

DIMENSIONAL AND ENERGY RATIOS IN PHOTOVOLTAIC PANELS: SECTIONAL STUDY IN THE LIMA MARKET (2024)

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Abstract:

When dimensioning photovoltaic systems, the accuracy and efficiency of the complete system are usually sought. The system's overall performance and efficiency are typically assessed by taking into account energy demand, solar irradiation, and the technological characteristics of its various components. However, for owners, architects, and builders, the geometrical magnitudes of the panels (length, width, and the resulting area they will occupy) are decisive in the estimation and architectural design phase, during which the energy demand may not have been defined, but the aim is to include the PV system in the building's design. The objective of the study is to determine existing ranges and correlations between power and solar panel area as a reference point for the architectural design phase, providing a basis for considering photovoltaic systems based on the available roof area. To this end, technical information was collected on the different types of panels offered in Lima city, complemented by surveys of dealers and installers, taking into account the main brands and models on offer. Using technical data sheets linked to the panels, correlations between available geometric dimensions, power ranges and possible efficiencies per panel are sought. In this way, there is a wide range of geometric dimensions, however, the 1.50m² threshold divides two groups of panels, one with lower efficiency which tends to generate less energy and the second group with more efficient panels and a larger format. Similarly, the width is a dimension that shows little variation, with comparable measurements and similarities observed across different brands and panel capacities. Other related aspects such as frame thickness, reliability and warranty of the panels could be studied in further research, as well as estimation for projects with the potential to include PV installations at the available roof area in the design phase.

Keywords: BAPV, BIPV, AIPV, PV modules, PV sizing, PV optimization, architectural design

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INTRODUCTION

Harnessing the sun's energy, photovoltaic (PV) is one of the most promising renewable energy technologies (Budhiyant *et al.*, 2017). Globally, roof-mounted solar panels have been widely used to cover energy needs, either for stand-alone use (off-grid) or connected to a large grid system (on-grid). (Rumokoy *et al.*, 2022), and the underutilized rooftop space could be appropriated for the installation of solar photovoltaic (PV) systems for retrofitting in several types of buildings (Grossman *et al.*, 2016). Usually, the choice of a solar panel depends on several factors, mainly those related to technical and electrical considerations, trying to achieve an ideal composition for efficient energy production and increased cost-effectiveness, as well as on the availability of brands and power ratings on the market. However, estimates are required based on other aspects, such as the space required in relation to the geometric dimensions of the panel and arrays to facilitate decision-makers (users and architects or designers) in the initial process.

In this context, the Peruvian market is highly variable, and the availability of panels is diverse and temporary. Understanding the size of solar panels is a common concern among homeowners looking to harness solar energy, whether exploring for the first time or looking to upgrade an existing PV system (Brennan, 2024). Faced with two-panel options with different sizes, an important decision factor is the amount of space available on the ceiling of a building. One or the other will be preferred depending on which one best suits the space available for installation and leaves less unused space on the ceiling (Lo & Antonio, 2010). On the other hand, in some cases rooftop surfaces may be irrelevant if the spaces are ultimately used for other purposes, so in reality, the number of solar panels that fit on rooftops may be smaller due to their established dimensions (Liew, 2021).

Geometric dimensions in PV panels

Photovoltaic panels must be considered as an element of the architectural composition and part of the building design. To achieve this, the designer must integrate it into the design of a façade, roof and envelope, while preserving its specific formal or functional characteristics (Ouahiba, 2024). There is a wide variety of geometric formats of solar panels (Fig. 1). In all technical data sheets, the geometrical dimensions are included in the mechanical characteristics, which will determine the physical format of the panel (length and width). The dimensions of a PV panel have a significant influence on its energy production, and its formats are crucial for the planning of the buildings or areas to be installed. Although larger PV formats can capture more sunlight, the increased efficiency can be offset by shading and installation space limitations, among others.

These tend to produce more energy due to the larger surface area absorbing sunlight (Okello, 2024); but the efficiency of energy production can vary depending on the size of the panels. Larger panels may appear advantageous; however, they can lead to inefficiencies in confined spaces due to shading problems due to proximity to obstructions and cumbersome handling due to weight, highlighting the need for careful consideration of both size and electrical design in PV systems.

Several technologies aim to create more efficient cells. Innovative designs, such as those using light reflection methodologies, suggest that smaller panels can achieve higher efficiencies by improving light capture through reflective materials (Nayak *et al.*, 2023); however, most data sheets for smaller panels do not specify module efficiency. More advanced research tries optimizing the surface with experimental cell area using flexible forms (such as soft pyramidal protrusions) that could increase energy absorption by more than 20%, although shading problems caused by the texture itself must be avoided. (Okello, 2024). In any case, experimental technologies will take time to improve efficiencies for the global market.



Fig. 1 Size variability of PV panels in a shop on Paruro Street, Lima's most known PV retail center. Photo: Valdivia-Sisniegas 2024

Factors influencing PV panel sizes

The first factor is in manufacturing, where there are many models with different sizes, depending on their capacity and manufacturing technology. This is considered a disadvantage for planning and diversifying the dimensioning options. For the same dimension, there are different powers, which are determined by the size and capacity of the cells that make up the panel. In addition, the power of the panel and the technology (polycrystalline, monocrystalline, thin-film, etc.) play a fundamental role. Technological advances have been known to produce increasingly efficient panels in recent years, producing more energy in smaller areas.

