable in the case of monocrystalline panels than in the case of PV tiles, as estimated from yields published in other studies.

One hundred houses were randomly selected for three-dimensional modelling with the BIM tool Archicad 20 (Graphisoft@ 2018). Considering the representative textures (hatches) of the dimensions of crystalline silica PV panels of sixty cells and PV roof tiles, the geometric occupancy indices of the catchment surface per skirt surface are calculated (74% panel cases and 92% roof tile cases). Sixty-cell solar panels are approximately 165.0 cm long and 95.0 cm wide with little variation between commercial products; they are this size to promote the ease of handling, transport and installation, but solar tiles do not have standard dimensions and are variable in terms of format. Therefore, a product size published by Tesla of 35.6 cm long by 22.0 cm is used in this study (Cinnamon 2017a). Thus, an occupancy index is obtained and, as expected, the PV tiles provide a higher geometric occupation. Consequently, these indices are applied to estimate the amount of surface that can potentially be occupied, as previously determined in GIS based on the four characteristic orientations and a typical inclination of 18°. The resulting solar catchment surfaces are shown in Table 1. The catchment surface availability index values of silica panels and PV roof tiles compared to the city surface area are 23.4% and 29.1%, respectively.

3.3.2 Annual net supply capacity

Next, the feasible net production of the sectors and the associated significance are measured considering monthly demands and annual fluctuations (Figure 7). The PV production exhibits

TABLE 1. Skirting surfaces according to orientation and the occupancy surface area of silica PV panels and PV tiles.

Orientation	Skirt surface by orientation (m^2)	Silica PV panel occupancy (m^2)	PV tile occupancy (m^2)
North	85185	63037	78371
East	80941	59896	74465
South	82960	61390	76323
West	90142	66705	82930
Total	339228	251028	312089

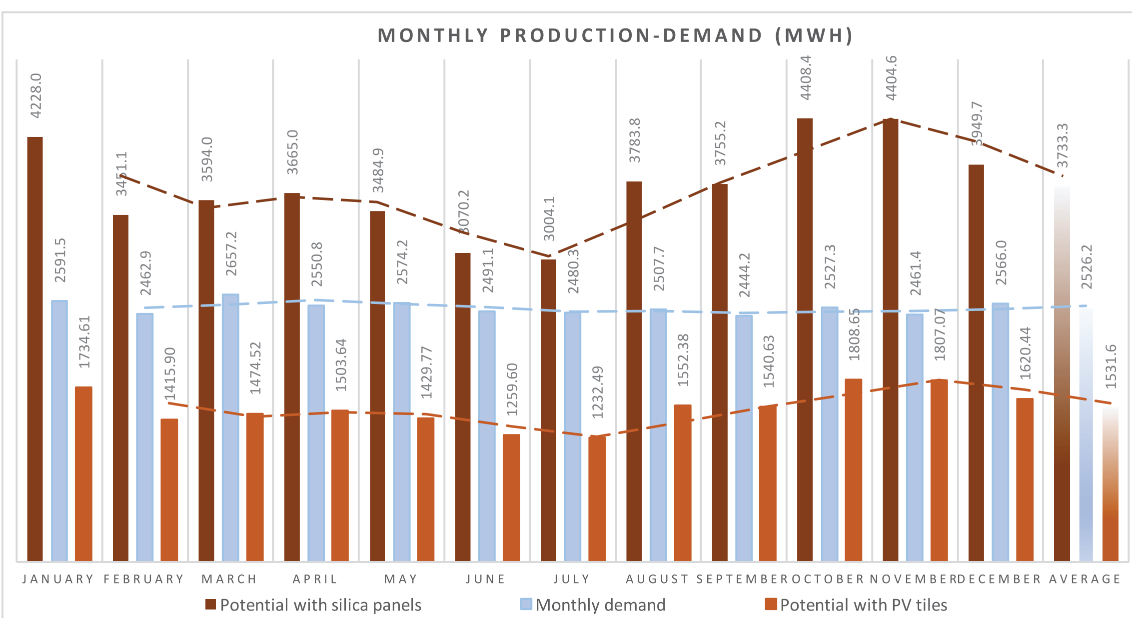
slight oscillations, reaching 174% with respect to demand for silica panels and up to 73% of the demand for PV roof tiles in months of good insolation (October-November). However, in July, the month with the lowest irradiation, the supply would reach 121% of the demand with silica panels and 50% with PV roof tiles. The annual average supply is estimated as 148% for silica panels and 61% for PV roof tiles. A production reduction of 30% is observed between extreme months. Comparatively, in similar studies conducted in moderate seasonal climates (latitude 38° south), production can triple in summer months with respect to winter months (Zalamea and García Alvarado 2014), and in Helsinki, which is located at a latitude and climate zone of extreme seasonal variability (latitude 60° north), the production-demand imbalance would be more than ten times higher than that observed in this study.

