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Photovoltaic Ventilated Roof for Reaching Net Zero and Plus Energy Housing in the Tropical Equatorial Context

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Abstract The energy requirements for dwellings in tropical equatorial climates are significant and ongoing throughout the year. Fortunately, significant and stable irradiation exists. We propose the redesign of a local-style, single-family home with a layout for a typical family of four. The methodology consists of real data on the electricity consumption of an existing case of a typical family, which is considered the source of the energy requirements to determine improvements. Once the house is characterized, it is redesigned. Its energetic behaviour is simulated with virtual tools such as ArchiCAD from Graphisoft and DesignBuilder to introduce passive strategies. Photovoltaic (PV) electrical self-supply of the building is integrated, and the inclusion of electric vehicles is considered. The house is virtually built as a dwelling with similar functions, but solar passive and active strategies are integrated to achieve high energy performance. The roof envelope configuration is the main energy source, and interior overheating is the cause. An initial reduction of 36.97% in energy requirements with only passive strategies and a double-ventilated roof is estimated. When simulating PV capability with the System Advisor Model software, nine standard PV 380 Wp panels are sized for the roof to meet the estimated power requirements, and nine additional units are needed to supply electric transportation sufficient for a single family. A model that can scalably integrate PV in accordance with demand is proposed.

Keywords Single-Family Home, BIPV, PV, Net-Zero Housing, Tropical Equatorial Region

1. Introduction

The combination of population growth, housing needs and improvement in quality of life has increased the energy demands to achieve residential comfort, especially in tropical climates [1]. In Ecuador, electricity for the housing sector in the tropical coastal region is typically priced at US$0.11 per kWh when consumption reaches 500.00 kWh/month. If consumption exceeds this amount, the associated cost grows gradually [2]. In the context of this research, the growth trend of cooling systems in dwellings implies additional energy pressure on utilities because along with economic and technological development, the demand for residential comfort is increasing.

The high consumption associated with cooling in Ecuador was first noted more than a decade ago, when authors determined that monthly costs for a basic house in the Ecuadorian tropical climate reached at least US$60.00 (15% of the national basic salary) for typical food refrigeration systems [3]. This cost increases significantly with the addition of air conditioning, which is now common in the middle and upper-middle classes. In tropical equatorial climates, to achieve comfort, energy demands are significant and ongoing throughout the year, increasing further in periods of greater heat and humidity.

A photovoltaic (PV) system becomes progressively more efficient as consumption rises due to the higher tariff on consumption, making the investment more quickly recoupable [4]. The health emergency due to the COVID-19 pandemic exacerbated the energy vulnerability of families by increasing demand in the residential typology compared with other types of buildings, many of which exhibited reduced energy consumption [5]. In the future, a change in the typical modes of work and educational study is expected with the virtual environment persisting in several areas. This aspect can be positive in terms of urban sustainability, but it also increases residential energy requirements [6].

In tropical climate conditions near the equator, roofs are strategic in preventing overheating throughout the year. As a consequence of solar exposure and the solar path, treating roofs and facade openings is strategic for reducing the effects of interior overheating. Exerting a convective effect in the roof though a ventilated roof proposal is an important option for mitigating the high solar incidence. Thus, integrating PV panels conforming to the external sheet of a ventilated roof constitutes an important strategy for reducing cooling demands and powering the self-supply effect.

A solar city that can supply itself with energy from its own buildings and homes is the ideal scenario for the future [7]–[9]. According to Ramón Roca in the El periódico de la energía (The energy newspaper), it is expected that by 2050, 80% of the energy matrix will be derived from renewable sources [10]. Under this urban concept, introducing houses that can meet their own energy requirements and, moreover, overproduce power to meet urban energy requirements is the main option for realizing net-zero energy communities based on a solar city model [11].

Currently, despite being an oil producer, Ecuador imports fuels for transportation and electricity generation. At present, the transportation sector is the greatest source of pollution in the population centres of the country. Alternatively, all sectors could be made electric in regard to both buildings and transport. Although the use of fossil fuels for the generation of electrical energy and residential supply will continue to be part of the social and economic development of the global energy system, alternative sources are rapidly being introduced. Currently, renewable sources do not account for a significant percentage as a means of supply. Thus, it is important to promote clean alternatives to redirect energy subsidies, which in Ecuador are currently intended for fuels [12].

This study analyses the potential of energy efficiency measures applied in tropical equatorial housing design to reduce the need for urban energy import and combustion and to reach a zero-energy balance or possibly even a negative energy balance in housing areas in tropical equatorial middle-class dwellings. This study also proposes to energize single-family electric vehicles (EVs), which are already considered household appliances [13], considering the high power as a consequence of cooling requirements. For this purpose, residential solar self-supply technologies from the source of greatest potential in the equatorial zone are applied based on a more efficient and resilient model, which in turn will promote a healthier environment.

The prototype is developed from a pre-existing house (case study) to compare real-case scenario data from an existing comparable model against the hypothetical proposed home to determine the degree of improvement (see Figure 1). The study area is the city of Portoviejo, Manabí, Ecuador (1.057702 ° Lat. S; 80.456978 ° Lon. W), which is situated along the coastal region of Ecuador at sea level and has a humid tropical climate [14]. Being close to the equator, the solar radiation with a high azimuth at noon is relatively stable throughout the year, averaging 4,850.00 kWh/m^2/day [15]. The climate and sunlight, as well as the average annual temperature, are influenced by cloud cover, as shown in Figure 2. Due to the climate, residential energy demands are significant because houses require ongoing environmental cooling for comfort.

Source: [15]

Figure 1. Single-family house case study from satellite imagery and the facade

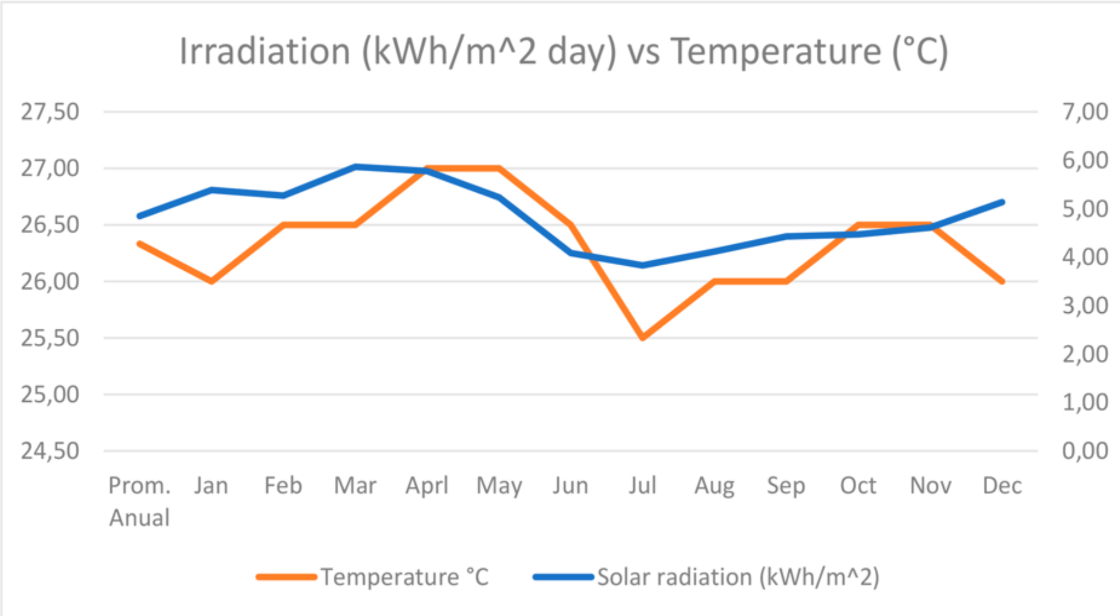


Figure 2. Irradiation vs. average temperature fluctuation per month in Portoviejo, Ecuador. Source: [14]

