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Photovoltaics for reaching Net-Zero Energy Standard in Educational buildings

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Abstract. Buildings should become energy-neutral to reduce pressure on the planet's resources and the atmosphere. Then cities must be energized with in-site renewables integrated to reach low-impact sustainable cities. This research project is an initial step to figuring out the feasibility of reaching the Net Zero Energy condition in the Architecture Department buildings of the University of Cuenca, as a case sample of higher-educational facilities located next to the equator and on the highlands of the Andes mountains range. In this research we had just determined the photovoltaic (PV) potential to reach the actual energy requirement as an initial step, to do so, we had virtually constructed the building facilities and obtained the building energy requirements, considering full power requirements measured before the COVID restrictions. As the main results, we determined, that 88,6 % of the 2019 energy requirements could be solved with solar PV considering roof availability and architectural restrictions. The financial analysis also reveals that it is a profitable strategy. Next research will determine that comfort levels are adequate to foresee the total requirements to reach the NZEB standard.

Key words. Architecture, Energy Supply, Renewable energy sources, Academic buildings, Solar energy

1. Introduction

Cities consume about 65 % of the energy human requirements, so, more than 70% of greenhouse gas emissions and associated effects are the consequence of the energy consumption [1]. There are several cities located close to the equator line at a medium altitude above sea level, on plate valleys between the Andes Mountain range (between 2000 m above sea level and 3000 m above sea level), these valleys do have a very huge potential to reach the energy neutrality through solar PV integrated, since the low energy requirements for heating, cooling and air conditioning (HVAC). Cuenca city (Ecuador), located in the torrid tropical zone of the planet, there are no excessively uncomfortable temperatures, rather it is under a mild temperate climate condition most of the time, with a few short hourly periods when the temperature could reach close to 30 º C in sunny afternoons, and others when is close to 0 ºC very early in the morning. These climate conditions imply very particular urban and building energy requirements, where indoor spaces on different types of buildings do not require heating and air conditioning systems, and energy demands are nonexistent as a consequence. The analysis of this particular climate could be significant in other South American regions, with similar conditions as Cuenca, like Bogota or Quito, capital cities; or several mid-size cities and countless small towns and populated spots. This special climate quality and with specific implications for energy requirements had been analyzed by the authors in previous research [2].

In Ecuador since 2018, a regulation has been extended to permit building owners to install small distributed generation systems connected to the grid to the required extent to achieve an energy self-supply [4]. This regulation which has been actualised recently by [5], admits to achieving energy self-supply without power surpluses exceeding recognition. Still, the surpluses remain after two years as credit.

Any energy simulation output process from any intermittent energy resources that is performed, no matter how accurate has been built, as a consequence of the different inputs required and that consider climate condition incidence and additionally the model normal inaccuracy as a consequence of the difficulty of taking in account all the possible variable aspects, the simulated results could differ in more or less extent from reality and outputs, but it is not known to what extent. Then, the only alternative is programming the simulation model as the best and most precise definition following the real model. To determine the variance from simulation to reality in energy potential and environmental conditions, it is possible to compare in-site measurements with simulation results. For that, to have the climate data for the simulation tools, the information must be taken on-site, to run the simulation afterwards, so then it is possible to determine the tool's accuracy.

A. *Energy demands for PV integration*

The energy requirements for the Architecture Department buildings analyzed are determined by power requirements. These buildings contain indoor spaces for educational uses such as classrooms, laboratories, offices, and others, which due to the prolonged permanence of users require adequate comfort conditions. The indoor area is about 3483.40 m^2; complemented by bathrooms, staff rooms, and support in general, they are also interior spaces, which are less demanding on environmental comfort requirements since they are not intended for long permanence. In total, the buildings of the complex have 4418,16 m^2. Accordingly, to the climatic conditions described before, the building complex analyzed currently consumes only electricity. There are no heating or hot water requirements, so the energy consumption corresponds mainly to lighting, electronic equipment such as computers, projectors, and support equipment for computational systems. In addition, the Architecture Department buildings also include a carpentry workshop that also requires electrical consumption for mechanical equipment for woodwork and wooden board cutting, machines that do require high power output momentary when this equipment is in use. Table 1 shows the energy consumption in 2019, just before the COVID pandemic event. This consumption implies a requirement index of 30.5 kWh/m^2 in a year, much lower than the measurements performed in other educational buildings under seasonal climates, where the energy requirement oscillates between 55 kWh /m^2 yearly to 195 kWh /m^2 yearly, depending if the climate corresponds to north or south Europe context [22]. In this table, it is possible to observe that contrary to what is expected and happens in buildings in seasonal locations, the power consumption increases during months with academic activity, without any correspondence to climate oscillations.