3.4 Daily and hourly production-demand variability

When comparing monthly demand and PV production in the study area, the demand exhibits considerable stability, as opposed to a more pronounced oscillation in the PV potential; Figure 7 clearly shows these trends. However, at the daily scale in a weekly timeframe, the consumptions are highly oscillatory on non-working days and normally cyclical with stable consumption on weekdays and reduced consumption on weekends. However, clearly, these consumption oscillations are small compared with the variability in electricity generation, e.g., nonexistent at night and extremely pronounced at noon (Figures 5 and 8).

When comparing the net daily production on extreme days in the months of March and July, which are representative of the maximum and minimum demand (Tables 2 and 3), the maximum overproduction of 255% of the demand is observed on a day of high irradiation in March, and in the same month, contrary to what might be expected, the day with the lowest overproduction of 63% of the demand is observed. The curves also indicate that the months

FIGURE 7. Average monthly energy demands versus feasible production with silica PV panels and PV roof tiles.



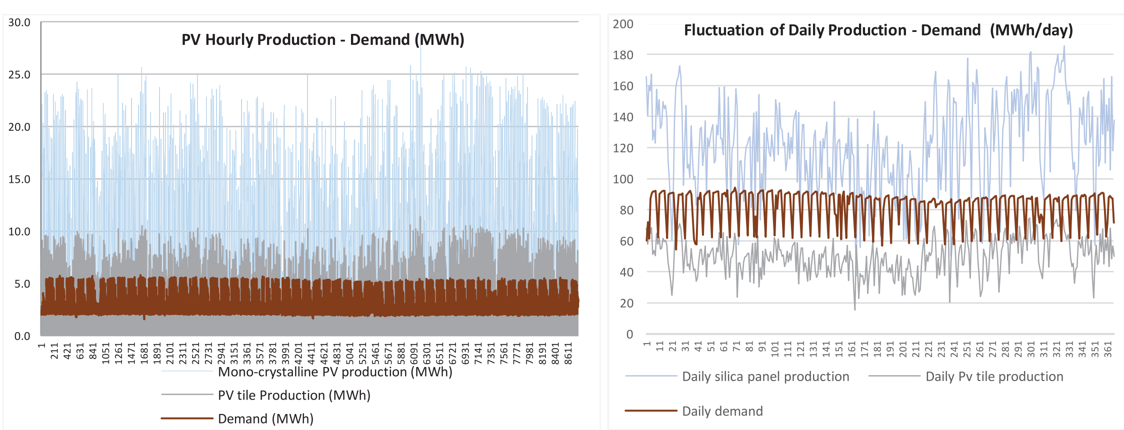
with the highest consumption, on average, also have higher surpluses as a consequence of greater insolation. The results can be used to infer the irradiation conditions and their variability predominate with respect to fluctuations in consumption. Specifically, the highest overproduction values will be observed on days with the highest insolation and, to a lesser extent, days of low consumption.

