

Incidence of non-working days on limiting photovoltaic potential on a building with day-hours high power consumption, without storage and grid injection

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Abstract. This study investigates the practicality of a 7 kWp photovoltaic (PV) system designed to partially supply power to the Faculty of Architecture and Urbanism buildings at the University of Cuenca, Ecuador, without storage or bidirectional meter. Leveraging theoretical capacity alignment with irradiation, the system aims to avoid surpluses, as it is not connected to the grid through net metering, net billing, or a storage system. Despite the equatorial location's low seasonal fluctuations and reduced irradiation and energy demand variations, significant consumption fluctuations between working and non-working days pose a primary challenge. Implementing a system with the potential to cover around 7,5% of the total annual demand, surpluses occur at midday on non-working days, reaching 2,7 kW, yet annually constituting only 0,17% of overall consumption or 2,2% of total energy production. This underscores the limitations of non-working day fluctuations despite the system's potential for on-site energy generation during working hours.

Key words. Building Integrated PV; Energy efficiency; PV production self-consumptions; PV matching.

1. Introduction

Since the end of the past century, it has been established that the future energy supply to buildings from solar sources would be essential to achieve energy sustainability. Under this concept, experimental solar PV integrated into housing was developed in the United States [1]. Then, if the buildings can generate their own, the next step is implementing many buildings in energy-neutral urban environments. This implies the possibility that, in addition to being self-sufficient, they can even achieve buildings that deliver surpluses, even exceeding their demands, like the Plus-energy buildings concept, which was defined in the

first decade by Rulph Dich, in his manifesto [2]. Higher standards indicate that energetically the buildings should generate higher energy amounts, for example, the buildings defined under the Powerhouse Buildings standard, in Norway [3].

Under these circumstances, the analysis corresponds to carrying out local studies that allow proper conditions to introduce urban micro-generation, under the concept of reaching high energy self-supply. Each place has its solar potential and local characteristic needs that differ, the self-supply capacity is associated with the presence or not of irradiation, demands to be satisfied, coincidence or not of demands with irradiation and technical possibilities for temporary energy management [4]. In addition to this, space for irradiation capture, and architectural and geometric aspects of a building and an urban area also affect the ability to take advantage of the sun [5]. However, mismatching between power PV production and power consumption is an important barrier to be solved for using the urban power grid as a virtual battery. But in some circumstances where there are limited resources or no possibility to exchange power with the urban grid, or local regulations are affected due to grid connection regulations like applying the called “grid tools” penalization, which implies that power exceeding are bought by the utility, in a fraction of the power selling price, considering buying the power to the micro producer at the same price that the retail price. Then injecting exceedings is not economical but is the actual tendency to keep the “long-time sustainability” of the micro producer integration.

This work describes the performance of a PV plant integrated accordingly to mid-day base demands of a university educational building complex, located in South America's equatorial latitude of the Andean region (2.901724°S; 79.010263°W). The geographical characteristics of the location of these buildings imply that, due to the excellent climatic conditions and the minimal seasonal variation, there are ideal conditions to supply since the lower consumption required of the building since there are no internal thermal demands for reaching thermal comfort; then, without seasonal demands fluctuations as observed in seasonal countries, and with a low seasonal PV production fluctuations, it would imply to achieve important PV power self-supply without surpluses to store. Secondly, the PV plant and the demands to be satisfied are described in dimensioning avoiding exceedingly as explained. In the third instance, the results of the energy obtained in the period of monitors of the PV system are shown. Finally, based on real measurements, the proportion of self-consumption is determined, and it is also determined if there is some power exceeding injected into the grid. The novelty of this work is to propose a methodology that allows determining what is the capability of reaching a maximum power supply of a PV power plant, to what extent there is power exceeding and what it should mean in energy that is not accounted as exceeding in a net-metering scenario.

1.1 Building Description

The educational building infrastructure where the PV system is under analysis is close to the urban centre, located at 2.550 meters above sea level. As a consequence of the excellent climate conditions, very few buildings contemplate heating or cooling systems, even, on average, the average temperature of the city is between 15 °C to 15,5 °C, but internal buildings reach most of the time comfort temperatures and as a consequence of the stable temperature throughout the entire year, solar passive capture and internal gains [6].