A second factor is the choice of panel size for a PV installation, defined by energy sizing and encompasses aspects such as consumption profile, energy storage, system costs, and location. It has been found that traditional system sizing methods usually prioritize economic benefits (da Rocha *et al.*, 2022), leading to smaller systems trying to be conservative for quick payback; while other considerations such as inflation rate, hourly irradiance, temperature and energy demand are considered uncertain parameters associated with economic and environmental factors (Attia *et al.*, 2023).

There are barriers that architects face during the design and construction of buildings with PV systems, such as the complexity and uncertainty in estimating PV performance based on available areas. Decision tools were proposed more than a decade ago to guide professionals in the sizing of PV systems during the early design phases by trying to approximate the accuracy of specific parameters through software that allows the user to evaluate the electrical output of different PV system configurations, as well as their physical impact on the building envelope (Attia & De Herde, 2010). But most part of the PV software are designed according to specific databases or for each location at the solar radiation, panel types, and therefore always requires information available on the market, which is constantly evolving. In particular, understandable architectural design parameters such as mounting system, tilt, orientation angles and panel areas are required, and more technical considerations such as the efficiency of storage systems or cost-benefit are the subject of specialized calculations.

In this sense, online software has helped to provide information on radiation incidence according to the tilt and azimuth angles proposed; however, the relation between powers and areas is too relative to complete the adequate information for building envelope planning.

PV installations in Perú for multifamily buildings.

Urban surfaces, such as rooftops, offer significant potential for solar energy integration, contributing to energy efficiency and sustainability in cities (Gholami, 2024). To be sustainable, the compact cities, requires

multi-family housing to provide density. Therefore, more sustainable versions of this housing type are sought (Valdivia-Sisniegas *et al.*, 2024), and the higher density of cities can bring efficiency gains (Sharifi & Lehmann, 2015). Distributed energy generation contributes to more efficient electricity production on-site, with lower losses and payback possibilities for building or flat owners. Therefore, it is very relevant to introduce distributed energy generation for a faster energy transition in compact cities, as both the urban fact with adequate densities and the energy transition to renewable sources consolidate the reduction of emissions directly and indirectly.

In urban areas of Peru, users and builders can voluntarily opt for PV systems for small-scale energy installations; and there are few opportunities to require them from the project phase. The option of these systems is advancing slowly with the installation of on-grid systems in multi-family buildings in Lima as a requirement for the MiVivienda Sostenible (Ministerio de Vivienda Construcción y Saneamiento, 2024); a housing subsidy that is granted as a percentage up to 3% or 4% discount from the value of the financing cost for the purchase of sustainable housing in a certified project. In these projects the PV systems could be installed, but only for an electrical contribution to 50% of consumption in common areas (hallway lighting, among others), and with the obligatory need to use blockers to avoid electricity insertion into the public grid due to the absence of regulations on Distributed Energy Law. (Ley 28832 - Ley de Generación Eficiente, 2006). Despite the changes in the overall regulation for its application (Decreto Legislativo 1221, 2015), and the draft to establish the official regulation code (Ministerio de Energía y Minas, 2018), this has still been postponed.

Studies on MiVivienda Sostenible social housing projects have identified the need to incorporate solar energy since the feasibility study phase (Santos Marrufo, 2023), related to the area in the roof plant occupied by PV panels, because roof terraces can be used for private or communal services, and builders try to optimize this space to profit, but also the design and construction phase. It is necessary to provide information on the geometric dimensions that address the production of solar panels from an architectural design perspective in the conception phase. As one of the main qualities understood by customers, architects and builders, the existing area is key for decision-makers in the choice for solar installation and implies the final aesthetic integration to fit the photovoltaic area in the building.

The article aims to show the results of a sectional study in the year 2024 on the availability of photovoltaic panel dimensions on the market in the city of Lima in terms of geometric dimensions (length, width and area), as well as size ranges according to the existing powers. It also intends to determine the

advantages and disadvantages of some choices and their influence on calculation methods based on the available space. Dimensioning by available space refers to the process of measuring and evaluating the space available to determine how many solar panels can be installed (Sykes, 2024; Cao, 2024). This information could allow architects to estimate possible PV areas to promote volumetric and spatial integration according to certain powers, which can be precisely defined with specialized help later.

STATE OF THE ART

The size of PV panels

Usually, the idea of the size of an installation tends toward the dimensioning of the PV system related to the coverage of the energy demand. A search focused on the geometrical dimensions of PV panels in manufacturers' websites results in a wide scale of information according to the country. The size influences their performance as well as their energy production; and their geometric dimensions depend on their factory production, the manufacturing technology (monocrystalline, polycrystalline or thin film) and, finally, depending on the use and place where they will be used (generation, industrial, commercial or residential sector). For example, in Spain, the average size of a solar panel is 1.9 m²; however, the standard size of a solar panel is usually 1.7 m × 1.00 m (Alba Solar, 2022). Thus, Table 1 shows reference formats that exceed the possible standards introduced in the post-pandemic market.