Photovoltaic production varies hourly, and cities in the high Andes are characterized by substantial cloudiness (Figure 8a). Additionally, overproduction reaches 25 MWh in only seven specific hours of the year. Hour 6204 (on September 15) exceeds 28 MWh of electrical production, which is potentially explainable by the equinox and consequent canicular irradiation. However, these peaks do last for more than an hour. In terms of the production-demand differential, in certain hours, there is an overproduction of 18 MWh on workdays, which potentially increases to 23 MWh on non-work days, coinciding with days of high irradiation. Thus, the grid would receive the maximum amount of produced electricity. The excess electricity should be redistributed to other sectors of the city. Under the scenario of the massive installation of PV tiles, it is typical to reach between 5 and 7 MWh of overproduction in hours of high irradiation.

Figure 8b shows the fluctuation in daily net production with monocrystalline silica panels and PV roof tiles versus the demand. Notably, it is normal to surpass 50 MWh per day of surplus production. In November, these surpluses can be close to 100 MWh, and there are extremely few days when a deficit would exist. These days generally occur in the months of June and July. For PV tiles, a deficit exists during most of the year, and production exceeds demand on very few days concentrated between October and January.

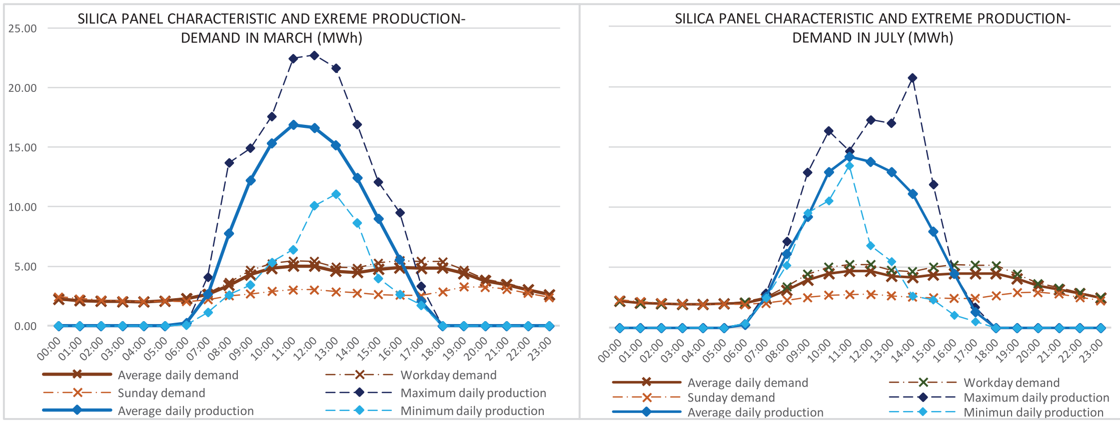
In a large-scale PV urban electricity production scenario, it is important to understand the production imbalances and implications of overproduction in the grid (Mikkola and Lund 2014; Ramirez Camargo et al. 2015). The efficiency of crystalline silica PV technology enables a high-energy potential. Therefore, hourly oscillations in production and demand are measured on characteristic days and extreme days in terms of irradiation.

FIGURE 8. (a) Hourly production-demand variations for PV production versus demand. (b) Average daily net PV production versus average demand.



(a) (b)

FIGURE 9. Characteristics in months of maximum and minimum demand.



3.4.1 Potential supply in extreme months of maximum demand and minimum demand with monocrystalline silica panels

The months with maximum and minimum demands are March and July, respectively. In March, the maximum overproduction level (19 MWh) is reached despite having higher demands; however, it is a month with high relative irradiation. Likewise, the day with the minimum overproduction is also in March (6.1 MWh) because despite having higher average irradiation, there is a specific day with high cloudiness that coincides with high demand (Figure 9). It is concluded that the peaks in overproduction are not necessarily observed in months of reduced demand. Tables 2 and 3 show comparisons and the proportions of net production with respect to characteristic and extreme demands in the months of March and July, which verify, in general, that the highest self-supply potential occurs in March.

3.4.2 Potential supply in extreme months of maximum demand (March) and minimum demand (July) for generation with PV tiles.

PV tiles with reduced efficiency are a potential option due to their smaller visual-architectural impact. A comparison of production-demand curves is shown in Figure 10. Maximum and

TABLE 2. Supply percentage with PV silica panels comparing net production and daily characteristic demands in March.