1.2 State of the art

For building integrated PV systems applied on a university campus has been investigated in Egypt, it has been experimenting with a PV system for feeding the energy requirements for the Mechanical Engineering Department Building of the Faculty of Engineering Building of Ain Shams University, complemented with energy savings retrofitting. Through simulations with Energy Plus software, it was estimated that with passive strategies, it is possible to achieve 36 % energy savings. Then, applying 2567 sqm of PV solar arrays it was determined that it is possible to reach power neutrality and achieve internal thermal comfort in the buildings. This is a very extensive area with thermal comfort improvement because of the high energy requirements for cooling mainly [7].

In another study in a seasonal climate condition as San Sebastian (Spain) affected by a heat period in summer but with mild cold climate conditions in winter, Irulegui and others [8] established the requirements for retrofitting the Architecture School building as an initial step towards reaching a NetZero Energy Building. They established that university students' thermal comfort is lower than that of other users or buildings (20 °C to 22 °C). When improving the building enclosure, reducing between 58 % to 62 % of

the energy requirements for heating and cooling would be possible. Then it is easier to reach the gap with in-site renewables.

Close to the equator line, tropical regions are especially advantageous since there is usually an important and stable irradiation availability in these locations. Also, the energy requirements in buildings, especially in educational buildings, are very high, especially when there is huge irradiation availability. Another important aspect is that as a consequence of the closeness to the equator, the seasonal climatic fluctuations are low compared to seasonal climate conditions far from the equatorial region. In Malaysia recently Md Khairy [9] performed a close analysis of the PV potential to feed the energy requirements of eight educational buildings located in eight different sites in Malaysia country. Each of these educational infrastructures has the capability of coursing between 500 to 1.000 young students. In each of them, there is an analysis of the energy requirements over a year. This research shows that the energy consumption in these climate conditions coincides timely with the irradiation availability throughout the day. They also measured the space and irradiation availability to spread PV systems in each building. In two of the eight buildings, the PV systems could partially cover the total energy requirements in one the total energy potential in the roof area must be utilized to reach the energy equilibrium, and in the five remaining buildings, the solar potential is higher than the total energy demands of each building, in one of them the solar potential is between 8 to 10 times higher than the total energy requirements although, the high energy needs for cooling. It is essential also to consider that PV requires geometrical adaptability to reach the maximum occupancy index. For example, on average, it was determined that for the habitual size of solar PV panels, in single-family house typology, the average roof occupancy would reach an average index between 63 to 64 %, of the total sloped roof area availability [10]. In previous and initial research considering several roof typologies, including flat roofs, the roof occupancy estimation in a seasonal context where the PV occupancy is reduced by lower solar altitude, a PV occupancy of 0,45 would be considered on average (By Bargamasco et al in 2011 for Italy, for example, [11]). However, this type of measurement and simulation had not been developed in equatorial solar incidence.

In this research, we proposed a novel analysis for determining the power capability to feed the electrical requirements of the Faculty of Architecture building at the University of Cuenca. After developing the total PV requirements for reaching the total energy requirements, but in concordance with financial investment availability and considering that the building complex does not have a bidirectional power meter, an initial system for covering the base energy midday requirements is dimensioned; for that, it has been analyzed that even there is a high and stable consumption during working days, but on non-working days and holidays when there are not academic activity, there is a considerable power reduction. With this analysis, we could obtain some applicable information for other types of buildings with similar geometrical characteristics and limitations under equatorial latitude. Also, when dimensioning a system to feed the minimal

midday requirements, we could obtain to what extent the overall energy requirements would be covered, without considering energy surpluses to the grid. As far as we search in the literature, we could not find an analysis for detecting implications of conceiving a PV system avoiding surpluses or not storage but supported by the grid connection, a scenario required when there is little advantage of injecting exceeding's for low selling prices or high costs of storage or for the required meter exchange.