In manufacturing, the dimensions and the number of cells in a panel determine its size. The most common panels are 60 cells (usually for the residential sector) and 72 cells (usually for the commercial sector) (Almerini & Lane, 2023). However, this is changing with the introduction of larger formats of 132 or 156 cells. **Figure 2** shows the relationship between the reference dimensions in the European case, the number of cells that make up the solar panel and the power achieved.

Panel efficiency is also an important characteristic linked to the area. Studies with different power ratings (340 W to 540 W) showed significant differences in on-grid energy production despite similar efficiencies (Tamoor *et al.*, 2022). Technology plays an

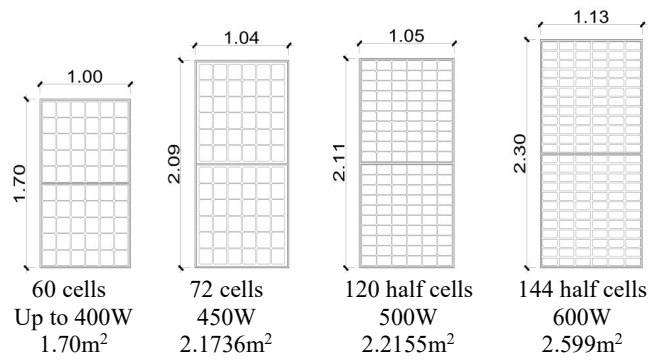


Fig. 2 Reference dimensions of panels as a function of the number of cells. Source: (Sunfields Europe, 2024)

important role, as monocrystalline panels tend to be somewhat larger, because they have gaps between the solar cells, whereas polycrystalline panels do not have such a gap. However, a typical monocrystalline panel can achieve 20-23% efficiency and generate 300-550 W or more, while polycrystalline panels only achieve up to 15-17% efficiency and produce 300-400 watts of power; while thin-film panels are lightweight and flexible, and although they offer the lowest efficiency of the three (6-15%), they are ideal for some installations where the roof or deck cannot support the larger, heavier panels (Lee, 2024).

In terms of their use, they tend to be the largest in generation plants or solar farms, as they have a lot of space and specific structures anchored to the ground. Those for commercial and industrial use tend to be large, mainly because the roof spaces are wide and without many loads, so these kinds of roofs can accommodate large panels in larger quantities (Sykes, 2024). In residential buildings, PV intermediate formats are required as the roof structure can support limited loads and facilitate the installation work. In the United States, the most commonly used solar panels in residential buildings are those between 250 and 400 W or between 150 and 370 W (SunPower, n.d.), although some of them are larger than 400 W with an average of 320 W (Airis Solutions, n.d.). In the UK, ranges are between 250 and 450W for residences with average dimensions of 1.89×1.00m, while for commercial PV installations, these are typically between 400 and 600W with average dimensions of 1.95 x 0.99m (Maza, 2024).

There is a trend towards larger solar modules, but indirect factors are not considered, which could have an impact on the final purchase price, transport and installation manoeuvres and their profitability in the medium and long term. According to experts, the panels with the best power/cost ratio are those with sizes smaller than 2.1m², highlighting the reduction of weight on the building structure and minimizing installation risks. According to **Fig. 3**, comparisons have also been made in similar areas of 10x10m installations grouping 50 panels (2×1m) of 450Wp each, which can achieve 22,500Wp, while a similar installation of 36 panels

Table 1. Reference dimensions for some large solar panel sizes.

Power	Large (m)	Width (m)	Depth (m)	Area (m ²)
400W	1.755	1.038	0.035	1.8217
450 W	2.094	1.038	0.035	2.1736
500 W	2.108	1.048	0.400	2.2092
550 W	2.256	1.133	0.400	2.556
600 W	2.304	1.134	0.400	2.6127
700 W	2.489	1.303	0.400	3.2432

Source: Alonso (2024).

(2.3x1.1) of 535Wp each can achieve up to 19,260Wp (Enchufe solar, 2021). It must be noted that, if the best final power/price ratio is sought, it is advisable to opt for medium-sized panels since, for the same surface area, an installation with smaller solar panels can produce more energy than with larger panels, reducing the weight during the installation; and minimizing the risks of the installation. On the other hand, for the case showed larger PV panels reduce the total PV solar area, which is very useful if the discounted area is required for different purposes in the project. It must be noted that these dimensional studies come from commercial websites and informative virtual blogs, constituting a pending level of a more in-depth analysis of various brands, dimensions, powers and efficiencies.

PV panels averages and energy features

The technological evolution of crystalline silicon cells has led to the introduction of larger formats, allowing the production of modules with power ratings of over 600 W (Chen *et al.*, 2022), indicating a trend towards larger and more efficient panels. As Table 2 shows, for equal dimensions, there are different power and efficiency ranges.