However, the capacity of a PV system to generate energy at maximum efficiency is influenced by the latitude of the city under study, which defines the annual and monthly average values of PV electricity. Thus, for Portoviejo, the estimated PV capacity is 1,233.70 kWh/kWp installed [17]. The introduction of PV sheets, which are set as external surface ventilated skin, has largely been evaluated in terms of the cooling façade effect [18], [19]. The ventilation effect on the PV sheets also improves their performance, avoiding overheating and the consequent reduction in PV performance. The main novelty of this research lies in the fact that it integrates ventilated roofs for a tropical context only, revealing the main capability of ventilated PVs in the tropical equatorial context and analysing the comparative strategies proposed for the highest energy capability in accordance with residential-transport demands. To the best of our knowledge, these aspects that have not yet been analysed. The methodological process also corresponds to the software that is typically used by architects and that could be applied to another context or other building typologies.

In this research, we first present as a reference case studies that integrate both passive and active solar strategies as a way of reducing energy demands and as a theoretical basis for the strategies adopted in this work, including prioritization studies to find the best options among strategies in tropical climate conditions. Then, we describe the tools and criteria adopted to develop a prototype dwelling considering passive and active strategies to achieve a net-zero energy dwelling in the tropical equatorial context. Third, we describe the application of the methodological process and the main results obtained in the simulation process considering three scenarios. The case study is the baseline. Then, energy neutrality is realized by meeting all the residential energy requirements normally met by a fossil fuel-based power supply. Additionally, reasonable energy requirements for a family's electric EVs are integrated. Finally, we present the main conclusions and discussion in accordance with the results obtained and the potential of the dwelling prototype.

1.1. Literature Review

Previous studies regarding PV capacity in equatorial regions have determined that the solar incidence is greater on the roof. Accordingly, when PV panels are arranged with a low inclination, they can be placed in any orientation without a significant reduction in performance [20], [21]. However, the completely horizontal installation of solar collectors is not recommended due to the accumulation of dust, whereas slightly inclined PV panels have the potential for natural cleaning [22], [23].

The many projects around the world that have identified high energy standards include the following:

Energy House – Lifethings [24] – was developed in Korea and is one of the first buildings classified as a net-zero energy building. Located in a temperate climate, this building utilizes, among other features, cross-ventilation and incorporates a PV system in the roof in addition to a solar thermal DHW system. It directs the skirt that supports the panels towards the angle with the best solar capture during the day and demonstrates the ability to combine two strategies.

Although it is not a residence, the extension of the secondary school in Dano, which is a building located in a constant tropical climate, is another case reference. It adopts passive roofing strategies to keep its interior cool and applies a suspended and inclined ventilated roof that is cantilevered and arranged for the entry-exit of winds to maximize interior ventilation, establishing a ventilated roof system [25].

In contrast, Chaves and others have found significant results from roof cooling strategies in hot, humid climates, demonstrating a possible reduction in inside temperatures of up to 8 ℃ during the hours of critical heat [26]. To meet low-energy requirements, ventilated facades produced very optimal results to evacuate excess heat incident on a building. Integrating solar PV panels as an external envelope on roofs also increased PV performance, as demonstrated by Abd Rahman and others in tropical Malaysia [27].

A review study, serving as the main reference in this work, on the analysis of net-zero buildings in tropical-humid climates is presented by Feng Wei and collaborators [28]. They consider 34 buildings in a tropical climate and reveal the most frequently used strategies for achieving energy consumption reductions. They find that in the cases analysed, 27 active and passive strategies are used. Of the most important strategies, the following are prioritized: 1 – PV roofs; 2 – advanced envelopes; 3 – natural ventilation; 4 – efficient lighting; 5 – optimized architectural plans; and 6 – the blocking of solar incidence. Other strategies, such as solar capture by skylights and louvers in windows, are mentioned less frequently.

The studies described have served as a reference point for this project, and based on the study of Feng Wei and others, applicable passive strategies are prioritized. Then, the use of the roof to maximize ventilation is the next strategy that we consider important in the proposal, given that the roof is the surface with the greatest exposure to solar radiation, which increases unwanted thermal gains. The integration of PV panels as the outside layer in the configuration of initially ventilated façades has been widely applied [18]. Subsequently, the criterion was reinterpreted for roofs [29], [30]. The integration of PV panels as the primary strategy for supplying energy to the home is combined with passive strategies to propose a net-zero home.

2. Materials and Methods

In the approach used for our redesign proposal, several aspects concerning the functional and aesthetic criteria of solar PV technology in architecture are analysed in combination with passive strategies applied to buildings to minimize unwanted thermal gains in tropical climates. This research is based on quantitative data collection methodologies related to analyses performed on a representative case study and a proposal for the house system's redesign. The demands are programmed in virtual simulation models, which are validated based on the consumption recorded for billing purposes by the local electricity distribution company, Corporación Nacional de Electricidad (CNEL EP).

The collected data are identified and then processed based on monthly energy consumption for comparison between the base case and the proposed improved case, based on the stipulated residential requirements, to diagnose key improvements. Seeking the greatest degree of similarity in terms of the areas, spaces, materials and thicknesses compared to the base case, a redesign proposal is presented in which both passive and active strategies are incorporated under the concept of architectural building-integrated PV (BIPV) [31]–[33]. That is, the PV panels are applied so that in addition to their generation capacity, they fulfil a complementary function by serving as a ventilated roof to reduce overheating in the house, which is strategic at this latitude. Architectural-technological solutions that reduce energy consumption and promote energy-self-sufficient buildings are implemented.

The sunlight hitting various façades has also been modelled, determining the level of solar incidence on the interior of the buildings and allowing for the proposal of alternatives that reduce thermal gains but maintain appropriate levels of natural interior lighting. With DesignBuilder software, which uses the EnergyPlus calculation engine [32], the monthly annual average indoor temperature and the energy consumption demand of the houses are determined. With this tool, the comfort level is incorporated, a roof with two air chambers, one between the PV panels and the roofing sheet and another below the roof sheet, is implemented. This simulator considers only the double-layer air insulating capacity. The EnergyPlus calculation engine of DesignBuilder [34], does not consider the convective effect. Therefore, the cooling capacity results obtained on the ventilated roof (Figures 5 and 6) are probably lower than the real results, but the increased effect of the two air gaps is observed even with stationary air simulation. The System Advisor Model (SAM) is a tool that allows the energy production of the PV system to be calculated by configuring the arrangement and inclination of panels in a specific location and time zone by taking into account the size of the system and the availability of products currently on the market.

