21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

Photovoltaic assessment to achieve energy neutral buildings and cities in equatorial Andean climate

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Abstract. Energy is an important issue in the entire world and in under-development countries especially in these regions is where the main growth of energy requirements is expected. For more than fifty years ago Ecuador has been subsidizing fuels, considering that energy prices do have a huge impact on low-income families. Cities and buildings do play a relevant role in reducing energy requirements to import energy to urban areas in order to achieve the maximum energy self-supply capability in buildings and cities. This study describes shortly recent works performed in Cuenca to decipher the energy resources available and the capability to self-supply in Cuenca, Ecuador. The main results obtained show that photovoltaics (PV) in buildings is the best option, it could supply the entire power requirements in the city, and around 22 % of the electrical requirements of industrial high-consumption buildings, also for a single-family home it is only required around 7 m^2 of roof that corresponds around 10 % of a typical roof availability of a typical 2-floor house, and for higher education building it is possible to achieve the total power requirement with PV technology, but grid limitations imply limitations also to PV capability.

Key words. Solar energy, Building energy self-supply, Cities energy self-supply, Equatorial Andean context.

1. Introduction

Cities are responsible of the 80 % of the energy requirements and carbon emission in the globe as consequence [1]. In order to reduce this huge impact it is important to apply energy efficiency measures in first instances [2], then to achieve neutral and plus energy buildings to reach low energy requirements on communities [3] it is required to integrate renewables in cities and buildings. To achieve this goal, it is required to determine the energy requirements, the special- temporal requirements and resource availability [4] and the capability of combining resources and demands accordingly to each context requirements, and space and times of energy production and consumption in space and time parameters [5].

In concordance to climate conditions, urban context characterization, the energy requirements are all parameters that fluctuate in more or less extent. Ten years ago, P. Lund did analyzed Shanghai and Helsinki energy requirements and solar potential, determining spatial and time production and demands considering that the mismatch effect is a main barrier to integrate solar energy in a large scale without storage capability, so this researcher figure out alternatives to conduct and store energy through the grid conduction of power combined with huge seasonal thermal storage systems [6]. Actually, big systems of energy storage are available to incorporate to the grid in order to manage energy exceeding's to aloud increasing renewable capabilities. The main barriers detected to achieving a larger fraction of the energy self-supply capability is the seasonal fluctuations, especially when solar energy is taken as the main resource for urban energy self-supply, it implies periods with high and low irradiation levels, that coincide with the main energy requirements. As an example, in Concepcion, Chile it has been determined that as a consequence of climate fluctuations and the grid limitations to manage power exceeding's, it implies that with large-scale solar self-supply in buildings connected to the grid, it is possible to reach only between 15 % to 27 % of the overall energy requirements.

1.1 Context analysis

The equatorial Andean context does have unique and special climate conditions. As a consequence of the closeness to the equatorial line, the climate condition fluctuations are very low compared to seasonal regions present in middle and high latitudes close to the poles. But normally in these latitudes, there are warm to extremely hot temperatures throughout the entire year. Normally in tropical climate conditions, there are considerable energy requirements in buildings and cities for cooling throughout the entire year, day and night, especially in humid tropical regions, as most of the South-American tropical region. But in south America also there is a special climate condition that it is not observed in other equatorial regions in the world as happens in the Andes mountains range.

These are sites at the middle and high altitudes close to the equatorial line where there are valleys with very good climate conditions for reaching easily adequate comfort levels in buildings, where normally there are no energy requirements for cooling or warming internal spaces or the requirements are very low, that could be solved easily with passive strategies as strategic material selection, adequate solar capture or blockade, and good standard of the construction process, especially in the building’s envelope. In these valleys, there are several cities including capital cities such as Bogota or Quito, in addition to several middle sizes and small towns located in Venezuela, Colombia, Ecuador, and Peru. These urban areas do have two-way benefits for energy self-supply the first aspect is the non-need for equipment for air conditioning or heating and therefore the non-need for energy consumption to reach adequate levels of internal comfort.

The second aspect is the regular climate conditions, even in warmer o cooler cities or towns located close to 3000 masl or 2000 masl, where in some instances there are cooling or heating requirements, the energy consumption are homogenous throughout the year. In the same way that consumption is almost constant, differing only as the day corresponds to weekdays, weekends or holidays, the solar resource is also relatively stable compared to other contexts. This implies that the mismatching effect of energy consumption and irradiation availability as a consequence of the seasonal variability is significantly reduced. An extensive analysis of these climate characteristics and conditions had been performed before [7].