Production-Demand Relationships (March)		Extreme Relationships (March)	
Characteristic Production/ Characteristic Demand:	**135.3%**	Maximum Production/ Sunday:	255.1%
Maximum Production/ Working Day	174.5%	Minimum Production/ Working Day	62.7%
Minimum Production/Sunday	91.7%		

TABLE 3. Supply percentage with silica PV panels comparing net production and daily characteristic demands in July.

Production-Demand Relationships (July)		Extreme Relationships (July)	
Characteristic Production/ Characteristic Demand:	121.1%	Maximum Production/ Sunday:	219.2%
Maximum Production/ Working Day	146.3%	Minimum Production/ Working Day	69.4%
Minimum Production/Sunday	103.9%		

minimum overproduction are observed in March, and the maximum is 6.5 MWh; however, on the day of lowest production, considering the consumption on a working day, there would be no surplus, and the grid will experience a deficit (-0.4 MWh) at the moment of highest production.

When consolidating and comparing net energy production levels with PV roof tiles in March and July, a surplus only exists under conditions of maximum irradiation in March, and it barely exceeds 5% of the demand. Generally, the demand is not exceeded. On a working day, only 26% of the demand would be covered on a low irradiation day, and considering the production and demand on average days, both months exhibit similar supply percentages (Tables 4 and 5).

3.4.3 Potential supply in extreme months due to the availability of maximum and minimum irradiation with supply generated by monocrystalline silica panels.

Production-demand situations are analysed for extreme days in months with the maximum and minimum available irradiation. When performing simulations and using November as the month of maximum irradiation, it can be seen that on a clear day, overproduction varies between 20 and 18 MWh at midday depending on whether the day is a weekday or weekend. In contrast, during the month of minimum irradiation in June, during a high-demand working

FIGURE 10. Electric supply with PV tiles considering demands on characteristic days in months of maximum and minimum demand.

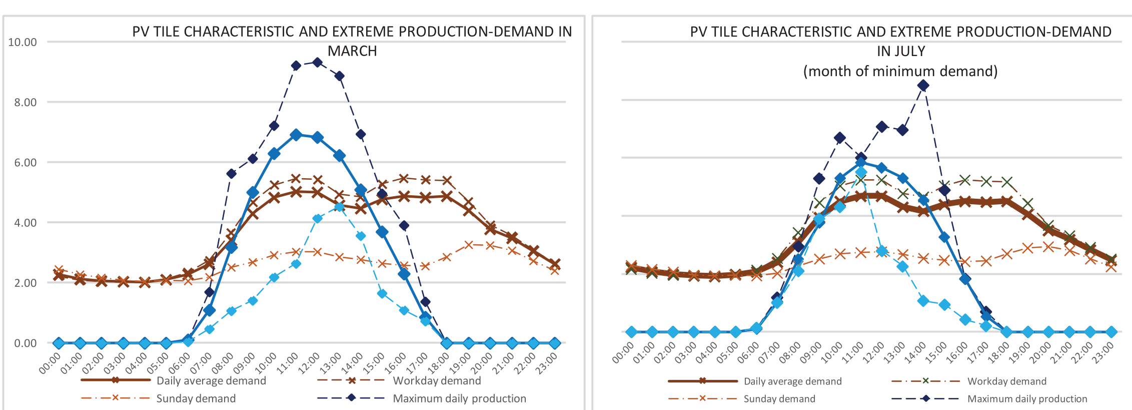


TABLE 4. Supply percentage with PV roof tiles comparing net production and daily characteristic demands in March.