Table 1: Energy consumption and spent power bill, in the School of Architecture of Cuenca University

Monthly power bills ($) (2019)

Utility Account code	Department	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
2857694	Architecture	1.039	776	768	935	1.032	1.079	1.147	630	787	952	961	934	11.041

Montly Power Consumption (kWh) (2019)

Utility Account code	Department	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
2857694	Architecture	12.763	9.302	9.875	12.172	12.415	13.043	13.777	7.603	9.554	11.489	11.654	11.308	134955

2. Background research

Recently, in the last two decades, several research approaches to decipher cities as energy sources by themselves have been performed. Research studies about urban energy capability started at the beginning of this century with the methodological process to decipher irradiation availability on urban fabric surfaces, especially on roofs, detecting the solar incidence and irradiation availability as Campagnon proposed at the beginning of this century applying Radiance Lightning software [6]. Several other different methodological processes had been implemented also to figure out the solar potential of an entire country or city, through satellite information as performed by Izquierdo et.al in Spain, they determined the overall solar availability of entire Spaniard regions on its buildings [7], this type of analysis had been developed afterwards in different cities and countries like Ecuador, where, Tapia et.al had dimensioned in 2022 that in the three main cities Quito, Guayaquil and Cuenca, there is the availability of 144 km^2 on roof spaces to integrate PVs, and with this area, there is a potential to cover twice the power requirements of the three cities in 2019.

Each climate condition supposes different requirements for different typologies and different uses. For PV technology integrated into a building to reach a good performance the PV installation must be performed in concordance with energy consumption and establishing a good match between consumption and irradiance availability is essential to maximize the PV potential reducing possible affection to the grid as a consequence of power exceeding when the coincidence of high energy output with low energy requirements [8]. Then, local analysis is required to detect the best strategies for achieving building energy self-sufficiency.

Energy efficiency strategies and energy requirements do have special implications under equatorial middle altitudes such as the Andes Mountain range, where normally there is low or no heating or cooling requirement indoors. Computers have incorporated tools for building and renewable energy for integrated design, and specialized tools for simulation and design of renewables integrated with buildings as SAM software are available [10]. Building modelling makes it possible to forecast comfort and energy parameters in response to climate parameters, in unity with shape, materiality, and setting regarding the environmental context and the complete performance of the building as a consequence [11].

However, simulations usually are not contrasted with reality. In previous research, comparisons have been made between different software tools [12]–[14] but very rarely are simulations compared with the reality simulated, considering the completeness of real data with the input in the simulations and real conditions, that is, a comparison with survey data obtained from a weather station emplaced in-site of an existing building and taking data of PV energy output generated in the site when the simulation takes place. So, in this research, we are obtaining the PV requirements, sizing a PV installation according to power requirements through software analysis, also determining the economic viability of the proposed system by local prices and regulations. This is the starting point for further research that will determine the real performance of a PV system that is under construction process. Therefore, using the equipment and capacity available at the Faculty of Architecture and Urbanism buildings (blocks built with a precise functional program), taking advantage of an existing weather station taking weather data, it is possible to model the PV requirements in the software SAM with site climate condition; future analysis will complement the analysis of internal comfort, and requirements to achieve the NZEB standard.

3. Methodology

This research is intended to plan the different parameters and requirements to develop a higher education building into an NZEB. To do so it is required to get the energy requirements to be solved through within-site renewables. Considering the operational energy consumptions that have been determined just before the COVID pandemic period, when these buildings were being used to their full capacity and irradiation availability it is possible to determine and size a PV plant to feed the energy requirements. The energy demands of the year 2019 were obtained through the energy bills that are available as an input of the energy analysis. In Ecuador is possible to obtain the power requirement from the power utilities since they are state-owned, and the bills are freely available online [15]. This building complex only has power demands, there are no requirements for another type of energy for its functional process, consequently, it is only necessary to resolve the electrical demands to cover all the energy demands.

In concordance with the power requirements, a PV system placed into buildings is programmed in the System Advisor Modeling software of the NREL [10]. This free online software does have the capability to perform static simulations to determine the power output of specific solar products in a complete PV installation considering a complete system such as power inverters, protections, and the entire electrical wiring. In addition, the losses associated with dirt that have previously been determined locally remain less than 5% due to the high local rainfall [16] when PVs are set with the required tilt for rainfall self-cleaning. In addition, the losses associated with the loss associated over time in PV panels are considered, which are normally in the order of 0.5% annual reduction [17]. In concordance with PV products available in Ecuador, and in concordance with the aesthetics of the PV products and their visual impact, Trinasolar Vertex S Black Structured PV Half Cell [18] has been chosen, and with this, it has been dimensioned the PV power plant required to achieve the total projected power requirement. Another limitation considered corresponds to the electrical transformer that powers the building complex, the three blocks are connected to a 75 kVa transformer, but since it must conduct a bidirectional power in/power out, an important issue has to be taken into account the maximum possible electrical surpluses on specific moments and days when high irradiation levels are coinciding with moments of low consumption.