2. Methodology

First, as starting data, we had the power requirements of the higher educational building complex of the Faculty of Architecture of the University of Cuenca. We also consider the space area availability feasible to integrate PV technology jointly with improving more efficient lighting technology. Due to the economic resources existing and the costs of integrating a bidirectional meter, the system will be dimensioned to avoid power surpluses, proposing and installing a system dimensioned to achieve the maximum base consumption. To achieve this, the power consumption monitoring was first measured on a representative day when the infrastructure at this building was at plenty of occupancy and on a characteristic weekend day. In equatorial latitude, the seasonal fluctuations are pretty low; consequently, the power consumption fluctuation as a consequence of seasonal fluctuation is considered negligible. Locally is habitual to characterize the power requirements and fluctuation as a consequence of being working or not working days. In previous research in Cuenca, Ecuador in an urban area location, it was detected that the main energy consumption fluctuations result since it is a normal working day (Monday to Friday) or if it corresponds to a weekend day or holiday. It was established that in a hundred urban blocks solar PV potential, comparing the month with high power consumption with the lower one, there is only a 6,7 % difference in the total power consumption. Still, if we compare the working day with a weekend day, the energy power consumption fluctuates by 31,0 % [12].

After defining the base power consumption, it is necessary to find the available space to emplace the PV system. For this also it is necessary to consider that in this city, as a difference compared to seasonal and far from the equator locations, where solar panels should be oriented towards the equator, it has been defined that locally the best orientation is toward the east since cloudiness incidence is lower during the morning hours, but with small benefit compared with orienting to any other direction with a maximum of a 7 % difference comparing the best orientation with worst one, when the panel tilt is lower than a 27 ° slope [13].

Then the implementation of the solar PV system is built and integrated into one of the available buildings, in concordance with the power minimum requirements at midday. Even in an educational building complex, on a normal working day, the matching between irradiation availability with power requirements is quite good, but on weekends, holidays, and break periods (at least 140 days), the energy requirements are pretty low. Additionally, the regular meter deployed in buildings in Cuenca, if this is not set as bidirectional, and the bidirectional change supposes high expenditure, then the energy surpluses are metered as

consumption, then the power expenditure may grow significantly if there are power exceeding. For this reason, even when a project for reaching the energy balance between production and consumption is initially developed, the initial part has been determined with the lowest consumption registered, this is determined by [1]installing a FLUKE 435 Series II (Power Quality and Energy Analyzer) [14].

In concordance with the minimum power requirements detected at midday, it is dimensioned that the PV system can reach this base consumption coinciding with midday. After installing the PV system and when it is under production and connected to the building's internal grid, the fluctuation between production and consumption is measured in a week when the courses are running, and it is possible to determine the weekly energy balance. From this, it would be possible to determine the proportion of energy-self-supply.

Additionally, and considering that there is a climate station Delta T model [16] installed on the building taking climate data inside the PV production, it is possible to determine and compare the real energy PV production with simulation performed in one of the most used tools (Systema Advisor Modelling tool of National Renewable Laboratory of the United States) [17] to predetermine the performance of a PV system. So, with the climate information obtained in this, the real performance with the simulation could be approximate.

3. Results

3.1 PV system for reaching NetZero Energy standard

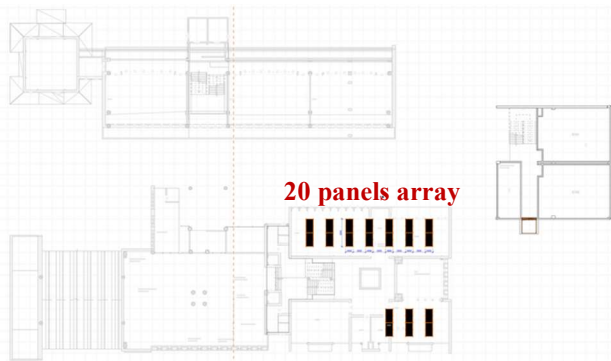
The initial data for dimensioning a PV self-supply system corresponds to the faculty energy consumption history. The yearly data on electricity consumption were obtained from the utility bills, which provide the monthly energy spent. In concordance with the annual energy requirement is possible to determine the total energy needs and the necessary power output for the system to achieve the energy equilibrium production-consumption every year. For the initial design stage, the input data considered is the year 2019 since the system design was performed in 2021 when as a consequence of the pandemic event, the consumption in 2020 and 2021 were not regular periods. Table 1 shows the energy consumption every month and the total annual.