The current study is based on a comparison of data between the existing scenario and a simulated proposal to analyse the degree of technical and economic feasibility of installing PV systems in a constant tropical context, thus covering a margin of reference that is applicable for cities that share the same characteristics.

2.1. Passive Strategies Used in the Redesign Proposal

For net-zero buildings, passive design should be prioritized when considering adaptations that help reduce the energy requirements of a building. The case study is located in the city of Portoviejo in the province of Manabí, which has maximum temperatures of 29 ℃ to 23 ℃ throughout the day, depending on the time of year. Thus, it is necessary to use an efficient architectural strategy that minimizes thermal gains.

To minimize thermal gains, eaves and sunshades are created on the front, rear, and side façades. In this way, solar radiation does not directly affect the interior. Natural lighting is enhanced by diffuse solar incidence and the use of light colours on floors, walls, and ceilings, which better distributes the incident light.

In addition, cross-ventilation is a fundamental strategy for reducing relative humidity and temperature and improving comfort, especially when the outside temperature is lower and the introduction of outside air is an adequate solution. Therefore, 2.40-m-high spans are proposed to maximize the entry of winds, mainly towards rooms and social areas. Natural ventilation is important to consider when the outside temperature can affect the interior, that is, at times when the exterior can effectively cool the interior. The ceiling height is programmed at 2.70 m from the floor to reduce the heat concentration in closed environments with respect to the typical mezzanine height of 2.40 m.

To reduce the incidence of irradiation and enhance the effect of convection in the roof, the concept of a ventilated roof is applied. A single inclined skirt is produced through the use of ventilated trusses with a ventilated air chamber, arranged in an inclined layout to enhance the evacuation of hot air. The PV panel surface is designed in accordance with energy requirement scenarios. The remaining roof spaces that do not include PV panels can be complemented with “dummy” elements, which are not PV panels but are similar in format and chromatic configuration to achieve adequate architectural integration [35]. In addition, configuring a second ventilated chamber 10 cm above the skirt cools the lower zone of the panels, creating an initial ventilated façade and reducing the temperature of the PV panels, which improves their performance [36].

2.2. Active Strategies Used in the Redesign Proposal

A PV system connected to the urban electric network and exchanging electricity based on “net metering” at the same sales cost in accordance with the current norm is proposed. The surplus energy produced is designated for subsequent use during high-demand hours when solar radiation is absent. If there are monthly surpluses, they serve as a reserve for the following period based on the regulatory stipulation, which is recognized except when surpluses are generated for more than two years, at which point the surpluses are no longer recognized [37]. PV sizing is also proposed to supply the family transport system. Despite the restriction of surpluses, the total geometric solar potential of the roof is also analysed to provide useful information regarding the residential potential to contribute to achieving net-zero communities [10], [38], considering that a proposal that can integrate the number of PV panels in a modular way, adaptable to different demand conditions, is developed.

3. Results

3.1. Characterization and Evaluation of the Energy Consumption and Demand of the Base Case Study

The housing case study was selected due to its size and layout, being a commonly repeated model in this area, with spatial construction characteristics that are typical for an average family of four according to the last Population and Housing Census (Censo de Población y Vivienda, CPV). It is also a recurring model for the Costa del Ecuador region (concrete block masonry, structured in reinforced concrete). Consequently, the case study model is considered representative of the energy consumption of a family that inhabits it under typical conditions in a tropical equatorial climate. Based on this house, a new solution is proposed, and performance comparisons are established (Figure 3).

3.2. Energy Consumption of the Case Study

This case study analysis includes a study of different types of residential energy consumption: lighting, cooling and domestic hot water (DHW). Furthermore, the consumption and possibility of substituting typical residential consumption supplied by liquefied petroleum gas (LPG) for cooking are analysed, in addition to the gasoline requirement for residential transportation. The resulting values are converted to demands for equipment powered by clean electricity.

3.2.1. Electric Consumption

The utility bills of the house, which reflect consumption due to lighting, cooling and DHW, are compiled. In this way, a monthly average value of 381.67 kWh was obtained for October, November, and December 2019 (pre-pandemic), while the average monthly value for October, November and December 2020 (COVID-19 pandemic) was 456.33 kWh, indicating an increase of 74.66 kWh per month.

3.2.2. Thermal Consumption

In reference to the consumption of LPG in the case study, based on the current use of the house, a monthly average of 2.5 cylinders of 15 kg of LPG each for the kitchen and the clothes dryer is determined. For self-sufficiency, the replacement of this equipment by alternative, similar electric equipment is proposed. To replace the use of LPG, the consumption that would be produced taking into account the conversion of units from equivalence and efficiency [39] is 238.83 kWh monthly.

3.2.3. Total household consumption

From the calculation of the average monthly electrical and thermal consumption in the residential area, a potential demand of 921.16 kWh is determined, which would represent a monthly cost of US$96.72 with the current electric subsidy but a real monthly value of US$147.39 without the subsidy.

3.2.4. Energy Consumption Incorporating Electric Transport (Vehicle and Scooter)

In addition, energy consumption is evaluated by replacing the use of the conventional vehicle (gasoline) with an EV and two electric scooters for family members as an alternative to the energy demand for personal mobility in the energy balance of the home. Taking as a reference the average annual distance of 20,000.00 km that a particular vehicle would drive for normal activities, the annual energy consumed by the vehicle is determined [40] to be an equivalent of 341.66 kWh per month. Similarly, the characteristics of an average electric scooter in the current market have been analysed. Considering two scooters for the home under study with a speed of 25 km/h (usual mode), a distance of 10 km per day for each scooter, that is, 400 km/month (Monday to Friday for school, college or university studies), and the characteristics of the roof elements themselves, a consumption of 4.40 kWh/month is estimated to meet the basic travel needs of the children [41].

Once the electrical, thermal and electric transport consumptions of the case study are obtained, approximately 1267.22 kWh/month is required to satisfy the electrical demand under this scenario.

Figure 3. Case study – ground floor and upper floor

3.3. Proposal for the redesign and evaluation of alternative consumption

The house is redesigned for a tropical equatorial climate based on passive architectural strategies. In this phase, solutions are sought to achieve comfort and reduced energy demand in the redesign of the base case with the objective of taking advantage of the conditions of the site.

The passive design criteria that were selected focus on reducing overheating, ensuring ventilation in the roof façade and in the internal environment and reducing energy consumption. From the strategies established and prioritized by Feng Wei and others [28], the design elements are proposed from most to least important as follows: roofs and ventilated façades, eaves, sunshades and wide openings all with control of solar incidence. Notably, in this redesign of the base case, the construction surface is taken as a reference, including the ground conditions of the real reference, while preserving the functional typology of the house. On this basis, we proceed to redesign the ground floor, upper floor, roof plan and 3D model for DesignBuilder simulation. The roof is modelled as a double open-air chamber considering that this is the most critical element of the envelope in hot-humid climates because it transfers the greatest amount of heat to the interior of the house. Among the passive strategies implemented, the incidence of natural lighting is regulated by reducing the volume to create better natural lighting in the central area of the house, and indirect overhead lighting is introduced into the bathrooms (Figure 4).