In concordance with this initial analysis, the climate data of Cuenca from the NREL available for SAM is obtained, through a free download process. After performing a simple solar availability through a recent solar potential according to slope and orientation, it is possible to predict initially the area requirement for solar capture [2]. With previous simulations, it has been observed that according to orientation and collector slope parameters, when the tilt is lower than 22 º, the power capability is only reduced maximum in 6,1 % when comparing the best orientation with the worst orientation (260,09 kWh/year by m^2 of PV installed orientated toward the east versus 244,41 kWh/year by m^2 of PV installed oriented toward West-South) [2]. Then, for the solar PV plant, it has been considered to set the PVs oriented towards the four cardinal orientations, to achieve higher power production at different hours in different arrays, it permits to distribute the power throughout the day evenly as described by Hachem [19]. Deploying the PV arrays towards different orientations in the future will be very useful to further research also.

With these simulations of the PV performance, further work after the installation of the PV arrays and the connection to the grid is to define the real reliability and deviation of the tools for simulation. It is foreseen that in the future climate, information will be taken from the climatic station that is already installed and functional on the roofs of the Faculty of Architecture building infrastructure. So, with this information, and PV power output and programming software for PV simulation like SAM or DesignBuilder software, it will be possible to perform a comparison of these tools with the real performance of this solar equipment, in this and further research.

This study is part of overall research that will compare different levels of building indoor comfort parameters and in-site renewable production, comparing real data of performance with software simulations through virtual building construction in comparative precise best similarity with indoor spaces in the three blocks of the Faculty of Architecture and Urbanism (FAUC) of the Cuenca University, climatic files constructed from data taken from a climatic station located in the FAUC three-block building roof while the levels of thermal comfort of 18 interior spaces of permanence for students (temperature and CO_2 detection). The climate data will be collected on-site when the PV plant is generating power. These climate data afterwards could be converted through Meteonorm software, in files .csv , .epw or .tm2 type to run in the simulation software like Archicad's Ecodesigner [20] and Designbuilder software [21]. This process is expected to detect real performance data for the requirements to achieve the NZEB standard.

Universities play a crucial role in specialized education, research, and link to knowledge with society. Therefore, higher education institutions can adopt and translate Sustainable Development initiatives not only from the intellectual and conceptual framework. The sustainable management of a university campus makes it possible to demonstrate practically the effect that society can have in the face of local, regional, or global environmental problems. In other words, universities have a social responsibility to incorporate sustainability into their actions, acting by example.

For building PV integration, it is necessary to consider the PV performance, in this particular context has been determined as a particular region with ideal characteristics to achieve an important proportion in self-energy supply capability on buildings and communities. The high irradiation levels, relatively low climate seasonal fluctuations, and the minimal thermal requirements for achieving internal comfort make it possible to integrate and feed an important energy fraction of building and urban energy requirements with relatively reduced-size PV installations [8]. So, detecting the energy capability of individual building typologies and deploying the technology to observe its real performance is the first step to achieving neutral energy communities taking advantage of the particular enormous opportunity, thanks to the excellent local conditions as explained.

4. Results

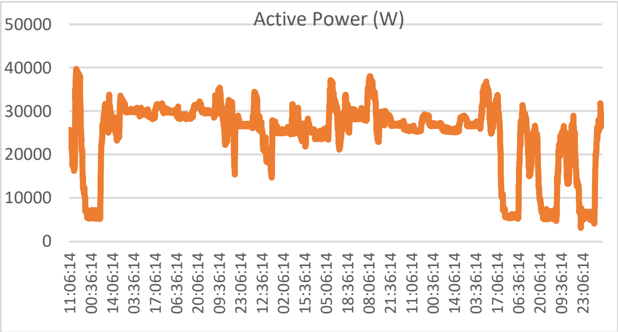

Fig. 1 Monitoring and registering power and other variables with FLUKE 345 equipment in the electrical transformer that feeds buildings, during ten days (authors

