POTENTIAL OF SOLAR INCIDENCE IN MULTI-FAMILY STUDENTS' PROJECTS IN LIMA, PERU

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ABSTRACT

This research focuses on evaluating the solar incidence obtained from students' projects in the second year of architectural academic learning and establishes ratios and performances according to the quantity of photovoltaic (PV) areas and dwellings designed in Lima, Peru. Projects were developed considering the introduction of the architectural integration of PV (AIPV) concept in conventional multi-storey buildings typology. The resulting solar incidence validates an original teaching process carried out for an effective AIPV as part of the intermediate training in the architecture course; and it can also be considered as a valuable source to inform about the enormous possibilities of solar potential in relevant projects and expected policies addressed to housing and energy sectors in Lima. Numerous multi-family projects inside urban blocks with internal patios were evaluated. Although PV array orientations may differ between −49° and +75° with respect to the recommended azimuth (north = ± 0°), acceptable performances are achieved (an average up to 80.55% of the available solar incidence by square meter at PV arrays), by using 41.49% of rooftop area. However, if better performances are expected, efforts are required to obtain more convenient azimuth orientation angles (from NNW to NNE) as well as reduce shading effects by separation and geometry configurations at rooftops. The average PV area per property could cover a large part of the electrical needs of dwellings in Lima, and it is very encouraging to allow owners to become self-consumers or even prosumers in the future, facilitating adaptation and mitigation scenarios to climate change in the urban environment. Other technical problems (other than solar incidence) can be studied in further research.

Keywords: architectural integrated PV, PV integration, solar incidence, multifamily, dwelling, roofs.

1 INTRODUCTION

Solar energy is one of the more useful renewable resources to apply in the building envelope [1], [2]; its integration in buildings has a great potential for application if it is addressed at the design phase of the building [3]. Thanks to current policies of distributed energy in urban areas over the world that promote the Building Integrated Photovoltaic (BIPV), the study of the energy yield of PV systems installed on building rooftops is essential [4]. Usually, the BIPV approach involves very technical or engineering planning issues, where PV systems are integrated into the building components and their removal compromise the functionality of the building envelope as well as the conceptual design of the building itself [5]. In addition, installations must comply with technical and legal regulations [6]. But their low efficiency has also been noticed when used on facades, surfaces with low solar incidence, except in latitudes far away from tropical zones. On the other hand, building-applied photovoltaics (BAPV) consist in PV systems mounted upon a metallic support structure on the roof of the

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building, but, no special interest is given to the aesthetic integration of the system and priority is generally granted to its ability to capture solar radiation on the roof [7].

For the Spanish CTE regulation, the maximum PV loss depends on the construction type to include PV system. These can be classified as: a) general, b) superimposed or c) integrated. 'Integrated' refers to the PV panels with the double mission of being an architectural part of the building at the same time as an energy installation, substituting other construction elements such as cladding or envelope (BIPV). 'Superposition' refers to the PV panels placed parallel to the building envelope, not substituting the construction elements of the envelope: in example, PV panels installed on the tiles of the roof. Finally, 'general' defines all PV installations neither integrated nor superposed, as PV panels supported by inclined structures [4], cantilevered volumes or even movable parts. So, since an open scope, it is possible to obtain an architectural integration of photovoltaics (AIPV) with any of three types. Nevertheless, it is known since many decades ago that PV is not automatically considered an indispensable material in architectural terms. This is why, no matter how well it is integrated, PV remains an 'added' element [8], despite it being usually possible to do AIPV, i.e., integrate the systems in an architecturally good way so that the aesthetics of the building is enhanced; however, it may always not be that easy to do BIPV [9].

Anyway, the initial energy losses in PV systems is, most part of the time, consequence of a careless architectural design of the envelope with respect to the solar incidence. Therefore, an approach based on an AIPV considering solar energy collection is important from the beginning. During the apprenticeship period in architecture faculties, AIPV is often not part of the basic knowledge for students, despite its aesthetic potential in configuration of buildings and interesting relations with multiples building parts and volumetric issues. This paper evaluates the solar incidence achieved in the 65 students' projects at the finals of second year, in a Studio Project course at the Faculty of Architecture and Urbanism in Ricardo Palma University (FAU-URP). The PV inclusion is considered after resolving internal organization and relations with the surrounding, adapting it to the typical coast Peruvian model of 6 floors multi-family urban housing inserted in a block.