Production-Demand Relationships (March)		Extreme Relationships (March)	
Characteristic Production/ Characteristic Demand:	**55.5%**	Maximum Production/ Sunday:	104.7%
Maximum Production/ Working Day	71.6%	Minimum Production/ Working Day	25.7%
Minimum Production/Sunday	37.6%		

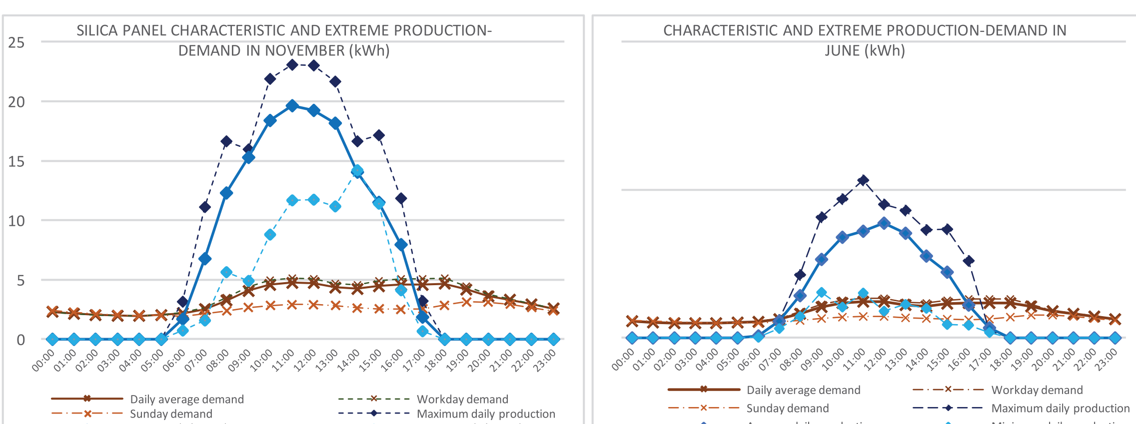
TABLE 5. Supply percentage with PV roof tiles comparing net production and daily characteristic demands in July.

Production-Demand Relationships (July)		Extreme Relationships (July)	
Characteristic Production/ Characteristic Demand:	**49.7%**	Maximum Production/ Sunday:	89.9%
Maximum Production/ Working Day	60.0%	Minimum Production/ Working Day	28.5%
Minimum Production/Sunday	42.6%		

day, there is a moment of overproduction of just 1.6 MWh at approximately 9 AM and not at midday, as usual (Figure 11).

When comparing daily total energy production in November and June, there is an overproduction of up to three times the demand for the scenario of maximum irradiation on non-work

FIGURE 11. Electrical supply with monocrystalline silica panels compared with demands on characteristic days in months of maximum and minimum irradiation.



days; in contrast, on the day of minimum irradiation in June considering the working day demand, only 42% is of the demand is supplied (Tables 6 and 7).

3.4.4 Potential supply in extreme months of maximum and minimum irradiation with supply generated from PV tiles

With PV tiles in months of maximum and minimum irradiation, on non-working days in both months (for example, Sunday on the graph), there is a potential overproduction of 6.2 MWh, whereas on a characteristic working day with minimum irradiation in June at noon, there is a deficit of −2.8 MWh. The characteristic curves of this condition and comparisons are shown in Figure 12.

The potential in November with PV tiles, on average, would reach 73%, and the demand in June is projected to reach 51%. The maximum net supply measured on a day of maximum irradiation is expected to reach 125% of the demand, whereas considering minimum irradiation on a characteristic working day, only 17% is supplied. Comparisons of production on extreme and characteristic days are shown in Tables 8 and 9.

4. DISCUSSION

The annual net demand of the study area is on the order of 30,157 MWh/year. Additionally, the net production with monocrystalline PV is estimated at 44,799 MWh/year (148% of the demand), and that of the PV tile is estimated at 18,376 MWh/year (61% of the demand). This