Active power was measured in the power transformer detecting what is the consumption at different hours and, so it could be contrasted with PV's possible output detecting any risk of exceeding the maximum capacity of the transformer. The graphic presented in Figure 1 shows the monitoring equipment FLUKE 435 Series II (Power Quality and Energy Analyzer) and the active power fluctuation. During ten days, data every 5 minutes were taken, it shows that the lower power consumption detected is near 5000 W at night time; but at noon the lower consumption never gets lower than 12000 Wp, including weekend days. Then the admissible capacity was determined to a maximum of 88 kWp PV plant.
Then introducing this consumption is considered as expected demands as inputs. Considering the limitation of exceeding the capability of the electrical transformer, the SAM simulator software, as required to proceed to dimension the PV system to reach the power requirement in a full year consumption as said before, to adjust to the local utility requirements.

n concordance with the PV product and available inverters, in the SAM simulator software, the integration of 228 PV units of 385 Wp, the overall plant capacity could reach a maximum output of 87.8 kWp; but when simulating a reduction output as a consequence of orientation and tilt of the PV panels, a maximum power output of 86,6 kW is determined. With this size, the PV plant is found to achieve close to the required power output, deployed in the three built blocks according to the roof availability as shown in Figure 2. Figure 3 shows an aerial view of the PV arrangement on the roofs. To avoid the accumulation of dirt and dust, it is strategic to set PVs with slope, therefore they are placed with a 15-degree tilt, which has been shown that this inclination reduces minimally the power output since the best theoretical performance next to the equator is set horizontally to capture more direct solar incidence [16]. Buy the sloped arrangement of PVs maximizes cleaning due to the high and constant levels of rainfall in the area. The Architecture Department buildings had been catalogued as having "patrimonial value" so, any intervention must consider a low impact and must be a reversible intervention. In consequence, the PV arrangement has been performed according to Kaan and Reijenga's conceptualization of [23]. In concordance with Kaan qualification, PV solar integration architectural guidelines, the PV had been deployed the PV arrangement provoking chromatic mimicry or making them invisible. From the ground perspective, the arrays have been classified as Level 1, according to those authors, the arrays are not visible from most ground points of view. The PV arrays are visible from the sky and from over other buildings, so the PV arrays are arranged symmetrically paired with each other in pairs, as well these had been arranged also symmetrically according to the roof configuration. The PVs selected also consider mimicry, so the type is an all-black PV product, an alternative that fits better over the old grey concrete roof, so the product selected is DE05-09 full black product from Trina Solar [18]. The arrangement of the PV arrays is close to the four cardinal points, with a 7 º deviation, as a consequence of the deviation of the roofs and buildings. The energy output as a consequence will be very close to the unit as if the PVs were exactly arranged facing the cardinal points directly. As a consequence of special availability and visual coupling, 60 PV units were arranged facing East, 60 West, 54 to North, and 54 South as observed in Figure 2. For each orientation, an individual inverter has been considered, in concordance with the power output. Additionally, the losses for dust were set on a 5 % average, and as a consequence of shadowing loss where set 0, there is no shadowing effect observed since there are no high objects or buildings that could project shadowing on the roofs. With the achieved production 90 % of the energy requirement is achieved with an 86,6 kWp PV installation, considering the gap to not overproduce and in concordance with actual regulations [9], and with a reasonable margin to ensure avoiding overproduction that could exceed the transformer capability.

Fig.3. Aerial view of the PV deployment of 228 PV units of 385 Wp according to architectural criteria (authors).

A. PV Potential and financial results

The simulation has been performed in SAM software, with installation proposed with the PV installation proposed, it is possible to reach 119563 kWh annually from 134954.64 kWh consumption in 2019, corresponding to 88.6%. This generation does oscillate monthly according to irradiation availability as well as the monthly consumption when it is observed when there is less academic activity as in February, March, August, and September, in Figure 4 it can be observed. It shows that in the months with higher irradiation, in September or December 1000 kWh of exceeding, in June and July with low irradiation, in addition to PV generation, about 5,000 to 4,000 kWh additional power from the grid is required, in months where these buildings are fully operational.