2 MEASUREMENTS IN PV STUDENTS' PROJECTS

Research in architecture focused on students' design processes related to solar use exist for testing projects and competition proposals, as well for research and postgraduate student projects [10]; most parts of them experimented with the solar incidence in both, outside and inside of the projects searching more architectural purposes. Some other have been exploring natural lighting through the use of instruments and software [11]. Since a technical and engineering approach, several simulation tools exist to assess the energy production of BIPV systems of built and unbuilt projects, with emphasis on complete results reaching the energy balance and the return of investment of BIPV projects [12], [13]. Other interesting tools based on engineering criteria address the conceptual phase of the design, allowing the control of the evolutionary progress through the interactive selection of parent solutions by mean of parametric modelling, performance simulation software, genetic algorithms and an online database, concluding about the key role played by geometry in architecture in relation to performance-oriented design [14]. Other researches use interesting methodologies to evaluate the performance of various types of projects in different locations in Europe [15], but due to the large geographical scope and variation of solar irradiation, there is not a similar performance and specific conclusion about solar incidence results. Some engineering schools are committed to develop tools for student engineering explorations through modelling and simulations with the use of CAD, developing advanced solar schemes for single-family homes [16], without consider multifamily buildings due to their complexity.

However, all these technical approaches require a lot of information about the energy production, architectural design features, cost aspects of BIPV systems and many other to obtain results. Moreover, architects often characterise those tools as ‘difficult to use’, ‘complex’, and ‘cumbersome’ [17]. Therefore, researchers suggest that the building information modelling (BIM) approach and modelling tools are needed to facilitate collaboration and gather more insights. Studies mention great advances in the use of BIM on the determination of solar incidence [18], but when the analysis and model simulations are carried out by consultants, architects must have the ability to handle the input and output geometry data from the model that is needed to analysis the software. As is known, to carry out this kind of analysis requires a good building knowledge that is, construction technologies, their influence on the thermal performance of the building, and how to interpret graphs, tables and equations [19]. This is probably the greatest difficulty to introduce solar energy in architecture courses at early stages in academic architecture learning, so, in this case the Studio Project course has proposed a sculptural and geometric approach, using PV as an element integrated into the envelope (AIPV) with a simplified scope, postponing the more technical details for advanced training later.

3 ARCHITECTURAL INTEGRATION OF PV SYSTEMS

Martín Chivelet and Fernández Solla [20] establish five types of architectural PV integration: 1) the invisible or unnoticed form; 2) the overlay on the design; 3) the addition of value to the architectural image; 4) the establishment of the architectural image; and 5) the new architectural concepts. Different types of integration can be used depending on the architectural typology, for example, in social housing projects the option can be selected from the types 1 to 3, while in institutional or innovation projects, it can try types 4 or 5.

3.1 The solar incidence

The geometric configuration of PV systems, defined by the azimuth and tilt angles, is the basis in the energy yield of the PV system. The incoming solar irradiation depends on the latitude which determines the sun path in every location. In that sense, the azimuth and the tilt angles obtained by the roof geometries do not usually match the optimal for a PV system [4]. Different investigations have been performed in order to determine the optimal tilt angle for a known latitude in temperate zones. To increase the efficiency of the solar energy system, optimum orientation and tilt angle are necessary, and some simple rules were specified for the collector tilt angle, relative only to the latitude [21]. Since the amount of solar radiation incident on a photovoltaic panel is strongly affected by its installation angle and orientation, finding the optimum tilt angle to receive maximum solar radiation on a photovoltaic module is the cheapest and most effective method [22]. In the context of responsiveness to following the direction of the sun during the day, an adequate tilt angle of a solar module can greatly affect its overall performance [23]. Therefore, considering the tilt angle in a motionless position equal to the latitude of the PV system location is the most extended, and usually, the best azimuth angle is defined by the hemisphere, the south orientation being recommended for northern hemisphere and north orientation for the southern hemisphere.