Panel: 450Wp (2mx1m)	Panel: 535Wp (2.3mx1.1m)
N° panels: 50	N° panels: 36
Power output: 22,500Wp	Power output: 19,260Wp
Area: 100%	Area: 91.08%
% Production: 100%	% Production: 85.6%

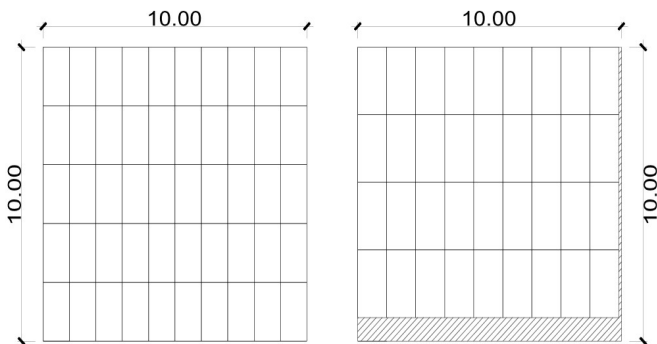


Fig. 3 Comparison of two similar areas with different panel types and the possible power to be produced (Enchufe solar, 2021). The reduction of production is higher than the reduction of area.

Table 2. Some larger panel dimensions and averages benchmark range for commercial and residential buildings.

Types	Energy features		Geometric features		
	Power (W)	Efficiency (%)	Large (m)	Width (m)	Area (m ²)
a.132/156 celd.	560-680		2.400	1.300	3.120
a.132/156 celd.	350-560		2.300	1.100	2.530
a.72/144 celd.	350 - 490		2.000	1.000	2.000
b.Rang. Com.	400 - 600	20.00 – 22.10	1.950	0.990	1.930
b. Average	320	16.50 – 20.30	1.755	1.039	1.823
b.Rang. Res.	250 - 450	15.34 – 20.70	1.890	1.000	1.890
a.60/120 celdas	285 - 400		1.70	1.00	1.700
b.Low. Res.	150	15.00 – 17.64	1.460	0.660	0.963

Source: a) Standard panel dimensions according to the number of cells. (Enchufe solar, 2021). b) Standard PV panel dimensions depending on the intended use. (Maza, 2024) with efficiencies taken from technical data sheets.

At the 2020 SNEC PV Power Expo in Shanghai, JA Solar presented a 785-810W panel, Tongwei brand presented a 760-780W panel, and Trina brand presented a 650-670W panel (Shaw, 2020) At the 2020 SNEC PV Power Expo in Shanghai, JA Solar presented a 785-810W panel, Tongwei brand presented a 760-780W panel, and Trina brand presented a 650-670W panel, whose dimensions appear in Table 3. However, weight and manoeuvrability may complicate their installation and structural compatibility in residential buildings, so they are mostly intended for power plants, solar farms or industries. In the case of the Tongwei and Sungi panels, the geometric characteristics can vary significantly for the same power range. The dimension information for Peru corresponds to monocrystalline solar panels (AutoSolar Perú, n.d.), estimating an average of 2.38 m², and it can be seen that between the maximum values found in Peru and the largest formats at the international level, the width increases the most.

Efficiency is the percentage of light hitting the surface of a panel converted into usable electricity. Module efficiency also plays an important role. Higher-efficiency panels may require less space to produce the same amount of energy as lower-efficiency panels; meanwhile, some large panels could have lower efficiency. The current efficiency ranges of solar panels are from 17% to 22.8% for some *premium* models. (Almerini & Lane, 2023). The new generation of monocrystalline panels is 5% more efficient than the previous one; and according to the time of manufacture, there is no significant difference in size between 400 W and 500 W panels, as the power output of the solar panel depends on the materials and their efficiency (Lee, 2024).

Studies related to the size of PV panels

There are various methods for sizing solar systems. In most part of them, the demand for energy consumption prevails in conventional calculation methods associated with future or existing consumption (Sizing by power). Other option starts from the consumption indicated in

Table 3. Largest panel sizes: worldwide and average reference ranges in Peru

Commercial brands	Energy features		Geometric features		
	Power (W)	Efficiency (%)	Large (m)	Width (m)	Area (m ²)
a) JA Solar	785 - 810	20.10 - 20.80	2.219	1.757	3.898
a) Tongwei	760 - 780	21.30 - 21.90	2.357	1.512	3.563
a) Sungi	760 - 780	22.26 - 22.84	2.620	1.303	3.414
a) Trina	650 - 670	20.90 - 21.60	2.384	1.303	3.106
b) Tensite	610	22.60	2.384	1.134	2.703
b) Tensite	550	21.00	2.279	1.134	2.584
b) JA Solar	530 -555	20.50 - 21.50	2.278	1.134	2.583
b) JA Solar	480-505	20.20 - 21.30	2.093	1.134	2.373
b) Tensite	460	21.00	2.094	1.038	2.173
b) JA Solar	455 - 470	20.00 – 21.20	2.112	1.052	2.221

Source: a) Larger formats worldwide (Bellini, 2020) with efficiencies extracted from data sheets; b) Benchmarking information in Peru to 2024 (AutoSolar Perú, n.d.) with efficiencies extracted from data sheets.

the electricity bill to determine the power of the photovoltaic system, either on-grid or off-grid (Sizing by energy substitution). It is not usual to find guides or tools for estimations focused on determining the final powering by conditions based on the possible area to use. Although relative and inaccurate estimations can be generated, it could help both architects and owners to estimate the possibilities of power output based on available rooftop space. The surface area of the panel is considered inside a group of miscellaneous factors with a role in affecting the performance of the system (Fouad *et al.*, 2017).