Table I. Monthly Power Consumption (kWh) (2019)

Jan	12.763	Jul	13.777
Feb	9.302	Aug	7.603
Mar	9.875	Sep	9.554
Apr	12.172	Oct	11.489
May	12.415	Nov	11.654
Jun	13.043	Dec	11.308
TOTAL ANNUALLY	134.955		

In concordance with this, it is observed that the yearly energy demand is about 134.955 kWh. Real data from the year 2022, obtained from the 35 kW PV solar farm at the Micro-Grid Laboratory building [15] an academic facility located on another campus of the University of Cuenca just a few kilometres from the building under study, revealed that the capacity factor for the polycrystalline panel array reached 14% during that year. By utilizing this information alongside the annual energy consumption of the architecture faculty building, it becomes feasible to ascertain the required installed capacity for the PV solar installation to meet the entire demand-supply. The calculation indicates a necessary capacity of 110 kW. But as a consequence of the limitations in the power transformer (75 kVA), it is allowed to install a system with a maximum power output of 75 kWp. Then with it, the power requirement would be fulfilled theoretically at about 68 %. This would be achieved with 195 PV panels of 385 Wp. Additionally, during the pandemic event, the luminaries' buildings were replaced with neon lighting to LED lightning technology, so as a consequence of the more efficient technology, a reduction in energy consumption is expected. Finally, a preliminary estimate was conducted to determine the maximum number of PV panels that can be physically installed on the available rooftops of the building, aiming to establish a technical limit. The findings are illustrated in Figure 1.

Figure 1: Maximum number of PV panels that can be installed on the building's rooftop



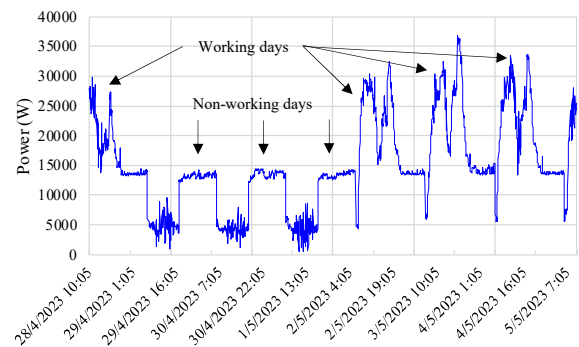
3.2 PV system for covering the base consumption and lightning energy efficiency measures

Following budget considerations and recognizing the substantial local cost of the smart meter (approximately USD 1800,00), the initial decision was to implement a system that could partially meet the power needs of the architecture faculty's building complex. Aligning with the typical hourly occupancy patterns, the maximum energy requirements were identified from early morning (7 am) until early night, with a slight reduction at midday. This allowed for the integration of a PV system with sufficient capacity without entering the net metering arrangement, eliminating the need for a smart meter to monitor power injected into the grid.

It's worth noting that local regulations mandate approval for the PV system, even if the excess power injected into the grid does not qualify for a refund. To establish the consumption baseline, the minimum power required to

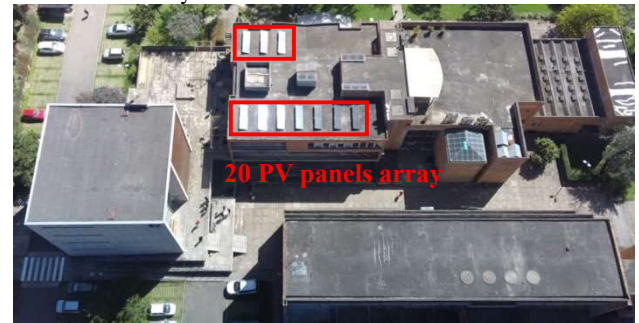
avoid exceeding limits was measured using the FLUKE 435 power analyzer. Figure 2 displays a weekly energy consumption profile for the architecture faculty blocks from March 28th to May 5th, 2023, covering both workdays and non-workdays. This is a typical consumption profile exhibited by the installation since 2022, the year when detailed measurements of instantaneous power became available. On non-workdays, a consistent and flat energy consumption pattern is evident, peaking around 12,0 kW during daylight hours and decreasing to an average of 4,5 kW during the evening and early morning, attributed to the activation of outdoor space lighting. On workdays, the consumption curve sharply rises, forming an envelope with peaks that reach 36,0 kW around the 12,0kW baseline.