2. Methodology

In this report, we are showing the estimate of different renewable sources that are available inner city´s border, in Cuenca, Ecuador, this is a midsize city located between 2350 to 2600 masl. Previous separate research has determined from the overall energy potential that has been detected from several energy sources existing within the city boundaries to the energy potential on different building typologies. This justifies why solar energy and concretely photovoltaic (PV) technology corresponds to the main alternative to reach energy self-sufficiency in buildings. Then a short comparison between building typologies for PV potential also have been performed. In this instance, a comparison between industrial typology, mixed use typology and single-family dwelling, showing with this, from the highest to the lowest PV potential determined in this equatorial Andean city, as case studies. Finally, a recent work to achieve power neutrality also is presented, showing to the reader the capability of PV technology on buildings for supplying power demands.

3. Results

3.1 Energy sources capability inside city-limits border

In the year 2015, there was no real data compilation about the energy requirements and the energy sources availability and capability existing inner city border of Cuenca. So in the research project “ Abastecimiento energético urbano desde recursos endógenos en la ciudad de Cuenca, Ecuador”, supporting Antonio Barragan research project [8] it was determined the main global data for analyzing the energy capabilities for energy self-supply in Cuenca. In this research were determined the total energy requirements for different urban consumptions of the year 2015 were shown in a Sankey diagram (Figure 1). This diagram stands out that transportation is the major energy requirement to be solved, representing almost 60 % of the total energy requirement in the city. Second, corresponds to industrial requirements, this sector needs about almost 21 % of the total energy requirements in the city. Residential use only appears in third place with an energy demand that represents less than 14 % of the total. These results show the low energy requirements for housing, and the huge energy requirement for transportation, this is obviously as a consequence of the low or non-energy requirements for housing and buildings' thermal comfort, as a consequence of the great climate condition existing in the city.

After a methodological selection through different methodologies applied to determine the potential of the different sources which can be observed in proceedings research [9], [10] process accordingly to different criteria, it was deciphered the five main technologies that accordingly to the availability of energy sources could mean the best possibilities to supply energy requirements [11]. Also, it measured the energy requirements in the city. Finally, a comparison of the overall energy potential with the five sources compared with energy requirements was obtained and a proposal of conducting these energy sources to the determined demands was exposed. The results were represented in a Sankey diagram as shown below in Figure 2.

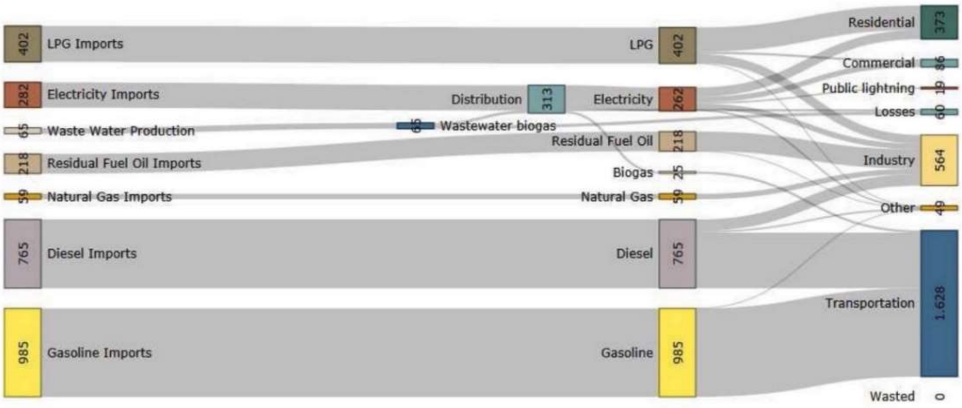

Fig. 1. Sankey diagram that consider energy requirements for 2016 [8].