A research has determined the power of the PV system either on-grid or off-grid, has considered a range of PV panels between 125 W and 480 W in the Romanian market. (Mihaela, 2021). A study in Bangladesh has found that using different panel sizes (from 70W to 330W) and holding all constant parameters, the resulting outputs have a large variation, raising serious questions about selecting the right panel size to obtain the optimum output in any given location. (Sayem *et al.*, 2021).

An evaluation was carried out in Poland with six types of panels from leading European manufacturers about the sustainable production of photovoltaic panels in terms of quality-cost-environment performance. (Gawlik *et al.*, 2024) found that, on a scale of 0 to 1, efficiency is the crucial quality criterion (0.48) and dimensions in second place (0.16), followed by maximum voltage, power rating, degree of integration, colour and weight (0.10, 0.06, 0.05 and 0.03 respectively). 48) and dimensions in second place (0.16), followed by maximum voltage, power rating, degree of integration, colour and weight (0.10, 0.06, 0.05, 0.03, respectively), determining the need to consider efficiency as an element associated with geometrical dimensions.

Some methods for dimensioning a PV system are based on the available roof area, like the case of an installation for a beverage industry in Colégio Politécnico da UFSM in Santa Maria (Brazil), which demonstrates a sufficient area to meet almost all of its energy demand with a software (Siluk *et al.*, 2016). Other algorithms consider the available area as a crucial parameter for dimensioning PV systems in the case of distributed energy (Bouhouras *et al.*, 2012), and PV area panel can be part of multi-objective optimization model for sizing for grid-connected photovoltaic systems (Attia *et al.*, 2021).

The area of PV panels and consumption of dwellings

Few studies have focused on establishing ratios between panel area and the monthly or annual electricity consumption of dwellings or buildings. However, these are very needed to enlighten people who want to install PV systems without much knowledge about the subject. Moreover, architects and designers require local

knowledge; thus, more site-specific studies are required. In locations such as Gaza (Palestine), a photovoltaic surface of 5m² with an inclination angle of 30° can satisfy the basic needs of a family (Asfour, 2013), understanding that parameters such as consumption and power about the area of the panel also vary in time and cannot be the same for other locations. In the case of Peru, in 2018, there is diverse information, since the national average electricity consumption for houses was 93kWh/month and in urban areas, it reached 113kWh/month, Metropolitan Lima was the region that registered the highest level of electricity consumption in the country, reaching an average consumption of 135 kWh/month per dwelling (Osinermin, 2018), but more recently, during the pandemic, the average reached up to 172kWh/month per dwelling. (Osinermin, 2021).

However, this electricity demand differs greatly according to the type of dwelling, with higher consumption in single-family homes and lower consumption in flats. As there is no opportunity for grid feed-in due to the lack of regulation of the Distributed Energy Law, most sources propose installations with high consumption considering the safety factor for system self-sufficiency (at least 20% additional), which increases the load to give it reliability. Nevertheless, with distributed energy schemes, it would be possible to reduce the dimensions of installation, as the aim is not to be self-sufficient but to reduce electricity consumption to make savings. Commercial information has been found that proposes an installation to self-supply electricity to a two-storey single-family house, considering the minimum radiation, deducting a net panel area of 15.59m² (www.eiql.com.pe, 2023), for an estimated consumption of 339.59 kW.h/month, the safety factor is discounted. However, several bachelor's and master's theses consider different consumption. For example, in a proposal for a dwelling without electricity supply in Villa El Salvador district south of Lima (Villanueva Cubas, 2019), a net area of 42.68 m² is proposed, which would contribute only 329.41 kWh/month (47.02% of the demand for a final consumption of 700 kW.h/month). In terms of flats, PV panels are proposed for a multi-family dwelling with three flats on three floors, a PV net panel surface of 54.32 m² is calculated so that each flat corresponds to 18.10m² of panels for an estimated individual consumption of up to 181.04 kWh/month, which would include the consumption of common areas (Espinoza López & Portocarrero López, 2021).

In conclusion, currently, in the case of Lima, there is a very scattered and varied body of literature on the area ranges of solar panels, mainly from the commercial sector. The available information on commercial websites fulfils an orientation function because the area or surface has an evident magnitude for most of the population, making clear that there is a need for estimation tools for users and professionals indirectly

related. If such studies fill this gap, their usefulness can be improved by activities linked to phases such as conception, feasibility, and potential studies for architectural and constructive integration. Variable information is available, especially in the current circumstances of change, with the introduction of larger panel sizes. On the other hand, proposals for the inclusion of PV systems focus on the effectiveness and economic efficiency of off-grid or stand-alone systems, which increases costs and constitutes a barrier to energy transition.

METHOD

A sectional information gathering study was carried out (2024) to collect the dimensions of PV panels on the Lima market. Considering the variability of the solar panel market, this study was conducted to determine the trends and advantages and disadvantages of the supply of solar photovoltaic panel sizes. Knowing the Lima tropical latitude (-12°) where most of the radiation comes from the upper part of the celestial vault, the importance of considering the surface dimensions of panels is linked to their use in the space available on rooftops or roofs.