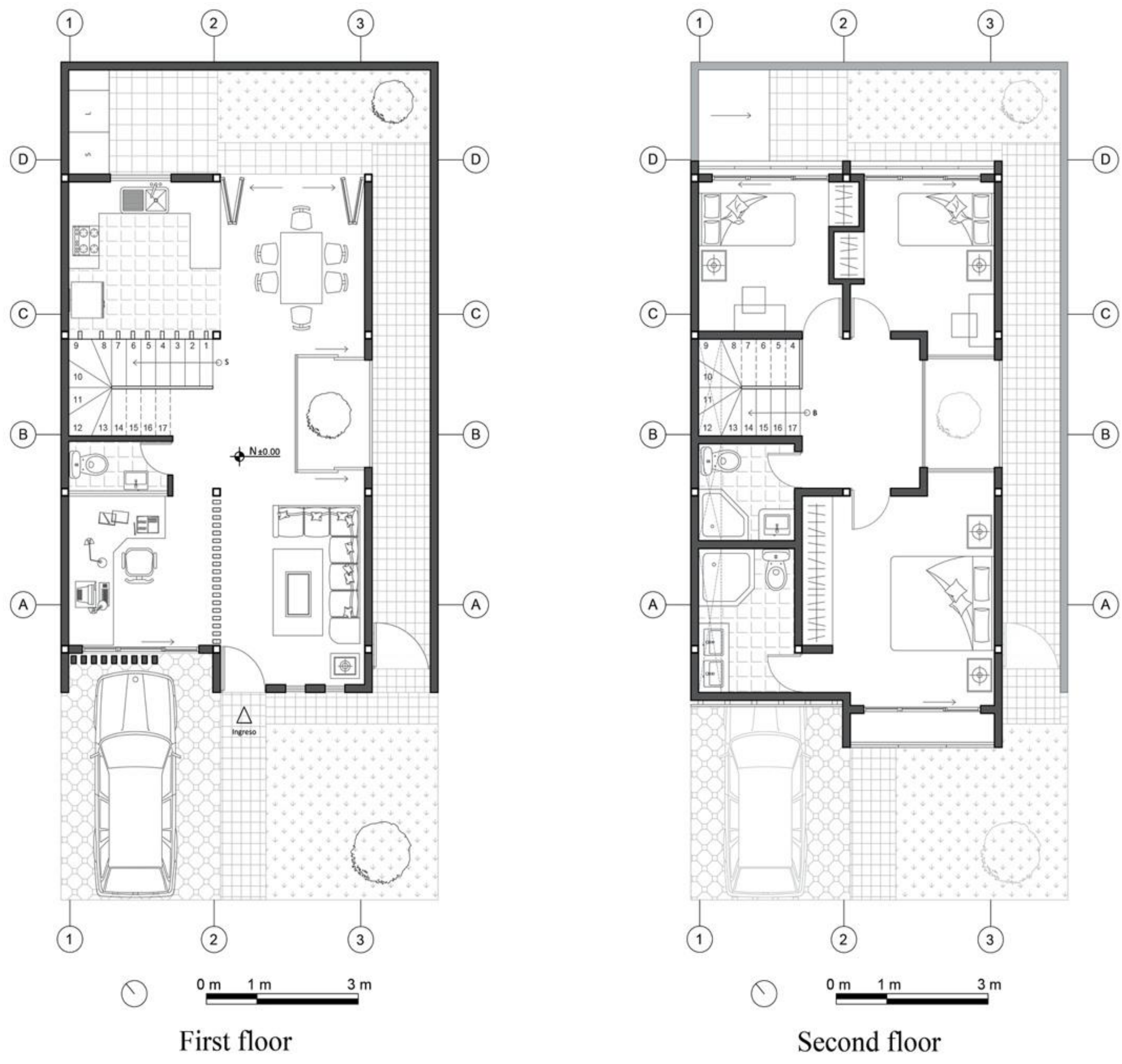


Figure 4. Redesign of the case study - Ground floor and Upper floor

3.4. Analysis of Energy Consumption

Using DesignBuilder software, the annual energy analysis of the redesign proposal is carried out based on the following imposed parameters: inhabitants in accordance with a typical nuclear family (four people), the configuration of activities that are carried out in each space, and the use of schedules, existing appliances, power and time at which the air conditioning is started to refine the results of the simulation for comparison with the energy consumption of the base case.

Only the use of centralized air conditioning equipment at 24,000 Btu in the living room is considered. Here, ignition is simulated based on a comfort range that prevents a temperature greater than 26 ℃ in indoor environments.

The analyses show consumption results per outlet (except air conditioners) with a monthly average of 81.02 kWh, unlike the base case, which presents a consumption of 94.88 kWh. For environmental cooling, there is a monthly average requirement of 152.02 kWh, in contrast to the base case, which presents a consumption of 323.13 kWh. Consumption for lighting has a monthly average of 71.15 kWh, which is greater in the base case, i.e., consumption of 116.00 kWh. Consumption for DHW has a monthly average of 46.31 kWh, as in the base case. By optimizing the design, there would be a significant reduction in the average monthly electricity consumption of 229.81 kWh and average monthly economic savings of US$26.57 compared to the average monthly energy consumption of the base case. Table 1 also indicates a 36.97% reduction in the average monthly energy consumption based on the use of passive strategies.

Table 2 compares the results of temperature, humidity and energy consumption levels, which constitute the main focus of this research. Regarding potential overheating, there is an average decrease of 3.2 ℃ on the ground floor and 4.7 ℃ on the upper floor, reaching a monthly average value of 25 ℃ inside the house, that is, reaching the maximum recommended. These results complement the values obtained in the humidity analysis because, by staying below 50%, they contribute to the evaporation of heat and improve occupants’ comfort. Regarding energy consumption, the reduction achieved is 229.81 kWh/month, a result that is mainly influenced by the low dependence on daily cooling in the redesign proposal, representing a decrease of 39.60% relative to the typical consumption.