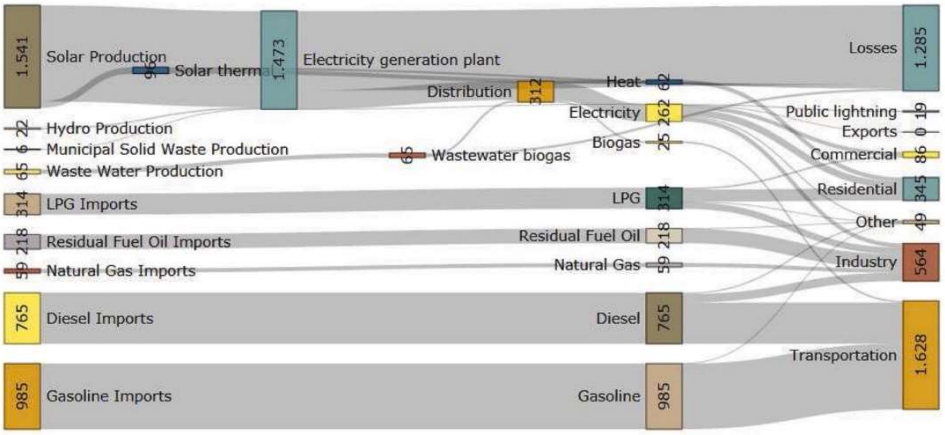

Fig. 2. Sankey diagram that consider energy sources availability and capability for energy requirements [8].

2.1 *Solar PV capability for power energy self-supply on different building typologies*

A. Industrial building

In first instance, the solar potential on an industrial building in Cuenca was determined [12]. This analysis was performed in 2017 then, the data of energy requirements of 2016 were considered in order to detect the ratio of power requirements versus PV potential. Also, with the PV technology available in those years were performed the simulation process (solar PV of 275 Wp of 1,65 m x 0,95m solar PV panel size). The methodology applied did include the inclusion of natural light analysis on roofs. The existing roof surface with adequate amplitude for PV disposal was 53,360.0 m^2. But when considering the space reductions for natural illumination requirements, it was possible to integrate 48,241.0 m^2 of PV capture surface (Figure 3). This area of PV technology then was compared to the power requirements annually in this industry. During 2016 the energy consumption was about 38,899.3 MWh, even it is only a partial energy requirement since most of the energy corresponds to Liquified Gas Petroleum (LGP) and diesel for industrial ovens for ceramic tiles manufacturing.

The research results show also that it's possible to supply around 22 % of the power requirements of these industrial buildings. The PV production could reach to 8560.0 MWh, even if this reaches less than a quarter of the power requirements, this energy production could solve the consumption of at least 17,000 citizens.

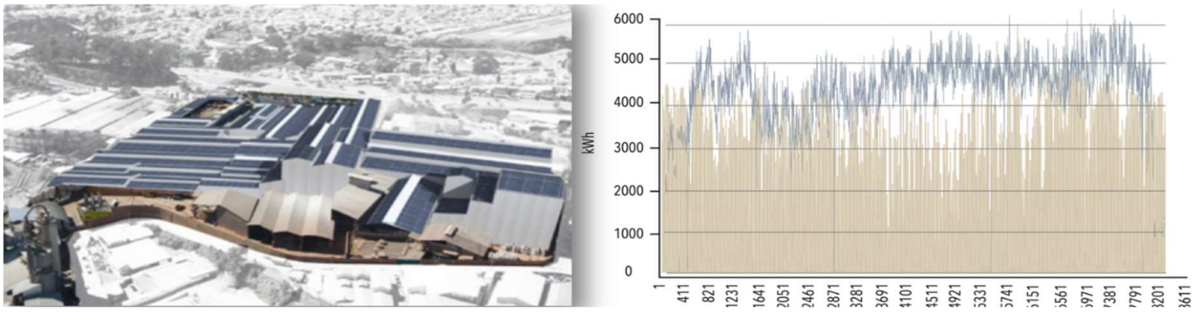

Fig. 3. Industrial building simulation of PV integration and hourly PV production versus consumption simulated [12].

B. *Mixed-residential use buildings*

The next typology to be analyzed corresponds to mixed-use buildings (residential, commercial and service offices) [13]. It is an interesting typology considering that a sustainable strategy is to integrate different uses in the same place, to achieve living neighborhoods. This analysis was performed on a six-floor high building, with the uses explained as before. The roof space available area is 654.5 m^2 and the annual power requirement of the 2018 annual period was close to 66.8 MWh. After considering architectural aspects, it was deciphered that it is possible to couple 351,5 m^2 of 335 Wp solar PV, so the PV array's overall capability was close to 70 KWp. the PV panels are oriented towards the four cardinal points. In the Andean region close to the equator at over middle altitude above sea level, the energy requirements for transportation are a main requirement as explained before, then results in a strategy to change the transportation model from fuel to electricity. As consequence, the building analyzed with the solar arrays proposed could cover 99.7 % of the power requirements, but it is considered to introduce electric vehicle (EV chargers), one for each habitable residence, considering for typical family use, and converting all the combustion equipment for residence use existing, the percentage of the energy requirement of the PV system as proposed it could reach to 27,9% of the expected demand. Figure 4 shows the adaption of PVs on the building's roof and hourly curves of different power demands compared to power PV possible production according to the PV integration and irradiation availability.