The first stage of the research starts with a virtual compilation of commercial brands and technical data sheets of the panels exhibited by local suppliers and marketers on the site web; compiling available technical information on the panels (power, length, width, and module efficiency).

In the second stage, surveys were delivered to marketers (suppliers or sellers) and installers to obtain more information about the technical characteristics related to panel sizes, the most used dimensions, and the sector of use, as well as opinions about the advantages and disadvantages related to panel size. The surveys were conducted in the best-known areas for buying and selling solar panels in Metropolitan Lima. Some providers respond to the same survey online.

The third stage consists of a dimensional study of the identified information, in which correlations between dimensions, areas, powers and efficiencies are established. This can be done with the help of online technical data sheets and those provided by the suppliers. Tables were created to graphically demonstrate the dimensional relationships. The aim is to provide an overview of the various geometric relationships associated with power, as well as considerations and recommendations for the photovoltaic panel market in the city of Lima.

RESULTS

Study of data sheets

A total of 33 commercial brands and 495 types of PV panels were reviewed using the online datasheet

collection, and information related to geometric dimensions (length and width) was used to calculate the area per type of panel. The nominal panel power and module efficiency were also reviewed.

Width to length ratios:

As shown in **Fig. 4**, the length-to-width correlation ratios of the available solar panels have the following specific characteristics:

- From 0.67m upwards, the widths of the panels have more constant dimensions, while the lengths have more variable dimensions.
- In the case of widths, up to three constant measurements can be made: 0.67 m, 0.992 m and 1.134 m.
- In the small format, a measurement of 0.67 m is more common for widths between 0.77 and 1.50 m.
- For large formats, frequent widths of 0.998 and 1.002m can be considered, with lengths ranging from 1.175 to 2.024 m.
- For the larger format, a width of 1.134 m was considered for panels with the longest length between 1.73 and 2.411 m.
- For the case of the lengths, similarity could only be determined in small formats, reaching 0.65 m, representing a measure of greater variety in the formats of the PV panels.
- In the case of smaller formats, the dimensions are much more variable, and there are no predominant values for width and length.

Panel area to nominal power ratios

According to **Fig. 5**, two main groups can be identified. The first group considers an area of up to 1,277 m², which covers lower powers from 5 to 200 W, and has a lower performance in terms of power and area. The second group exhibits performance improvement and comprises 1,675 m², which ranges from 250 W and higher wattages up to 600 W. There would be a range of 75 watts difference for the same type of area (formats between 250 and 315Wp), and then the range would increase to 100 watts when the panel area approaches

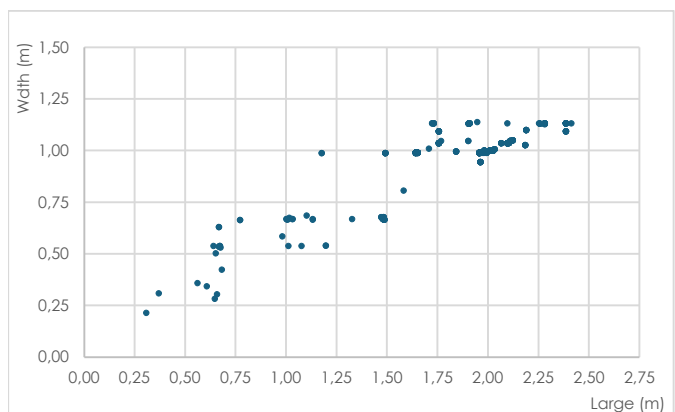


Fig. 4 Large and width correlations in pv panels

and borders 2m² (formats between 340 and 440Wp). For larger formats, the range of variation becomes narrower, such as those found for 2.174m² formats with a difference of 75 watts (420 and 495W), and very large formats with a difference of up to 40 watts (550 and 590W).

There are also two marked groups: Firstly, 1m² can range from 130 to 200 W, with this power maintained up to 1.5 m², which means a loss of efficiency in panels with this area (larger area for a similar power); while the second group considers a higher efficiency between area and power, from 1.627m² to 2.734m² at the maximum.

The results provide an overview of the variability in energy production per panel area, which is defined as the difference between the maximum and minimum possible power to obtain for a panel surface. This can help guide decision-making during the architectural design phase.

Panel area to module efficiency ratios

In the mid-20th century, a 1.7m² panel generated only 20W with an efficiency of 6%. By 2012, with the same area, a power of 200W was achieved, and its efficiency was around 15%; but as of 2015, 270W can be generated in the same area with an efficiency of 20% (Mártel, 2018).

The average value found in the investigated panels was 19.40%, and the most repeated value was 20.5%, reaching a maximum value of 23.17% and a minimum value of 9.92%. In panels smaller than 1 m², the efficiency module values range extensively, while from panels of 1.5 m² upwards, the amplitude decreases toward higher values and decreases further in panels larger than 2 m². As can be seen in **Fig. 6**, regarding the

relationship between panel areas and panel efficiency, it can be observed that there are intermediate and very large format panels with panel efficiencies between 15 and 22.90%.