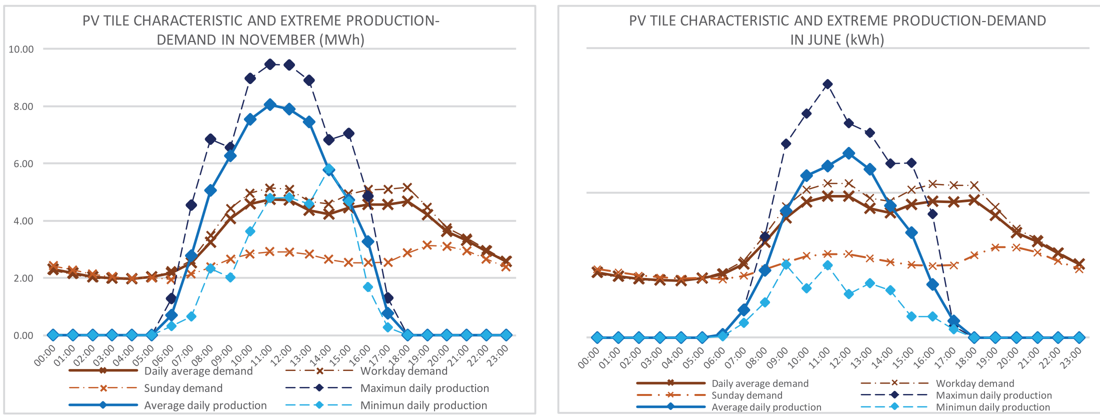
TABLE 6. Supply percentage with monocrystalline PV panels comparing net production and daily characteristic demands in November.

Production-Demand Relationships (November)		Extreme Relationships (November)	
Characteristic Production/ Characteristic Demand:	**178.9%**	Maximum Production/Day Sunday:	304.9%
Maximum Production/ Working Day	213.0%	Minimum Production/ Working Day	99.6%
Minimum Production/Sunday	142.5%		

TABLE 7. Supply percentage with monocrystalline PV panels comparing net production and daily characteristic demands in June.

Production-Demand Relationships (June)		Extreme Relationships (June)	
Characteristic Production/ Characteristic Demand:	**123.2%**	Maximum Production/ Sunday:	237.1%
Maximum Production/ Working Day	162.1%	Minimum Production/ Working Day	42.0%
Minimum Production/Sunday	61.4%		

FIGURE 12 Electrical supply with monocrystalline silica panels compared with demands on characteristic days in months of maximum and minimum irradiation.



potential is higher than that reported by Byrne et al. (2017), who obtained a value of 88% with respect to demand as a consequence of favourable irradiation conditions, such as the capacity to deploy collectors oriented in any direction and low urban energy demands. Moreover, the results are based on production potentials of 178 kWh/year per m^2 for monocrystalline silica PV panels and 59 kWh/year per m^2 for PV tiles.

TABLE 8. Supply percentage with PV tiles comparing net production and daily characteristic demands in November.

Production-Demand Relationships (November)		Extreme Relationships (November)	
Characteristic Production/ Characteristic Demand:	**73.4%**	Maximum Production/ Sunday:	125.1%
Maximum Production/ Working Day	87.4%	Minimum Production/ Working Day	40.8%
Minimum Production/Sunday	58.5%		

TABLE 9. Supply percentage with PV tiles comparing net production and daily characteristic demands in June.

Production-Demand Relationships (June)		Extreme Relationships (June)	
Characteristic Production/ Characteristic Demand:	**50.6%**	Maximum Production/ Sunday:	97.3%
Maximum Production/ Working Day	66.5%	Minimum Production/ Working Day	17.2%
Minimum Production/Sunday	25.2%		

Considering the variability in irradiation, the feasibility of achieving between 10% and 30% more production with silica panels compared to PV tiles is shown. However, architecturally, the deployment of PV tiles means less visual impact, and this remains a topic of discussion. If the objective is to maintain the authenticity of the material, it is debatable whether certain technological elements, such as PVs, should be used. Of course, the price of mimicry involves additional limitations, such as low efficiency and high costs, as well as technical limitations (Cinnamon 2016). In places where both technologies are commercially available, solar roof tile prices are 3.33 times higher those of regular monocrystalline or polycrystalline solar plates (Cinnamon 2017a).

Roof tiles undoubtedly provide an aspect of urban uniformity. However, the question remains as to what is more legitimate: to sacrifice wild spaces for energy supply, which would create limited areas that could not be considered renewable resources, or to make cities more resilient spaces and perhaps sacrifice "aesthetic" value for other values? In European cities with architectural value, many of which are even older and have lower solar potential, PV integration is already occurring on buildings, and the environment is prioritized without restricting analyses based on aesthetics (D'Orazio, Di Perna, and Di Giuseppe 2013). The creation of PV tiles has occurred in response to the problems addressed in these cities. Additionally, the future development of PV alternatives for buildings (BIPV) is expected to expand (Jelle 2016).