Figure 2: Typical weekly electricity consumption profile of the studied building.



In concordance with these observed fluctuations, it is noted that on typical working days, average consumption never drops below 15 kW. On non-working days, consumption decreases, averaging around 4,5 kW (fluctuating between 1,2 kW to 9,5 kW) during expected irradiation hours. Therefore, a proposed solution involves a 7,7 kWp PV system connected to a 7 kVA inverter, accounting for potential energy losses during peak irradiation periods as a consequence of cloudiness mainly. This choice is justified by the consideration that installing a system solely for the minimum power detected during the measurement week would permit a minimal PV system of less than 1,2 kWp. Despite anticipated losses, precise determination of the extent to which excess energy will be injected into the grid, where it will be available without economic recognition, is crucial.

Figure 3: Actual PV solar panels with 7,7 kWp installed on the roof of the Faculty of Architecture.

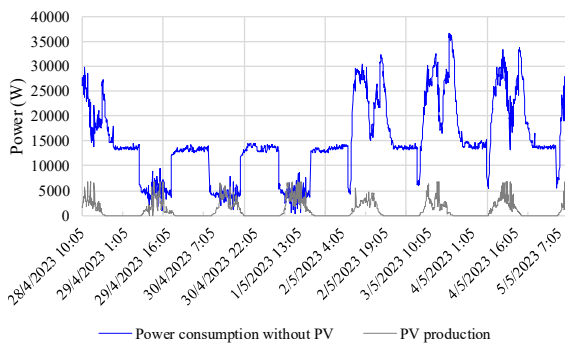


Compared to the original projected system (Figure 1), the proposed system, involving 20 PV solar panels, is situated in the northern block, facing exclusively eastward; the optimal orientation for local PV systems as previously described. The 20 PV panels are connected to two inverters: 14 panels to a 5 kVA inverter and six to a 2 kVA inverter. The PV system was implemented on June 4th, 2022, as depicted visually in Figure 3. Since its commencement, the system has been operating continuously up to the present day.

3.3 Daily PV output and self-supply capability

To compare the building's consumption profile with the actual power generated by the PV system, Figure 4 has been prepared based on measurements taken with the FLUKE 435 power quality analyzers from April 28th to May 5th, encompassing both non-working and working days. This timeframe facilitated the determination of PV output, consumption, and energy balance. Notably, power surpluses were observed on non-working days during periods of higher irradiation with no consumption. Overnight, baseline consumption, influenced by continuous outdoor lighting, ranged from 12,5 kW to 13,5 kW, decreasing on non-working days to as low as 0,388 kW. The overlap of power consumption with PV power output curves revealed that the energy capacity of the PV system falls short of generating surpluses on regular working days, even at peak moments (6,9 kW). While the 7 kWp PV system effectively utilizes total power production on-site during working days, surpluses occur on non-working days. However, without net-metering measurements, the injected power into the grid is disregarded.

Figure 4: Real power consumption profile vs PV production.



For completeness, Figure 5 has been prepared, illustrating the power balance discounted by the energy produced by the PV system, revealing surpluses during non-working days, peaking at 2.7 kW. Nevertheless, consumption and PV production oscillations limit their duration to a few hours or minutes.

Finally, when integrating the total power in energy production in kWh, and from this, the total energy injected in the grid as a surplus, only considering the holidays, in two days it was injected 1 kWh or less, and one day with higher irradiation it is observed a little more than 4 kWh, as a consequence of the higher irradiation. Then only considering the non-working days, in % of the total PV production, between 13% and 3% is injected without

energizing the building demand. Table 2 presents the production and energy surpluses, in that specific unusual week it reached 2.92 kWh since this week has three non-working days, but if we estimate proportional the total yearly holiday days, the surpluses expected would be 2,2 % of the total production.