Both the 1m² and 2m² thresholds show a large variability of efficiencies (from 13.67% to 19.75% for 1m², and from 16.90% to 22.30% for 2m²), which is an important factor to consider in panel selection and will create a wide range of power performances. However, for large formats greater than 2m² the efficiency should not currently be less than 20% or very close to this threshold. The panels with the lowest efficiency are generally those of small formats. These conditions result in better estimation accuracy when considering the available area.

Surveys conducted with marketers:

Nineteen commercial establishments (suppliers and sellers of modules) were interviewed, most of them belonging to one of Lima's most important retail centers, two importers, and two installers answered the survey virtually. Usually, the largest supply of solar panels is monocrystalline, with a decreasing supply of polycrystalline panels. This is because monocrystalline panels perform better in cloudy skies (coastline or bioclimatic zone 1 in EM.110 code), but their carbon footprint is higher due to manufacturing waste. In contrast, polycrystalline panels work better in warmer areas, such as deserts and highlands with few clouds (deserts or bioclimatic zone 2 in EM.110 code), and their production waste can be recycled. Respondents reported their preference for 28 solar panel brands.

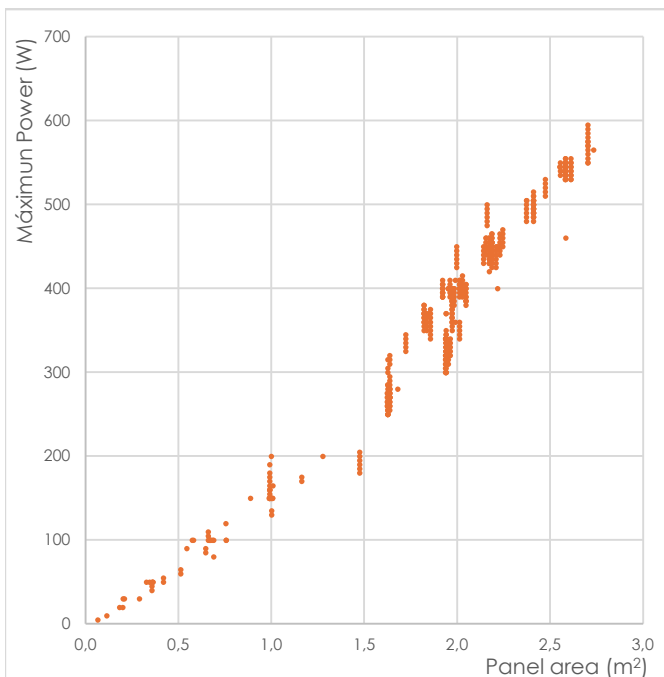


Fig. 5 Panel area and power correlation

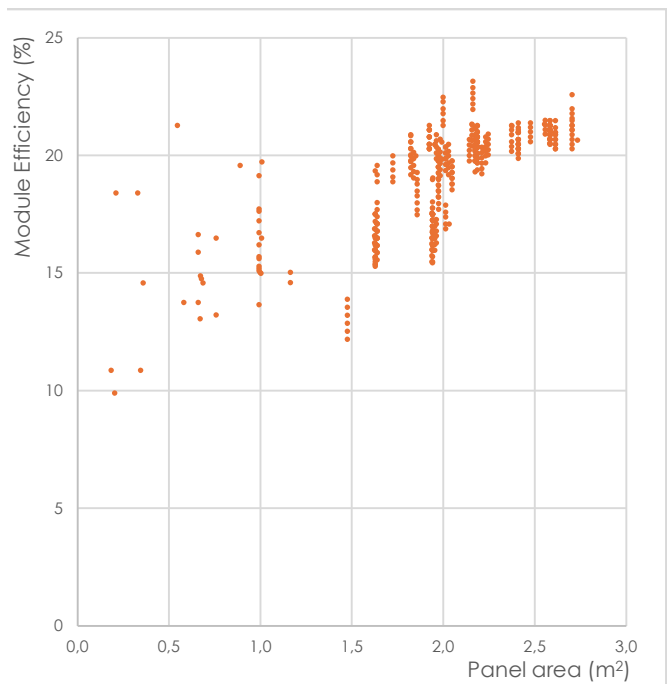


Fig. 6 Panel area and module efficiency correlation

About the contributions or benefits of large formats

- For importers: Benefits arise when seeking cost-effective installations of sizes that can accommodate the largest number of 66-cell panels, such as in off-grid PV installations and on specific structures anchored to the ground.
- For marketers: Larger sizes are more efficient and reduce installation space.
- For marketers: To bring more generation to customers.

About the disadvantages of large formats

- Inconvenience in roof assemblies' operations.
- The weight during mobilization is complicated.
- It occupies a larger area, which complicates handling.
- They are fragile to store.

About changes in storage due to larger formats

- Most respondents reported that this did not lead to changes in storage because it is planned from the beginning.
- One mentioned that sometimes there is no space.
- Two mentioned slight changes in storage.
- They require drives due to the electrical format.
- Larger panels involve loading and handling by two people.
- In the case of large panels, there are no standard dimensions; however, for medium size (200 Wp), there are some standard dimensions for storage.
- Most installations are for the countryside because of a lack of electricity.