4 METHODOLOGY

4.1 Context to consider AIPV in architectural education

Numerous South American countries have implemented laws and on-going regulations for distributed energy. Actually, since 2015, Peru has a Distributed Energy Law [24] but the mandatory regulation has not yet been created [25], so PV can still be used in a voluntary way. Efforts to tackle climate change involve training students toward adaptation and mitigation actions through the use of affordable renewable energy in addition to other professional competences. Considering the importance of AIPV at the second year of architectural academic learning, efforts were centred at geometry, orientation and inclination of surfaces favouring solar incidence. Therefore, the AIPV concept has been considered by means of the ‘superposition’ and the ‘general’ integration modes mentioned by CTE (Spain), allowing a greater degree of decisions for architectural solutions according to the building typology and climate conditions. On the other hand, being located in a tropical zone, rooftop solar integration allows flexibility to the architecture underneath design. However, many of the students’ projects have considered interior forms to coincide with sloping or framing edges of the exterior solar surfaces when static arrays have been introduced in the project. It is known that, in the central coast of Peru, the most part of solar radiation is mainly received on the roofs (usually flat, large, and unused surfaces), but greatest effort was focused on dealing with technical installations (water tanks, ventilation ducts, mechanical-rooms, etc.) and inner courtyards, resulting in different proportions and geometries of variable contour in contrast to the compact geometries of temperate climates.

4.2 Educational process

The mentioned educational methodology is carried out in the Faculty of Architecture and Urbanism (FAU) of Ricardo Palma University (URP), in the Integral IV Architectural Design course (fourth semester) since 2014. The task consists in the design of a mixed building typology (commercial on the first floor and housing from the second to the sixth) in various locations in Lima. Formal and self-construction building typologies are included depending of the location. Before pandemic (2019) and pandemic restriction (2020), each student chooses the location and plot with a defined area range (600–800 m^2); in this way the students can associate the project with their closest environment and also learn about the diversity of locations and cases. Therefore, there is no ideal plot orientation in order to solve other architectural problems such as access, views, organization, ventilation, etc. Later, the AIPV concept has been introduced to the middle of the design process. As Fig. 1 shows, different types of PV arrays are allowed to generate different volumetric solutions and relations. Four main types are noted, with different impacts on shading effects and volumetric relations.

As Fig. 2 shows, the first steps are focused on the site analysis, then to propose the changing of road sections with sustainable mobility criteria and urban tree planting, as well as the study of basic dimensions for houses and small-scale business. Next, the organization

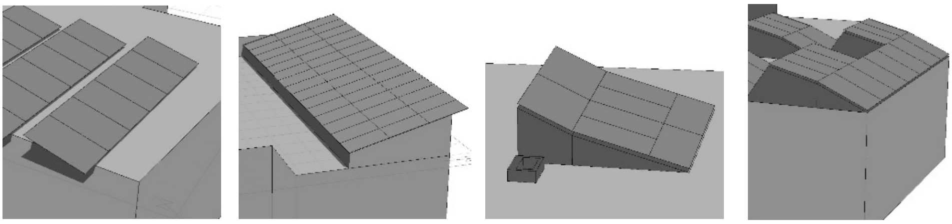
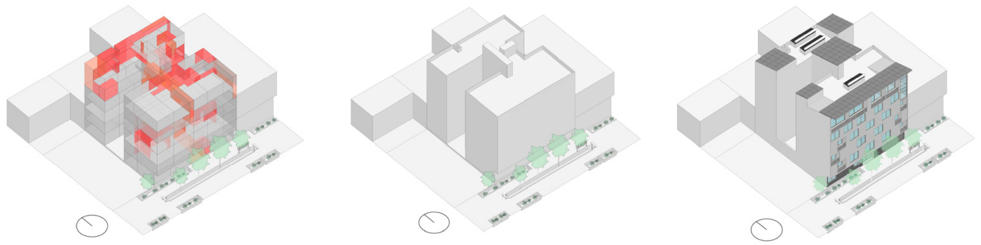