Table 1. Results of the annual energy consumption analysis

Month	Base consumption (kWh)	Cost ($)	Reduction in consumption in relation to the case study (%)
January	372.33	33.51	45.64
February	348.63	31.38	52.41
March	392.62	35.34	47.54
April	337.58	30.38	55.87
May	349.80	31.48	50.53
June	303.38	27.30	40.07
July	299.24	26.93	37.45
August	305.63	27.51	32.80
September	324.99	29.25	25.74
October	361.78	32.56	19.11
November	384.40	34.60	11.54
December	425.57	38.30	24.94
Total	**4205.95**	**378.54**	**443.63**
Monthly average	**350.50**	**31.55**	**36.97**

Table 2. Summary of thermal parameter analysis

ANALYSIS PERFORMED		UNIT	CASE STUDY	REDESIGN PROPOSAL	OPTIMAL
			Monthly average	Monthly average	
Temperature	Ground floor	℃	28.12	24.92	20 °in winter 25 °in summer
	Upper floor		29.18	24.71	
Humidity	Ground floor	%	72.53	48.13	30%-40% min. 60%-70% max.
	Upper floor		57.26	48.47	
Energy consumption	House	kWh	580.31	350.50	Variable

3.4. Roof Redesign with BIPV Technology

The roof redesign is characterized by a single slope of 3%, with an inclination of 1.57 ° (tilt) and an azimuth of 145 °. The azimuth corresponds to the real location of the case study, and the tilt (inclination) is proposed to be slightly inclined to introduce the ventilated roof feature. When using such a minimal slope, solar radiation capture is significant at this latitude. However, this arrangement requires constant cleaning, which is considered in the design. The system consists of steel trusses with an initial section of 30 cm and a final section of 60 cm and steel G profiles of 100 × 50 × 2 mm spaced every 100 cm, which supports a 0.90-mm Dipanel DP5 Galvalume panel on which the BIPV substructure is mounted.

The roof floor has an area of 62.19 m^2, of which 3.44 m^2 is used for overhead lighting of the upper floor bathrooms and stairs, while the remaining 58.75 m^2 is used for the installation of PV panels and for the circulation pathway that will allow their maintenance.

3.4.1. Installation of Roof-Integrated BIPV

Depending on the available space, the HoneyM Framed 120 Layout Module panel brand Trina Solar TSM-DE08M.08(II) measuring 1763 × 1040 × 35 mm and with a weight of 15 kg is selected. This panel has 120 monocrystalline half-cells distributed in two blocks of 60 half-cells each, with a power capability of 380 W and a maximum efficiency of 20.70%. It is a product with typical performance and has been available in the country since 2021.

3.4.2. PV Installation on Ventilated Roof Configuration

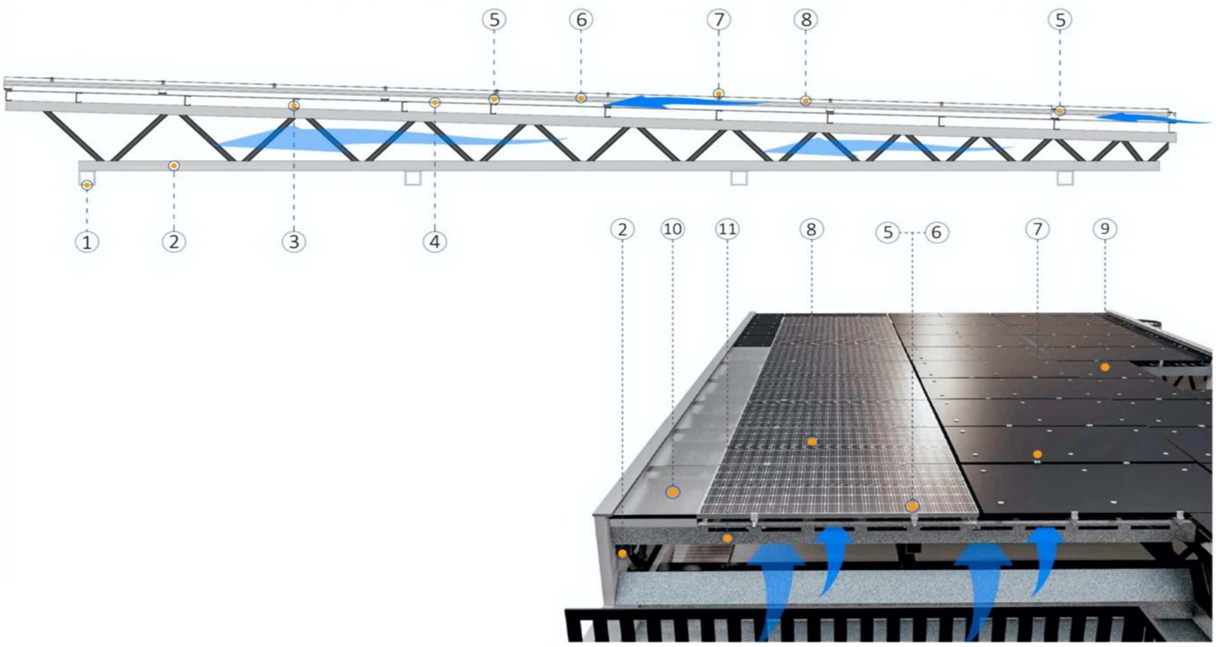
On the specified roof panel, the G profiles are screwed perpendicular to the trusses every 100 cm. These profiles serve as support for the installation of the 0.90-mm Dipanel DP5 Galvalume sheet. Based on the aluminium profiles for PV panels with their respective steel angles, the G profiles are anchored by means of screws to the frame of the PV panels, resulting in an integrated system, as shown in Figure 5 and Figure 6.

Along with the installation of the PV system, the installation of dummy modules is included. The dummy modules complement the roof spaces not occupied by the PV panels. These modules consist of panels with steel structures composed of angles and frame profiles with the same geometry as that of the PV panels. They have corrosion resistance to outdoor conditions and are appropriate for sustaining live loads. In this way, the view of the roof is more homogenous, providing an appearance of a diaphanous roof surface with an architecturally integrated format (see Figure 5).

Figure 5. Integration of PV panels and dummy modules in the roof for ventilated roof configuration (own elaboration)

Regarding the structural impact generated by the integration of these solar technologies, previous research has determined that there is no great impact on the roof elements because the weight of the aluminium structure and solar panels is not significant. At the national level, the Ecuadorian Construction Standard NEC-SE-CG Loads [41] is used, in which a value of 0.70 kN/m^2 is determined to be the minimum uniformly distributed overload for flat, inclined and curved roofs.

In the case of 120-cell monocrystalline PV panels weighing 15 kg each, they should not exert a load in excess of 0.20 kN/m^2 on the roof [42] (Figure 6).



Description
01. Steel profile 10 × 10 cm
02. Steel truss 0.30 m in the initial section and 0.60 m in the end
03. Steel profile G 100 × 50 × 15 × 2 mm every 100 cm
04. Dipanel DP5 Galvalume 0.90 mm
05. Aluminium profile support
06. 50 × 30 mm aluminium profile
07. Double angle for joining between panels
08. Monocrystalline panels of 120 cells/1763 × 1040 × 35 mm
09. Steel dummy modules
10. Glass skylight
11. Aluminium corner piece for finishing

Figure 6. Structure of the PV system – longitudinal section and aerial view (own elaboration)

3.5. PV Performance Simulation

The analysis was performed by using SAM software [43] to estimate and make predictions of the monthly and annual energy performance of the PV system, taking into account the base energy consumption previously simulated from the redesign proposal.