Free comments

- An importer has identified a brand that offers solutions suitable for the residential, commercial and industrial sectors.
- The larger the size, the more power, so higher-voltage systems can be designed, as inverter technology has also evolved.
- There is a preference for the sale of formats between 400Wp and 600Wp.
- As Table 4 shows, in a few cases, traders reported that they can provide panels of all sizes, which is noticed by long lines in the table.
- The group that responds to the online survey is located at the end of the table and works in large installations; therefore, their responses are focused on larger formats.

DISCUSSION

In the case of the first phase of the study, taking into account the geometry of the photovoltaic panels for their inclusion in architectural surfaces, their width usually has more constant dimensions, mainly in the values of 0.668 (intermediate formats), 0.992 (large formats), and 1.134m (larger formats), which can be of

great help in the planning of future arrays and available surfaces. As the length of the panel is the most variable measurement, it can be handled with greater flexibility, and it favors arrays with vertically arranged panels because when overhang extremes are used, this situation can be tolerated by the lower or upper sides.

In the case of the second stage, surveys addressed to marketers and installers, given the current circumstances of the photovoltaic panel market, an increase in the format is perceived. Formats close to 2.00m² offer a greater diversity of ranges and involve a difference of at least 115 watts (between 300W and 415W), representing at least 28.75% of the possible difference in energy generation if we consider the catchment area.

Regarding the efficiency between area and power, the difference between the group of small/medium panels and the group of large/larger panels is clear since the trend in the latter is becoming more efficient, and with less diversity of ranges, obtaining the most amount of watts per area, unlike the small and medium formats. Considering the area as a factor for calculating estimates would be very useful for projects with large solar panels.

There is also a reduction in the supply of formats between 260 and 350W (Fig. 4), an aspect ratified in the interviews with marketers and installers. For formats larger than 2 m², the range is reduced, at 2.16m² there is a 70 watts difference (16.8% variation); at 2.373m² there is 25 watts (6.8% variation); and for the larger than 2.70m² there is a range of 45 watts (9.2% variation). For sizing purposes by space, large and larger formats offer a higher degree of estimation or, in any case, a smaller range of variation.

In the case of larger panels from 2m² upwards, due to the smaller range in both cases, nominal values of power and efficiency of PV modules, calculations based on area could be more accurate, and the average of the range could be used. In the case of panels smaller than 2m² and having wider ranges, area calculations could be performed using the average or extreme values depending on the need for accuracy.

The supply of solar panels in one of Lima's most important retail centers is aimed at rural purposes, where energy coverage is often lacking or inadequate. However, there is a slight demand for buildings in Lima, part of which is oriented toward multifamily housing. It can be assumed that this slight increase is a positive consequence of the MiVivienda green bond, which could gradually increase. As these are technological systems, the brands that are in demand and positioned give quality as one of the main strengths. Large formats are beginning to appear in the offer, together with small ones, although it is expected that small formats will continue to be sold due to reduced disadvantages for importers, sellers, and installers. Currently, the benefits outweigh the costs.

However, it must be pointed out the need for care in transport, handling, and installation. The perceived maximum threshold in the Peruvian market is 610Wp; however, industrial and on-demand macro-generation projects can exceed this limit. Larger formats introduce other technical innovations, such as higher-capacity inverters.

CONCLUSIONS

Internationally and in Peru, larger formats are being progressively introduced because of improved efficiency and the incorporation of contemporary technologies. This represents a period of technological transition and innovation in solar panels. The disappearance of smaller formats is not expected, but an increase in diversity and supply of larger panels is foreseen. Small formats still have a high market presence because of their low cost. In the case of residential buildings, the impulse generated by the MiVivienda Verde bond is significant; as well, as regulations in local municipalities that try to innovate and stimulate the integration of PV energy. A gradual increase in this type of project is expected, at least for the energy supply in indoor common areas with limited on-grid PV installation. However, the use of large and larger format panels still has limitations for residential projects because of increased risks and disadvantages, such as panel breakdown, transportation, and installation complications. Projects with sufficiently free roof extensions (commercial and industrial use); can easily integrate larger PV solar panels.

In terms of geometric relationships, the width of the photovoltaic panels is a much more constant dimension than the length, and it can be taken into account from the architectural design phase to establish a collection area through a repetitive modular sequence, favoring its installation in a “standing” position with the length of the solar panel forming the horizontal angle of collection. In the case studied, for formats close to 2m² of area, at least one-third of the power difference can be considered for a standard range. However, in larger area formats, this range is drastically reduced by up to one-fifth, reducing the variability margin during planning and improving the approximation of the production estimation. For designs with higher efficiency per area and fewer transportation and installation problems, it is recommended the use of formats between 400W (1.953m²) and 600Wp (2.70m²) as a maximum, which are the ranges recommended by marketers. However, larger format panels require innovations to address the possible disadvantages (breakage verification from importation, transportation, structural planning, storage, on-site handling, and maintenance).

The usefulness of the geometrical and power ratios can be integrated for simple estimations using formulas that consider the net areas of photovoltaic production, which is even more useful in the planning design phase.

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