(a) (b) (c) (d)

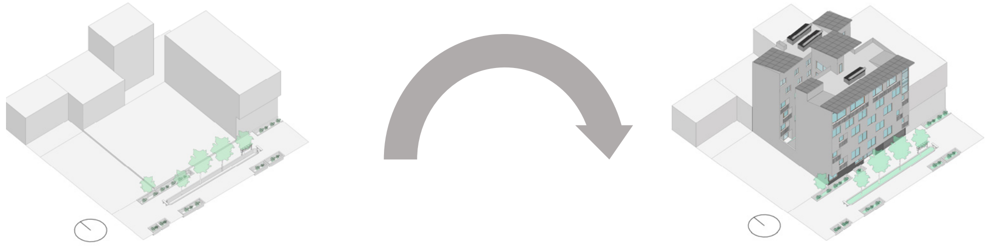
Figure 1: Different types to integrate solar panels in roof in students’ projects. (a) Simple PV integration on flat roof; (b) PV on inclined roof; (c) Concave joint thermal-PV; and (d) Convex joint PV-thermal.



2. Organization. ‘Served and servant’ concept in a 3D puzzle. Early passive energy considerations.

3. Volumetric idea. Courtyards and ducts create voids for ventilations and daylighting.

4. PV integration. PV integration using rooftop areas and façade design.



1. Site analysis. Selection of plot, site analysis and proposals for urban sustainable improving.

5. Optimization. A rotating movement in geometry to approximate north orientation.

Figure 2: Process for PV integration in students’ projects.

is carried out by means of a three-dimensional puzzle with ‘served and servant space’ concepts. This allows decisions about: views to the street, rear and side courtyards for natural lighting and ventilation; integrating a basic passive energy efficiency according to the climate of Lima and the type of building. So, a first volumetric idea of the building appears. Volumetric idea is developed at interior spaces by mean plans and sections, where other design competences are necessary to be completed. Subsequently, the PV integration is made on the roofs, making the best possible use of the existing orientation and geometry. The suggested tilt angle is 15° for PV panels and, in the most part of projects, 30° for thermal panels. Arrays must try to take advantage of orientations within the NW, N, NE ranges into usual multi-storey building, exploring geometry interactions and solutions. This PV integration on the roof is associated with the design of the façade, which must be adjusted and set with the solar idea. Different interactions, like the distance between arrays to avoid shading, affordable cleaning, roofs overhangs, and relationship with the facades, among others, need to be considered. As fixed systems, special attention was considered to reduce the shadings between the PV arrays themselves and the adjacent elements (machine-rooms, parapets, ventilation ducts, etc.). Finally, during the last phase, a smooth rotating movement for a part of the volumetric configuration is required to optimize some arrays to the north.

4.3 Data process

4.3.1 Project data

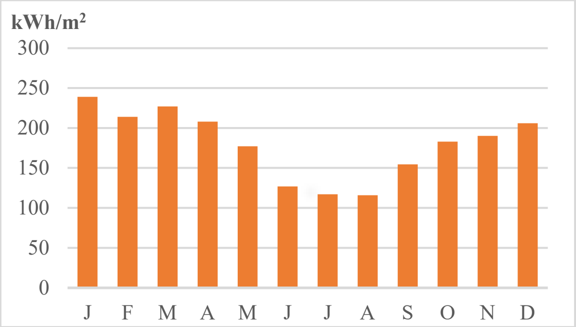
The 65 students’ projects were collected from 2019 to 2023 semesters according to the available data to simulation process. Different 3D models of six storey buildings were reviewed and compared with available digital plans, poster presentation and student's digital portfolios. Semesters and the respective number of projects are follows: 2019-II (18), 2020-I (13), 2020-II (7), 2021-I (5), 2021-II (2), 2022-I (7), 2022-II (11), 2023-I (2). Spreadsheets were organized for the accountancy of data. Population has been counted based on the number of rooms per apartment. For the stores, counting considered the area and the maximum capacity per square meter (2.8 m^2/person) set at local regulations. Different PV arrays were revised and registered.