3.5.1. Design of the PV System in Relation to Base Consumption, Maximum Demand and Maximum Feasible Production

In the first instance, the size of the PV panel system is determined based on the results of the “base consumption” level that corresponds to the model improved with energy efficiency measures. Then, the situation that we call “maximum demand”, which considers supplying electricity to EVs belonging to the house, is considered. Finally, a scenario that we call “maximum feasible production”, which involves determining the maximum solar potential beyond the demands, detects the production capacity based on the available surface on the roof. With the monocrystalline PV product described, the necessary amount is calculated to cover the base consumption, while the maximum demand and the maximum feasible production are determined using SAM software, taking into account the climate data on the city in which the project is located, the azimuth of the PV panels, as well as their inclination, and the capacity of the inverter, among other parameters, resulting in a total of nine panels, 18 panels and 22 panels, respectively, for each of the aforementioned cases (see Figure 7). Together, the sizes of the PV strings are defined based on the voltage range of the inverter and the voltage of the open circuit of the panel based on the corresponding data sheets of each product, resulting in the following:

-For the case of base consumption (see Table 3), it is possible to meet the expected supply and obtain a minimum annual surplus.

-For the case of maximum demand (see Table 3), the proposed intention of supplying the additional consumption generated by an EV and two scooters is fulfilled, in addition to having a minimum annual surplus of 0.23%.

-For the case of maximum feasible production (see Table 3), the purpose of covering the available space of the roof is met, generating 244.89% relative to the base consumption, in which the maximum capacity of the roof is determined, taken as the case of maximum capacity for the house. Thus, this option is proposed in this study, given that it is an important alternative for achieving communities closer to net zero [9], [44]. Therefore, in the future, it is a technical alternative that should be analysed.

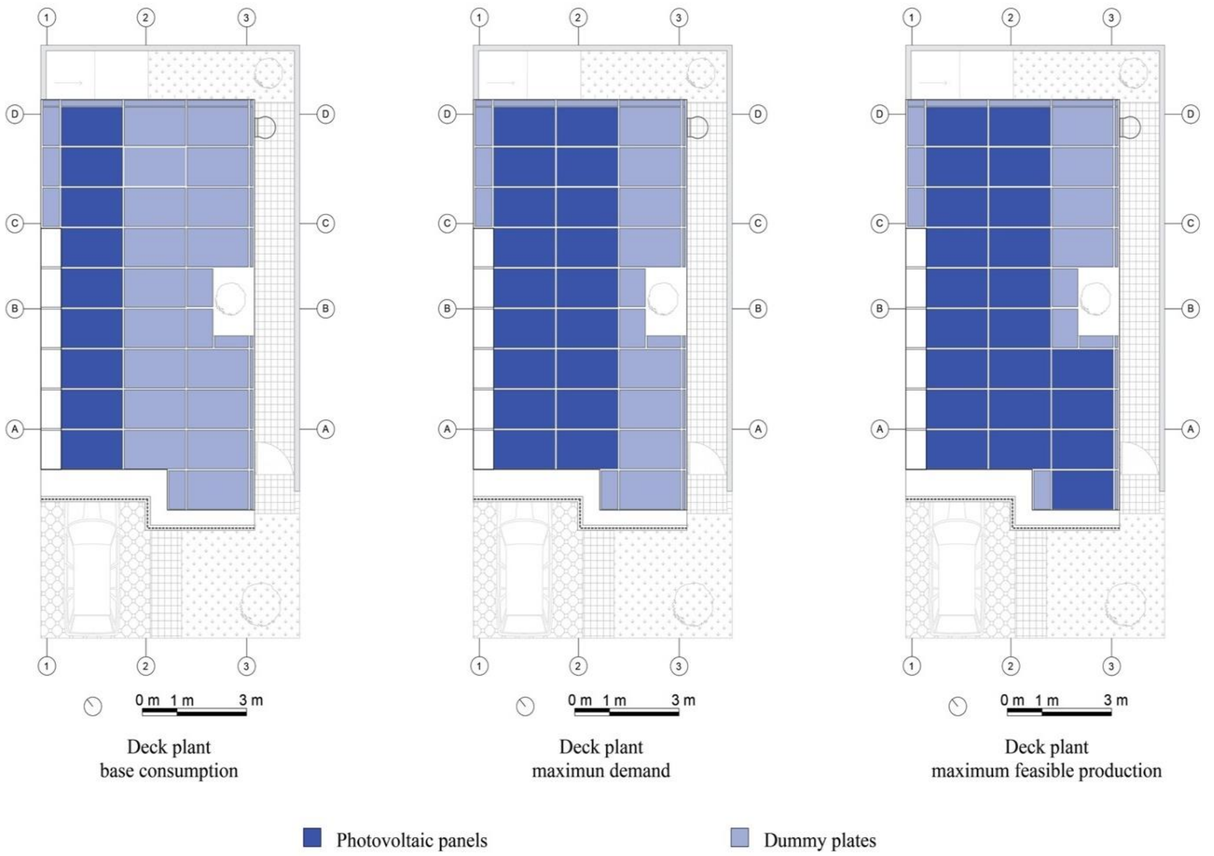


Figure 7. Floor of the supply roof base consumption case – maximum demand case and maximum feasible production case (own elaboration)

Table 3. Results of PV supply for base consumption – maximum demand and maximum feasible annual production

Scenarios	Consumption (passive strategies + electric cooking and drying)	Maximum demand (more vehicles)	Maximum feasible production
Demand (kWh/year)	4,205.95	8,358.67	4,205.95
PV production (kWh/year)	4,232.21	8,378.01	10,300.01
Number of panels of 385 Wp	9	18	22
Supply percentage	100.62%	100.23%	244.89%

4. Discussion and Conclusions

This work proposes a methodological approach to designing a dwelling with high energy performance and efficiency with renewables integrated. The main contribution of this work lies in the fact that it adopts a combination of three software tools in conjunction to reach this goal, i.e., ArchiCAD for architectural design, DesignBuilder software for determining comfort parameters and dimensioning the energy requirements, and SAM software for PV output performance, to reveal the energy capability of a PV power plant integrated in accordance with different energy scenarios, with the possibility of integration in any design process. Additionally, from the design perspective, the BIPV proposal makes possible double-sheet ventilated roofs and strategies that have been demonstrated in the referenced works presented in the introduction as a good alternative to reduce overheating. Then, this strategy is applied in a tropical equatorial context, resulting in an ideal option considering the solar incidence at this latitude for reducing low performance as a consequence of PV overheating, as demonstrated in reference cases [45]. As another contribution of this analysis, we present a proposal for a dwelling prototype that can integrate on its roof any required capability of PV panels in accordance with the appropriate energy requirements. First, the prototype simulation was modelled in accordance with the configuration of a typical single-family house. Then, it was considered to develop a close functional design seeking thermal improvement implemented on the irradiated facades and, in particular, on the roof. The proposal for the roof design considers scalably integrating PV panels in accordance with any family requirements, more or fewer PV solar panels, and the adoption of dummy plates for remaining roof spaces. This is an important strategy since we consider that energy requirements vary as a consequence of requirements based on the number of inhabitants or their particular lifestyles.