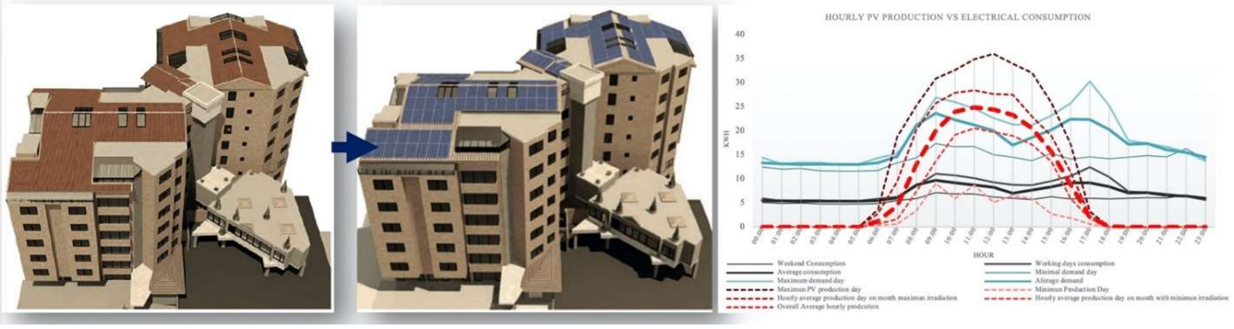

Fig. 4. Mixed-use building with PV integrated and daily production curves with different irradiation scenarios and different daily consumption scenario [13].

C. *Single-family dwelling*

The next analysis presented in this document corresponds to a single-family house for energy self-supply PV installation. In this case, it was observed that a home with 4 inhabitants consuming 160 kWh monthly on average, the power requirements could be solved with a 1.36 kWp PV that corresponds to four solar panel installations on its roof. The solar panels are deployed facing almost east with a little deviation to the north and with a 18º slope, but in previous research even it was determined that the best orientation corresponds towards east, but when the slope of the collectors are slow, the output increase as consequence in balance is lower than a 7 % in a year [14]. This installation was the first residential installation in the city, and in the first year of production from May of 2021 to April 2022, an 1810 kWh production was achieved, this production until today has generated surpluses on the net-metering with the utility, and even this production is expected to reduce in the upcoming years as a consequence of the natural slow degradation of the PV array performance as expected [15]. Figure 5 shows the four 340 Wp solar PV panels and the electricity bill from the utility, in this document, we can observe the first reduction of the energy bill during the next four months after the installation was functional (from June to Sept. 2021). Then the bidirectional metering equipment was installed, and the reduction of the billed energy reach almost to 0. Since this was the first house connected to the grid in Cuenca, and in the region, there was a required and extensive four-month period, but a reduction in administrative processes for the next residential installations is expected.

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VALOR TOTAL $3.88

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sde 03-10-2021

Días facturados 31

Fecha hasta 02-11-2021

Descripción	Fecha Hasta	Lectura Actual	Lectura Anterior	Diferencia Consumo	Consumo Subtotal	Consumo Int. Transfor.	Consumo Total	Unidad Medida	Monto
iva total	02-11-2021	20.00	18.00	0.00	2.00	0.00	2.00	KWH	0.18

pendientes

PENDIENTES (2) 0.00

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E FINANCIAMIENTO (3) 0.00

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MA DE PAGO	VALOR	PLAZO	TIEMPO

Servicio Eléctrico y Alumbrado Público	
Valor Consumo	0.18
Comercialización	1.41
Subsidio Cruzado Beneficiado	0.18-
Subtotal Servicio Eléctrico (SE)	1.41
Servicio Alumbrado Público	0.22
Subtotal Alumbrado Público	0.22
Base I.V.A. 0%	1.63
I.V.A. 0%	0.00
TOTAL SE Y AP (1)	1.63

Fig. 5. Single-family dwelling roof with four solar PV plates, and electricity bill with a 2,0 kWh month consumption when starting the bidirectional metering (Source Authors).