Figure 5: Weekly balance of power consumed by the building with the implementation of the PV system.

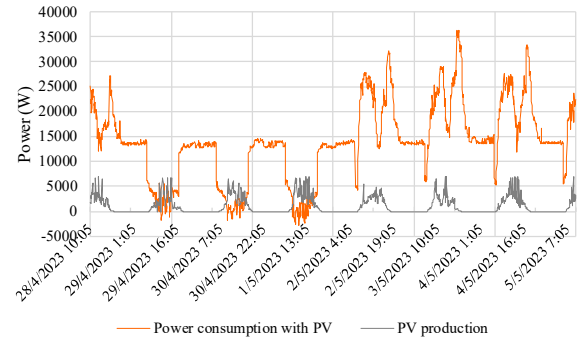


Table II. Daily Produced Energy vs Surplus Energy (*Non-working Day).

Date	Daily Produced Energy (kWh) (P)	Surplus Daily Energy to the Grid (kWh) (I)	Surplus Energy vs Produced Energy (I/P) (%)
28/4/2023	17.96	-	0.00
29/04/2023*	21.17	0.72	3.41
30/04/2023*	25.07	0.99	3.94
01/05/2023*	30.85	4.03	13.08
02/05/2023	23.06	-	0.00
03/04/2023	23.23	-	0.00
04/05/2023	26.67	-	0.00
Daily Produced Energy Average	24.00	1,91	2.92

In 2023, Ecuador had 12 public holidays, 52 Saturdays and 53 Sundays. This, therefore, means that if we considered an average of the exceeding detected in the three non-working days, about 223,50 kWh of annual surplus PV production would be expected to be injected into the grid and not accounted for by a non-bidirectional meter. In economic terms, this represents an annual loss of only USD 22,14 for the faculty with the actual subsidized electricity prices (0,099 USD/kWh), as this value is not deducted from the electricity bills but rather added to and accounted for as electricity consumption for them. Comparing this to the total energy requirements in practical terms, this non-billed surplus energy injected corresponds to only 0,17 % of the total annual energy consumed by the faculty.

4. Conclusion

PV power production and consumption fluctuate rapidly. While integrating Power Battery Storage or utilizing the grid as a virtual storage platform is an alternative, obstacles such as high costs of bidirectional meters or utility limitations may prevent counting PV systems surpluses. Theoretically, adopting PV without storage may

seem ideal in buildings with high consumption during peak irradiation periods. In this research, it has been demonstrated that as a consequence of the non-working days the limitation of adopting PVs without reaching surpluses is very limited as well, since even the system designed is far from reaching the noon power requirements at midday, but some surpluses appear in non-working days that are permanent throughout the year. An educational building typology that theoretically implies a good situation of matching-irradiation for reaching a good matching for self-supply, without storage or bidirectional meter are educational buildings, when this carries on must of this functionally during the day hours. The advantage of this research proposal is determining a maximum PV power capability and its consequence of momentary power surpluses on non-working days, for PV deployment without grid energy exchange or expensive storage. The limitation of PV capability for feeding is a 7,5% in the analysed case, of its total energy demand, sometimes the production is higher than the energy demand.

Then, after taking measurements of power PV power production and power consumption in a weekly period, in a week that also contains a holiday, it was possible to characterize the three scenarios and seven-day irradiation. Considering that the end of April is also a mid-term period, of average irradiation as a consequence of cloudiness, it would be representative only of PV production.

Even is supposed that with a small power plant and high energy consumption on daily hours, in working days the PV production is far from reaching the energy consumption, even considering that between 13:00 and 15:00 is a break period for the students, and normally are few students remaining at the buildings. However, it was observed some surpluses were only on non-working days, reaching up to 2,7 kWp injected into the grid. But considering only the energy balance in this type of day, between 3 % to 13 % of the production is expected not to be used in the building and it is energy that will not count as savings on the energy expenditure on not working days; during working days the total PV production is used. Let's consider the average energy exceeding on the three non-working days and the average of the working days, then it is expected that only 0,2 % of energy requirement is not catabolized as a consequence of exceeding the power consumption.

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