In this way, after analysing and comparing the results obtained, it is understood that the installation of PV systems on a building has a high degree of technical, sustainable, and economic feasibility, which can promote important strategies for achieving energy-self-sufficient communities in equatorial tropical climates.

After selecting and analysing the housing type for the case study, it is shown that this case requires a high amount of consumed energy – an average of 580.31 kWh per month – mainly due to the excessive use of cooling in interior spaces (59% of consumption) to counteract the high monthly maximum temperatures (29-31 ℃). Accordingly, the architectural redesign proposal maintains similarity in spaces, areas, the interior layout and materials. However, the redesign proposal focuses on a passive design that incorporates a ventilated roof, a ventilated fa çade, eaves, sunshades and ventilation flows. Natural lighting is also maximized, thereby reducing the energy dependency of the home to 350.50 kWh per month, which is energy that then serves as the scenario for base consumption. The approach of using three PV systems differentiated by the number of panels allows us to obtain a global and clear vision of the capabilities as benefits of installing active design systems such that the base consumption can be supplied by nine monocrystalline PV panels of 120 cells that can produce 352.68 kWh/month. In this same case, the use of one EV and two scooters is incorporated into the home, increasing the energy demand to 696.56 kWh/month. This demand can be met by 18 PV panels, reaching a production of 698.17 kWh/month. In the third scenario, to determine the maximum feasible energy production, that is, to achieve the maximum potential of the house from the area available on the roof, it would be possible to produce 858.37 kWh/month with 22 PV panels. In a quick financial analysis carried out by considering prices to date, if users could sell these surpluses to distribution companies for the case of maximum potential, then they would earn an income of US$548.40 per year in addition to covering their own current demands (US$ 378.54). Therefore, the PV investment would pay for itself in approximately seven years. As a result, a new strategy of directing public resources to citizens instead of contracting mega hydroelectric plants and thermal generators to foreign corporations to exploit large-scale energy sources would be feasible.

To the best of our knowledge, our study is the first proposal of a scalable roof envelope-integrated BIPV system. We demonstrate that it is possible to achieve a 36.97% reduction in energy requirements as a consequence of the ventilated roof and controlling the solar incidence on the main irradiated facades. However, with PV panels, it is feasible to meet the energy requirements of a single family, including the energy requirements of charging family vehicles. Therefore, these results coincide with the prioritization of strategies for the tropical context presented by Feng Wei [28], determining that PV integration as a strategy effectively has more potential than passive options, although such options are important for helping achieve energy neutrality. Due to the high and stable irradiation, integrating PV panels can produce more energy than the energy that could be saved by implementing passive strategies.

In this case prototype, with the available space existing on the roof, we observe that it is possible to install a PV system that covers almost 2.5 times the base case energy requirements. As a consequence of the cost reduction of PV technology, with high irradiation available, this could mean that PV technology is an affordable option and that PV integration is affordable compared to our example, making extreme investments in passive strategies such as enormous insulation in the building envelope.

From an urban sustainability perspective, in tropical equatorial contexts, during day time, there is enormous power consumption as a consequence of cooling systems running to avoid city overheating, and a good match between power demand and PV production is expected. However, it is important for future work to carefully analyse the matching PV production vs. power demands and the requirements for the grid and the implications of massively introducing PV systems to determine possible grid limitations that can occur in moments of maximum power surpluses.

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REFERENCES

[1] H. B. De Waal, “New recommendations for building in tropical climates,” *Build. Environ.*, vol. 28, no. 3, pp. 271–285, 1993.

[2] MERRNR, “GOBIERNO NACIONAL ADOPTA MEDIDAS DE COMPENSACIÓN EN TARIFAS ELÉCTRICAS DURANTE EMERGENCIA SANITARIA ARCONEL,” 2020. [Online]. Available: https://www.recursosyenergia.gob.ec/gobierno-nacional-adopta-medidas-de-compensacion-en-tarifas-electricas-durante-emergencia-sanitaria/. [Accessed: 01-Mar-2022].

[3] E. INEC, “VII Census of Population and VI of housing, National Institute of Statistics and Censuses,” 2010. [Online]. Available: https://www.ecuadorencifras.gob.ec/b

ase-de-datos-censo-de-poblacion-y-vivienda-2010/

[4] J. L. Iga and C. L. Iga, “Solar radiation in urban projects: Financial analysis of a photovoltaic system for a habitation house in the Metropolitan area of Monterrey, Nuevo Leon, Mexico,” *Rev. la Constr.*, vol. 14, no. 3, pp. 30–40, 2015.

[5] H. Kang, J. An, H. Kim, C. Ji, T. Hong, and S. Lee, “Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea,” *Renew. Sustain. Energy Rev.*, vol. 148, no. November 2020, pp. 111294, 2021.

[6] E. Chueca and Ariel Yepez, “Confinement and electrical energy: change in consumption patterns,” Energy for the Future, 2020. [Online]. Available: https://blogs.iadb.org/energia/es/confinamiento-y-energia-electrica-cambio-en-los-patrones-de- consumo/#:~:text=Se%20puede%20observar%20el%20tiempo,una%20hora%20concreta%20del%20día

[7] J. Taminiau, L. Kurdgelashvili, and K. N. Kim, “A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul,” *Renew. Sustain. Energy Rev.*, vol. 41, pp. 830–844, 2015.

[8] J. Byrne, J. Taminiau, K. N. Kim, J. Seo, and J. Lee, “A solar city strategy applied to six municipalities: Integrating market, finance, and policy factors for infrastructure-scale photovoltaic development in Amsterdam, London, Munich, New York, Seoul, and Tokyo,” *Wiley Interdiscip. Rev. Energy Environ.*, vol. 5, no. 1, pp. 68– 88, 2016.

[9] C. Hachem-Vermette, F. Guarino, V. La Rocca, and M. Cellura, “Towards achieving net-zero energy communities: Investigation of design strategies and seasonal solar collection and storage net-zero,” *Sol. Energy*, no. July, pp. 0–1, 2018.

[10] R. Roca, “La energía en el mundo en 2050: 50% renovables, 50% combustibles fósiles,” 2018.

[11] A. Kylili and P. A. Fokaides, “European smart cities: The role of zero energy buildings,” *Sustain. Cities Soc.*, vol. 15, pp. 86–95, 2015, doi: 10.1016/j.scs.2014.12.003

[12] B. Creamer-Guillen and R. Becerra-Robalino, “Quantification of Subsidies from Petroleum Derivatives to Hydrocarbons in Ecuador,” *Bol. Estadístico del Sect. Hidrocarburos*, vol. 2, pp. 9–26, 2016.

[13] E. Doroudchi, K. Alanne, Ö. Okur, J. Kyyrä, and M. Lehtonen, “Approaching net zero energy housing through integrated EV,” *Sustain. Cities Soc.*, vol. 38, no. January, pp. 534–542, 2018.

[14] A. Varela and S. Ron, “Geografía y clima del Ecuador,” *BIOWEB. PUCE,* Nov-2020. [Online]. Available: https://bioweb.bio/faunaweb/amphibiaweb/GeografiaClima/.