4.3.2 Simulation parameters

The climate file of Lima was extracted from a free climate data repository for building simulation with 2004–2018 information. Compared with other files, this one had an average performance, with a total annual solar incidence up to 2,157.591 kWh/m^2 in the global horizontal plane (Gh), as 100% of possible radiation as shown in Table 1. The different project models were simplified like roof areas to reduce the simulation time process but conserving the volumetric configuration and geometry elements. All models were orientated at different angles according to every project. The obtained data in every array was: 1) total annual solar incidence, 2) annual solar incidence obtained per m^2, and 3) the percentage of shadows. Additions and averages were used to stablished overall relations. For cumulative incidence in every project, all results on arrays areas were accumulated. For solar incidence by square meter and shade percentage, data was counted as averages.

Table 1: Solar energy database for Lima (−12° latitude, −77° longitude). TMYx 2004–2018. *(Source: www.onebuilding.com, 2023.)*

Month	**kWh/m^2**	**%**
Jan	238.952	11.07
Feb	213.968	9.92
March	226.850	10.51
April	208.008	9.64
May	177.008	8.20
June	126.730	5.87
July	117.080	5.43
August	115.716	5.36
September	154.420	7.16
October	182.923	8.48
November	190.049	8.81
December	205.887	9.54
Total	2,157.591	**100.00**



5 RESULTS

5.1 Social coverage and solar architectural capacity

As Table 2 shows, the properties include the houses and stores achieved in all the students' projects, creating up to around 1,157 properties, considering 4,339 permanent residents in 1,037 dwellings and at least 2,747 sporadic users in 120 stores. The average available roof surface is 351.02 m^2 (100%). While the average of additional projected surface: 8.93 m^2 consists in the areas created by the overhangs, cantilevered PV panels over the street or courtyards, and even on the same roof, representing a 2.54% addition to the roof area average

(35 projects used it). Finally, it had been possible to create a PV average surface up to 154.55 m^2 occupying 41.49% of rooftop area average. The rest roof area is destined to separation of arrays and technical installations. About the PV area per property (dwellings and stores), an average of 8.77 m^2 per property was reached, with minimum and maximum values up to 2.04 m^2 per property and 15.69 m^2 per property, respectively.

Table 2: Capacity obtained from the overall student's projects.

Social coverage					**Solar architectural capacity**			
Properties	No. of houses	Residents	Stores	Users	Roof surface (m^2)	Additional projected surface (m^2)	Average PV surface (m^2)	Ranges
1,157	1,037	4,339	120	2,747	171.05	1.19	44.18	Minimum
					351.02	8.93	154.55	Average
					778.00	81.50	470.00	Maximum

5.2 Solar incidence: PV surface, cumulated, average and shade effects

Tolerances for incidence losses are lower in tropical zones than those allowed for temperate zones [26]. As an example, in the case of establishing a single loss limit percentage for the whole Colombia, researches recommended this should be up to 16% while in Spain the CTE set it at 20% [26]. Simulations in every PV array in every student project are in Table 3.

Table 3: Solar incidence in students projects.

Description	**Cumulated annual incidence (W/h)**	**Incidence (Wh/m^2/year)**	**Incidence (%)**	**Avg. shade (%)**
Gh radiation		2,157,591.00	100.00	
Minimum	76,883,399	1,480,974.36	68.64	0.0027
Average	269,100,662	1,732,890.32	80.38	0.0322
Maximum	816,595,964	1,782,068.25	82.60	0.1748

Cumulated annual incidence has a large difference between minimum and maximum values, in contrast with the solar incidence per m^2. Cumulated annual incidence depends on roof and PV surfaces, while, the incidence per meter square depends on azimuth, tilt angles, and shades which are well considering in projects. Most part of projects reduce the shadows arriving to an average up to 3.22%, but some cases could be up to 17.48%. Tilt angles average is 15.09° with minimum and maximum values up to 10.78° and 20.00°, respectively.