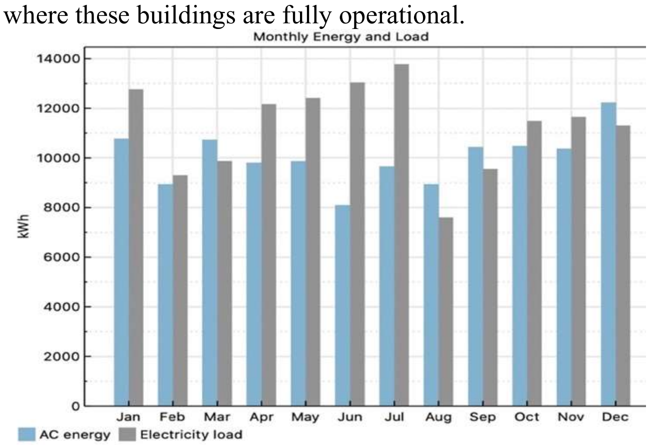

Fig. 4. Monthly power consumption recorded in the year 2019 versus PV potential

In addition, as a complementary result, the software makes a financial estimate. To perform this, it has considered and simulated the energy costs jointly with the costs of the PV installation. After a revision of the retail prices from a local installer [24], where the system is budgeted by the PV systems proposed, the solar products, and the planned arrangement system, a market cost of about 1.20 USD per Wp is obtained. This price and an annual efficiency reduction of 0.5% are also taken into account, typically a reduction for PV technology along the 25 years of useful life. If we consider the real price of the electricity considering production and distribution (around 15,6 cts the kWh) [25], the financial results show a payback of 7.9 years period. Therefore, the result shows that a bit more than 17 years of "free" electricity is obtained as a net benefit. But the price by kWh purchased from the utility by the university (public university) is 0.082 dollars, 25% less than the residential cost, this price is also 47.5% cheaper than the real estimated cost of production is around $ 0,156 kWh USD. Then, solar energy self-supply meant savings to the public accounts, and an interesting alternative to all public buildings, not only promoting private investment in self-provisioning electricity but also saving public spending. Figure 5 reflects the annual investment recovery. The overall cost of the PV plants is USD 115,150.00. This investment has a recovery period of 12.8 years if the electricity prices are maintained and subsidized. But considering only a 1 % increase, very low as expected (It has been about 37 % annual average from 2014 until 2019 according to the World Bank, from USD 0,079 average cost in 2014 to USD 0,119 in 2019), it would be reduced to 12,3 annual payback period, and it would be much higher if continue the recent price trends, affected by energy requirement and global warming effects.

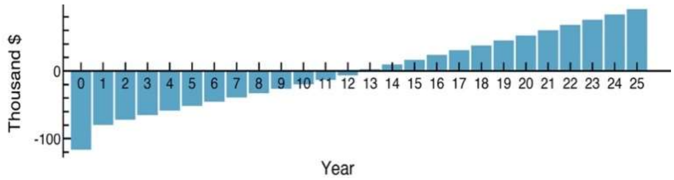

Fig.5. Annual investment recovery, considering not power retail price increase.

5. Conclusions

This research is the first step to determining the requirements for reaching the Net-Zero Energy standard in the Architecture Department buildings of Cuenca University, as a representative case of the educational building. Firstly, it has been determined that, in the 1076,35 m^2 of an overall flat regular roof, in this available space according to architectural impact, shadowing and maintenance aspects, it was possible to integrate 228 Vertex All Black Trinasolar Products, of 385 Wp each, which implies an available PV area for solar production of 438,3 m^2. In consequence, this implies an available PV surface of 40,7 % occupancy rate considering to total roof area available. Also, it expresses that in this building typology and this location, according to the case analyzed, it requires a very low solar capture area per m^2 indoor area of about 0,01 $m^{2,}$ according to the energy requirement index established, and in concordance with the PV efficiency selected (20 % efficiency).With this proposed PV system, it can potentially cover approximately 88.6 % of the 2019 power consumption. The size of the PV arrangement is supposed to be close to the overall energy requirement, considering there is not any fuel consumption currently in the building complex. In cost analysis, if it is considered the real cost of electricity without state subsidies, the PV plant proposed is affordable over time, but if we take the actual subsidized power cost, the time of recovery could extend more than twelve years which implies that it is not an attractive investment. Also, as a consequence of the subsidized cost of electricity, the period of return on the investment expected is 12,8 years, but if we consider real electricity price it would be reduced to 7,9 years.

The next step is determining the interior comfort level to reach the NZEB standard. Even though there are no HVAC systems integrated into these buildings, considering that in cities and places at this altitude above sea level and this latitude close to the equator, very favourable climatic conditions are observed most of the time that suppose the non-installation of the HVAC systems are normal in most houses and buildings. In consequence, this also supposes that there are few moments when thermal comfort conditions go out of adequate requirements

Achieving the NZEB in concordance con thermal comfort requirements will be performed in further research, but it can be established that with adequate construction conditions, especially in the building envelope, the necessary comfort requirements can be sufficiently achieved, then the energy requirements have been demonstrated that could be solved with a PV system. The overall 100 % reduction could be achieved also with energy efficiency measures like by improving actual luminaries from fluorescent lighting to LED lighting and analyzing complementary other equipment that could be a high-power requirement.

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