[15] M. Rodriguez Gámez, A. Vázquez Pérez, W. M. A. Saltos Arauz, and J. Ramos Guardarrama, “Solar Potential and Distributed Generation in the Province of Manabí in Ecuador, *Rev. Investig. en Energía, Medio Ambient. y Tecnol. RIEMAT ISSN 2588-0721*, vol. 2, no. 2, p. 41, 2017.

[16] Google Maps, “Caso de estudio 1°00’57.5"S 80°28’18.6"W,” 2021. [Online]. Available: https://www.google.com.ec/maps/place/1°00’57.5%22S+80°28’18.6%22W/@-1.0159722,-80.4740273,899m/data=!3m2!1e3!4b1!4m5!3m4!1s0x0:0xe59502ffd1da008f!8m2!3d-1.0159722!4d-80.4718333?hl=es. [Accessed: 11-Mar-2022].

[17] Global Solar Atlas, “Global Solar Atlas,” 2021.

[18] C. M. Lai and Y. P. Lin, “Energy saving evaluation of the ventilated BIPV walls,” *Energies*, vol. 4, no. 6, pp. 948–959, 2011.

[19] A. M. Ekoe A Akata, D. Njomo, and B. Agrawal, “Assessment of Building Integrated Photovoltaic (BIPV) for sustainable energy performance in tropical regions of Cameroon,” *Renew. Sustain. Energy Rev.*, vol. 80, no. September 2016, pp. 1138–1152, 2017.

[20] P. Fitriaty and Z. Shen, “Predicting energy generation from residential building attached Photovoltaic Cells in a tropical area using 3D modeling analysis,” *J. Clean. Prod.*, pp. 1–15, 2018.

[21] L. F. Mulcué-Nieto and L. Mora-López, “A new model to predict the energy generated by a photovoltaic system connected to the grid in low latitude countries,” *Sol. Energy*, vol. 107, no. September 2014, pp. 423–442, 2014.

[22] G. Cáceres, S. Nasirov, H. Zhang, and G. Araya-Letelier, “Residential solar PV planning in Santiago, Chile: Incorporating the PM10 parameter,” *Sustain.*, vol. 7, no. 1, pp. 422–440, 2015.

[23] I. F. Izquierdo-torres, M. G. Pacheco-portilla, L. G. Gonzalez-Morales, and E. F. Zalamea-Leon, “Photovoltaic simulation considering building integration parameters,” *INGENIUS Rev. Cienc. y Tecnol.*, vol. 21, pp. 9–19, 2019.

[24] INHABITAT, “Net Zero Energy House/ Lifethings,” 2013. [Online]. Available: https://inhabitat.com/sosoljip-is-a-self-sufficient-net-zero-energy-house-in-south-korea/. [Accessed: 25-Nov-2021].

[25] Arquitectura Viva, “High School, Dano - Diébédo Francis Kéré Kéré Architecture,” 2018. [Online]. Available: https://arquitecturaviva.com/obras/escuela-secundaria-de-dano. [Accessed: 01-Mar-2022].

[26] U. Chávez, C. E. Del Pozo, E. T. Haro, and J. M. Rodríguez, “A Thermal Assessment for an Innovative Passive Cooling System Designed for Flat Roofs in Tropical Climates,” *Energy Procedia*, vol. 91, pp. 284–293, 2016.

[27] N. M. A. Rahman, L. C. Haw, K. A. Kamaluddin, and M. S. I. Abdullah, “Investigating photovoltaic module performance using aluminium heat sink and forced cold-air circulation method in tropical climate conditions,” *Energy Reports*, vol. 9, pp. 2797–2809, 2023, doi: 10.1016/j.egyr.2023.01.130.

[28] W. Feng *et al.*, “A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings,” *Renew. Sustain. Energy Rev.*, vol. 114, no. July, pp. 109303, 2019.

[29] A. Michael and F. Bougiatioti, “Architectural Integration of Active Solar Systems on the Facades and Roofs of Existing Buildings in the East-Mediterranean Region,” no. 12, 2014.

[30] Solarwall, “PV/Thermal; Hybrid Solar Heating + Electricity,” 2017. [Online]. Available: https://www.solarwall.com/technology/pv-t/. [Accessed: 25-Nov-2021].

[31] H. Kaan and T. Reijenga, “Photovoltaics in an architectural context,” *Prog. Photovoltaics Res. Appl.*, vol. 12, no. 6, pp. 395–408, 2004.

[32] K. Farkas, "Designing photovoltaic systems for architectural integration. Criteria and guidelines for product and system developers," San Francisco, 2013.

[33] E. Biyik *et al.*, "A key review of building integrated photovoltaic (BIPV) systems," *Eng. Sci. Technol. an Int. J.*, vol. 20, no. 3, pp. 833–858, 2017.

[34] DesignBuilder Software Ltd, "Designbuilder," 2021. [Online]. Available: https://www.designbuilder.co.uk. [Accessed: 09-Mar-2021].

[35] K. Farkas *et al.*, "Designing photovoltaic systems for architectural integration. Criteria and guidelines for product and system developers," Solar Heating & Cooling Programme International Energy Agency, San Francisco, 2013.

[36] A. Buonomano, U. Montanaro, A. Palombo, and M. Vicidomini, "NZEBs in Mediterranean Climates: Energy Design and Optimization for a Non-residential Building," *Energy Procedia*, vol. 82, pp. 458–464, 2015.

[37] ARCERNNR, *Resolucion Nro.001/2021*. Ecuador, 2021.

[38] J. Byrne, J. Taminiau, J. Seo, J. Lee, and S. Shin, "Are solar cities feasible? A review of current research," *Int. J. Urban Sci.*, vol. 21, no. 3, pp. 239-256, 2017.

[39] A. Tama, "Cocina De Inducción Versus Cocina a Gas (Glp)," *Energ ú*, pp. 8–14, 2013.

[40] J. Torres, "Feasibility study in the implementation of electric vehicles in the city of Cuenca," pp. 1–176, 2015.

[41] CENERGIA, "How much power does an electric scooter consume?," 2020. [Online]. Available:https://cenergia.org.pe/blog/cuanta-energia-consume-un-scooter-electrico/. [Accessed: 01-Mar-2022].

[42] Ministry of Urban Development and Housing, (NON-SISMIC LOADS). 2014. [Online]. Available: https://www.habitatyvivienda.gob.ec/wp-content/uploads/2023/03/1.-NEC-SE-CG-Cargas-No-Sismicas.pdf [Accessed: 23-Jun-2023].

[43] NREL, "System Advisor Model (SAM)," 2022.

[44] A.-F. Marique and S. Reiter, "A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale," *Energy Build.*, vol. 82, pp. 114–122, 2014.

[45] N. M. A. Rahman, L. C. Haw, K. A. Kamaluddin, and M. S. I. Abdullah, "Investigating photovoltaic module performance using aluminium heat sink and forced cold-air circulation method in tropical climate conditions," *Energy Reports*, vol. 9, pp. 2797–2809, 2023, doi: 10.1016/j.egyr.2023.01.130