D. *Higher education buildings*

Another typology that has been analyzed corresponds to a university building complex in the Universidad de Cuenca. In this analysis, it was considered also the grid limitations to manage power surpluses as a consequence of the dimension and the power that will be generated under high irradiation scenario. This study was developed as an initial step to build the PV system here described. For the PV system design was considered the power requirements and the electric transformer that feed the building complex from the medium voltage grid to the low voltage network. The limitation is a 75 kVa electric transformer, which implies that when there are times when there is a low energy requirement coinciding with high irradiation and power generation, it could impact to the transformer's capacity to inject the exceedings to the grid. The annual power consumption to be covered is 135 MWh.

Considering these aspects, the originally designed installation, with available slab surfaces, reaches a PV installation of 86.8 kW. The PV arrays are composed of full black PV products for architectural integration. Then, considering the grid restrictions, the final PV installation could reach a 78.0 kWp installed with 192 PV panels of 405 Wp deployed on the flat slab roof facing towards the four cardinal directions, covering partially the available roof surface with a 40 % roof surface occupancy. Then the technical limitation does not correspond to the roof space availability.

The power requirements of the building complex determined according to the period before the COVID-19 restrictions were considered as energy requirements to be fed with the PV installation. In the year 2019, the total power consumption bought to the utility was 135.0 MWh/year. With the 78 kWp PV plant it is possible to cover close to 79.8 % of the 2019 energy requirement, it is expected to be maintained in the coming years. Figure 6 in the left corresponds to the adaptation of the total roof occupancy for 86,6 KW PV installation and on the right corresponds to a recent aerial picture where it is observed the current first stage installed of 7.7 kW. Fig. 6 displays the architectural image of the required system and the initial system feeding the power requirement, grid-connected

Fig. 6. Facultad de Arquitectura of the Universidad de Cuenca with projected total installation and in the right a 10 % of the solar plates installed in first instance. (Source Authors).

4. Conclusions

We presented some research case studies and real cases developed in the city of Cuenca of energy self-supply, in order to impulse energy-neutral buildings, accordingly to technologies' expected performance and real performance, with PV installations in Cuenca. In the first part, we presented the potential of diverse energy sources that exist in the city, concluding that solar energy is the main source to be incorporated into the energy matrix of the city to supply the energy requirements, especially through PV technology, since the thermal requirements to be solved by solar thermal technology is low, with PV it is possible to feed the 9 % of the total energy requirements in 2016, that is the total electricity consumption of that year. But if the fuel consumption in the city would be changed to electricity, the PV potential o capability could by multiplied by three, by changing fuel requirements with clean electricity.

Then, in a deeper analysis of some building typologies existing in Cuenca, it can be observed that for buildings with higher demands as industrial buildings, it was measured that PV technology it could be solved 22 % of the power requirements for the industrial process of the ceramic tiles manufacturing industry. As a consequence of the high energy requirement of this typology, even with an extensive surface available for solar PV, only a fraction of the power requirement is possible to be obtained, even the power PV production is very important. Then, in the middle-size mixed-use building typology, it was estimated that in a six-floor building, it is possible to obtain enough electricity to feed the entire electricity requirement of this type of building, but if it converted the actual fuel consumption for energy requirements of the building and considering to feed with electricity changing current vehicles to EVs for residents in the apartments, the fraction of power capability is reduced to feed the 27,9 % of the projected energy requirements. Then for a single-family home for four inhabitants, with a small 4 solar PV array less than 8 m^2 is enough to feed to the entire power requirement of a single-family dwelling, and for educational buildings, it was observed that with the roof available it's possible to reach the entire power requirement, but it is necessary to consider the grid and electric transformer equipment as a limitation to integrate PV systems, as we observed when proposing a PV plant for feed an educational building complex.

As a consequence of this analysis, it is possible to conclude that there are some typologies like single-family houses that with a small portion of these roofs could cover the entire power requirement. Then this typology of the building that in Cuenca corresponds to the majority in the city could serve as a support for reaching energy surpluses that could feed other typologies such as industrial buildings, but for, these, regulation of microgeneration process has to be changed and also it is important to design a smart-grid model in the existing power network to conduct power exceeding where there are required. Also, the conversion of transport systems actually energized with fossil fuels strategically should be converted to EVs, in order to reduce the main requirement for fuels in the city, the main cause of contamination and the main economic issue for fuel subsidy requirements.

Acknowledgement

This document do express results or research performed with support of the Vicerrectorado de Investigación de la Universidad de Cuenca and Virtualtec Research Group, as well of the Grupo de Investigación en Energía of the Universidad Politécnica Salesiana. This work is a result of the "Modelado y mediciones de condiciones ambientales interiores e integración de energía solar, para alcanzar el Estándar Net-Zero en Edificaciones FAUC" Research Project.

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