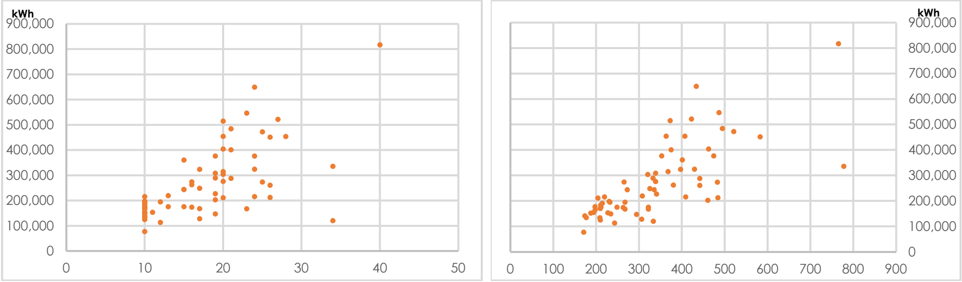
In Table 4, seven selected projects with similar values to the averages demonstrate that it is possibly a range of five to three panels per property (if considering 2 m^2 by PV panel). The project closer to roof surface average obtains a good percentage of incidence by PV/m^2, even with variable azimuth. The project proximate to PV surface average coincide with the cumulated annual incidence average, a good incidence per m^2 and very variable percentage of shadow average. The project closer to the incidence per m^2 average coincidence with N orientation and higher number of panels (5.5). The project closer to average shade percentage obtain a good incidence per m^2 and use NNW orientation with a high number of PV (5).

Table 4: Projects results closer to general average values (*).

Projects	m^2pv/ Prop.	No of prop.	No. of houses	Roof surface (m^2)	PV surface (m^2)	Azimuth angle		Annual incidence (W/h)	Avg. Wh/m2/y (%)	Avg. shade (%)
Average	**8.77**	**17.8**	**18.95**	**351.02**	**154.55**			**269,100,662**	**80.55**	**0.0322**
Project 1	(*)8.85	10	9	320.50	172.07	36.7		154,495,997	80.91	0.0388
Project 2	(*)8.85	19	18	332.80	168.13	+20.7	+17.9	289,089,630	79.63	0.0350
Project 3	9.26	19	16	(*)353.21	175.91	+12	+10.2	297,354,698	81.03	0.0172
Project 4	6.24	25	21	483.00	(*)156.00	+51.7	+34.5	(*)272,961,170	81.10	0.0027
Project 5	9.75	16	15	265.26	(*)156.00	−48.3	−52.3	273,731,354	81.09	0.0675
Project 6	11.20	10	9	232.44	112.00	+ 4		194,653,036	(*) 80.55	0.0238
Project 7	10.82	17	16	397.11	183.99	−27.93		323,254,216	81.01	(*)0.0324

5.3 Correlations between solar incidence considering the number of properties and rooftop areas

The correlation between solar incidence and the quantity of properties is 0.66, a positive value, and represents a good performance. But, a tendency is noted to reduce the solar incidence when projects involve more properties due to less available rooftop area and its efficient occupation. Projects were developed without pression for most PV arrays, only a strong awareness to obtain a visible capacity in rooftops, searching for orientations to the north, as recommended. While the correlation between solar incidence and rooftop area is 0.73, a positive value, that note an adequate relation according to the obtained rooftop area in students' projects. A slightly tendency to loss of incidence is related to more available rooftop area where other aspects like shading effects have more influence. Other installation elements at roof must be managed to have a better area for PV arrays. Fig. 3 shows a comparison centred in the cumulated solar incidence.