The performance of large-scale PVs in the proposed scenario demonstrates a geometric over-availability of roofing on which to apply silica PV panels and meet the current demands, but this is not so in the case of PV tiles (Figures 13a and 13b). However, significant production was also observed for this alternative. In addition, it has been demonstrated that it is feasible in this urban typology and under these particular environmental conditions to supply the electrical demand in totality, not only in the buildings themselves but of the entire urban environment, and perhaps contribute to mitigating emissions and external demands for transportation. These issues are primary current problem in this study city. Surpluses would potentially be able to partially meet transport demands, as has been proposed as an economic and environmental alternative (Maks Davis 2017).

FIGURE 13. (a) Photo of PV roof tiles on rooftops; (b) Photo of 60-cell silica panels on roofs

The production-demand imbalances, although they may be significant, are extremely small compared to those in other contexts, in which the seasons and the variability in consumption are radically different, such as in Canada; Finland; Shanghai, China; and other parts of Chile (Hachem, Athienitis, and Fazio 2011; Lund 2012; Mikkola and Lund 2014; Zalamea, García, and Sánchez 2016). Thus, the adaptation of the energy grid to an eventual distributed generation system should become less complex. When the supply is compared in extreme months considering consumption and irradiation conditions, large imbalances are a consequence of irradiation and to a lesser extent, the demand; however, non-working days amplify overproduction.

5. CONCLUSIONS

A methodology is proposed to estimate the urban PV potential considering the predominant building type, which has an inclined roof geometry and is relatively uniform in height and use. GIS tools, a BIM tool, and a SAM PV performance estimation model are used in this analysis. The results demonstrate the robustness of integrating both measured demands and technological performance and are validated with on-site hourly PV performance readings. The technological-architectural implications are discussed in a scenario where surfaces with high potential have an important aspectual value.

In the study area, the potential exists to install approximately 150,206 m^2 of crystalline silica PV panels or 173,400 m^2 of PV tiles. Typical PV technology is expected to annually supply approximately one and a half times the demand; conversely, with PV tiles, two-thirds of the demand is not met. Information is provided on potential surpluses that should be delivered to the grid or used as an alternative to meet thermal or transport demands, which are currently associated with high levels of environmental pollution, and switching to renewable electric systems is a promising alternative. Moreover, particularly in buildings, energy consumption is variable and even unpredictable; however, overall, the consumption curves are similar in different days and months. Market and economic factors extend beyond those addressed in this research, and potential factors in the future should be considered. Although recent studies have concluded that such changes would be profitable in Cuenca, reaching an internal rate of return of over 8%, it would be better to eliminate tariffs on imported goods, especially if the subsidies currently associated with polluting sources would be addressed. Such a situation is logical from both environmental and economic perspectives (Izquierdo and Pacheco 2017). Electricity consumption in Ecuador has increased by approximately 68.8% in the past ten years, and almost 90% of the energy matrix is now associated with large-scale hydrotechnology, which the government considers a renewable form of generation. However, the future implications of large-scale dams on Andean rivers should be discussed. Immediate energy diversification must be considered to provide reliability to the grid, rather than depending on just one energy source. Additionally, the energy supplies of urban areas and buildings should be considered (Ponce-Jara et al. 2018), and this research provides a potential alternative to the current approach.

Future studies will incorporate additional details and include the architectural-urban perspective regarding the consequences of installing PV silica panels and PV roof tiles, which, although in the second case would be similar in appearance to commonly used materials, are not traditional roof materials. In addition, it is necessary to analyse specific production-demand cases and grid implications for the purchase-sale of electricity to the grid and the associated effects. These issues have not yet been explored; however, the estimated magnitudes of production and demand provided in this study could be used in such future analyses.

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APPENDIX

GIS Images of roof geometry traces

BIM ·3D diagrams for obtaining geometry adaptability in 12 cases. Crystalline Solar cells and PV roof tiles.