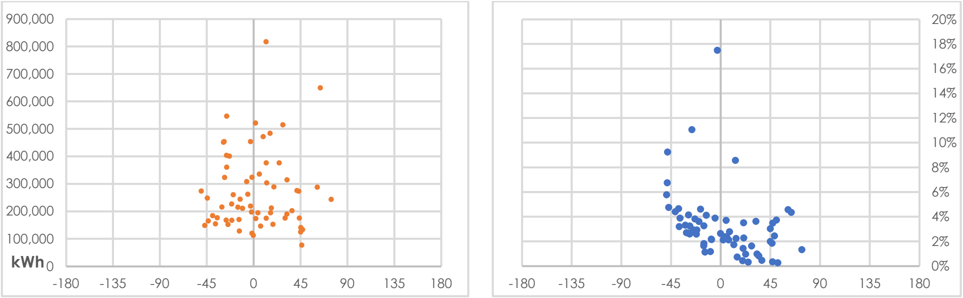


(a) (b)

Figure 3: Comparison of cumulated solar incidence considering the number of properties (a) and rooftop area (m^2) (b).

5.4 Correlations between azimuth angles considering solar incidence and shade average

According to Fig. 4, lower axis indicates azimuth angles: being 0 the N orientation, −45 is NW and +45 is NE. Knowing the degree of difficulty in achieving the exact north in all



(a) (b)

Figure 4: Azimuth angles from the north orientation considering solar incidence (a) and shade average (b).

projects, students had a degree of flexibility in orientation angles. Tendency to NW orientation have a few better results. Orientations from NW to NE were allowed, however exceeding these limits reduce the incidence. These inadequate decisions could only be compensated by a larger area for PV arrays. There are tendencies to create more shade effects in arrays oriented to NW rather than NE, but in both situations the percentage of shadows increase when angles overpass the limits of ±45°. However, some arrays oriented to N orientation could have more values of shading effects, due to few separations of arrays or possible to no-controlled geometry at rooftop. The most part of the student's projects creates a low average percentage situated near to 4%.

5.5 Correlation between solar incidence and percentage of incidence

According to Fig. 5, the most part of the projects reached values above the 80% of solar incidence, while just 11 projects were under this threshold, and 10 of them do not separate more than 74.96%. Even with an open range of azimuth angles, it has been possible to achieve this performance in solar incidence. Apparently, solar path and solar radiation behaviour define this condition, as well as the design decisions face to technical obstructions at roof areas. It can be noted the necessity to obtain more orientations to north and reduce the shading effects, separating the PV arrays between themselves and other solar obstructions.

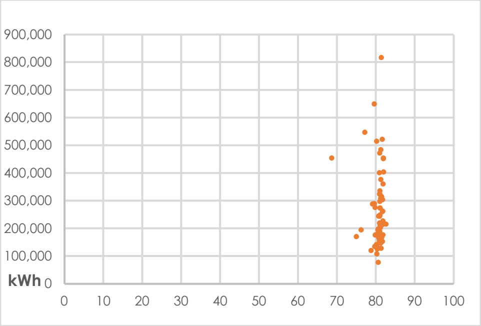


Figure 5: Solar incidence and percentage of incidence.

6 DISCUSIONS

The social coverage results inform about the range of possible people to benefit with this type of massive projects, very helpfully in case of stablishing urban parameters for a solar district or an eco-village in Lima. Building mixture and density have been considered to demonstrate feasible sustainable urban communities with a large range of sustainable aspects, including PV solar systems. The solar architectural capacity results indicate the use of an average up to 41.49% of rooftop area for PV systems, providing an optimal number of panels for each property. If the average of a conventional PV panel area is 2 m^2, a good distribution of panels could satisfy all residents and users by means of the obtained average of 8.79 m^2 (four panels per property). PV rail systems could offer additional surface by using cantilevered areas, or projecting panels, making it possible to obtain more incidence surface on and out the roof during design stage. Urban regulation, and even more, architects and owners could take these parameters to design PV systems in conventional and existing buildings with similar characteristics. Possible voltage drop caused by long distances from panels to properties need to be reviewed in further research, but in any case, building height (six floors) must be considered at least 16 m from rooftop to the first level; and the distribution of arrays areas at rooftop could be strategically planned to reduce this problem. More energy losses can be expected at lower levels (entrance, first and second level).

In average terms, 4/5 of the incidence (80.55% = 1,737,890.32 Wh/m^2) can be profited using 41.49% of the rooftop area, adapting the conventional six-storey family building typology. In Peru, there are not thresholds for percentage for PV solar incidence gains or losses, but in this case study about Lima conditions, it was possible to stablish a maximum average solar incidence up to 82.60%, a result between Spanish CTE (80%) and studies on Colombia (84%). Translating this solar energy incidence to possible energy source of electricity production by means of different types of PV connection (on/off grid), with different electricity exchange tariffs (net-billing, net-metering, self-consumption, etc.) could be reviewed also in further research.

Most part of azimuth angles are oriented within the range of −45° (NW) and +45° (NE) as recommended, however, the extreme range reached in projects is more open (−49° and +75°) but their incidence remains close to the average because of the vertical solar path behaviour, helping to reduce the loss effect on the not recommended orientations. Azimuth angles are the most difficult to manage for student designs, because the diversity of plots orientations and architectural configuration must be aligned with the edges of the plots. Apparently, to reduce the shade effect, azimuths angles between NNW and NNE (−22.5° and +22.5°) are recommendable but, anyway, separation and distances between arrays are very important even if north orientation is achieved as correlation analysis suggests. Separation of arrays and control of rooftop geometries (water tanks, machine rooms, ventilation ducts, etc.) from design stage are very important. On the other hand, tilt angles were more accepted, understood, and assumed since the beginning in most part of projects.

7 CONCLUSIONS

On a theoretical level, it is possible to achieve an effective AIPV in conventional multi-family housing projects in Lima with an optimal solar incidence through various volumetric configurations into the greatest variety of urban orientations. Ideal orientation conditions to collect solar incidence do not exist in urban environment; but it is possible to profit from the most part of it by means of an AIPV criterion to facilitate adaptation and mitigation scenarios to tackle climate change. The performances of social coverage and solar architectural capacity of this type of projects also demonstrate the versatility of PV energy use to be planned from the design stage and inform about the advantages of favouring the expected implementation of the current law of distributed generation in Peru.

In the case of Lima, and considering the solar path, the use of roofs allows a considerable solar incidence without rigid orientation parameters, granting to AIPV great opportunities and tolerable ranges of azimuth angles between NE, N and NW for the PV arrays. In this type of six-storey multi-family building, it is not necessary to occupy the entire roof area, but at least 41.49% of it, or slightly more, to ensure all owners have access to PV energy by means of a specific number of panels per property (between five and three panels, a possible architectural indicator in residential photovoltaic projects). The spacing of the arrays and the control of geometrical elements on the roof as well as azimuth angles between NNW and NNE are essential to obtain the highest solar incidence. Taking into account that in Peru there are no indicators of minimum solar incidence, in contrast to more evolved regulations, this measurement is a contribution to the case of Lima and similar regions of the Peruvian coast because, in the simulated projects, the solar incidence can reach an average of 80.55% of the global horizontal radiation (Gh) and, in the best case, 82.60% considering the wide range of orientations already mentioned.

On a practical level, the original learning method applied to achieve AIPV in students' projects, considers varied design phases, and introduces the solar energy at the intermediate phase, taking into account other important architectural design factors for a comprehensive result. This educational process addresses solar energy in conjunction with other multiple architectural problems to be solved before (internal organization, views, access, etc.) and after (façade). From an energy point of view, this integration should be focused mainly on improving the solar incidence than other technical problems, which can be studied later in their career (with more technical knowledge achieved by students, or with the assistance of experts). For the early stages of architectural learning process, it is possible to explore the design criteria of active solar energy, but focusing on geometry aspects (azimuth, tilt angle, and shading effects) assuming that for the architectural practice and learning, the quantity of panels and the quality of solar incidence could be the main targets to be taken into account.

Finally, the measurements in student projects demonstrate a great potential to reach a large part of the solar incidence at this latitude and validates the teaching process to introduce AIPV in architectural training. Other related aspects, such as energy generation options, problems related to energy losses and voltage drop by distance, electricity prices and payback surveys related to diverse type of PV systems can be studied in further research.

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