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Article

Retrofit Measures for Achieving NZE Single-Family Houses in a Tropical Climate via Multi-Objective Optimization

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Abstract: To achieve sustainable cities and communities, it is necessary to decarbonize existing buildings. Actions need to be taken to reduce the buildings' energy demand and ensure that the low remaining demand is met by energy produced from renewable sources. This leads to Net Zero Energy Buildings (NZEBs), whose impact on energy consumption is zero or positive, meaning that they are able to produce more energy than they require. The "zero" objective may be difficult to reach in hot and humid climates, where the cooling demand is prevalent. In this case, a combination of active and passive measures, together with appropriate interaction with users, is a viable way to obtain NZEBs. The present study aims to explore technological solutions for renovating existing buildings to NZEBs in a tropical climate. The analysis is developed through a parametric analysis, a sensitivity analysis, and an optimization directed at minimizing the site's net energy and hours of discomfort. Evaluations are conducted for a case study consisting of a single-family house located in Panama City. The results showed that photovoltaic size, cooling operation schedule, and cooling set-point temperature are the most influential variables for the attainment of NZEBs in a hot climate. Regarding the building envelope, the outcomes suggest the low insulation of dispersing structures and local solar shading of windows as recommended measures.

Keywords: building renovation; net zero energy buildings; optimization; parametric analysis; renewable energy; sensitivity analysis; thermal comfort; tropical climate

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1. Introduction

Building retrofit or building refurbishment is necessary to improve the building's energy performance to achieve an objective imposed by local energy regulations, second-life purposes, or users' requirements [1]. Due to recent the global goals regarding energy and emissions, local buildings' regulations objectives are becoming stricter [2]. Among such objectives is the improving the efficiency of all existing buildings to achieve nearly Zero Energy Buildings (nZEB) or even Net Zero Energy Buildings (NZEB). Buildings classified as NZEB are considered highly performant, managing to equally balance their annual energy consumption with on-site renewable energy generation, e.g., the electricity and thermal energy produced from solar energy at the building site. This balance is calculated annually per building's total surface area in terms of primary energy (kWh/m^2 year). An nZEB is a building which uses the minimum requirements to achieve a high performance. These requirements depend on the country, where the annual energy balance in primary energy terms is "close" to 0 kWh/m^2 year. This "close" value varies significantly per country [3].

The renovation of existing buildings is, in fact, one of the obstacles encountered in achieving the objectives of climate neutralization [4]. Government support is essential to encourage the renovation process [5] and the amount of incentives required increases when trying to reach nZEB levels and to ensure internal comfort conditions [6]. New indexes can be considered the basis for defining incentives, like the one proposed by [7], which takes into account CO_2-neutral exported electrical energy.

In this context, many countries have initiated retrofit actions in the building sector, which include improvements at the envelope level, at cooling or heating at the plant level, and also can go as far as focusing on the occupants' behavior level, while assuring the thermal comfort of the latter. In the literature, different approaches can be found, referring to simulation and experimental applications to optimize various aspects of the renovation measures. These include the four categories of retrofit [8], i.e., active strategies, passive strategies, occupants' interaction, and renewable systems. For example, Sami et al. [9] used TRNSYS (Thermal Energy System Specialists, LLC, Madison, WI, USA) to evaluate a cogeneration system designed for a multi-story building in Iran, while Aste et al. [10] simulated a four-story residential building in Italy using EnergyPlus (Department of Energy, USA), and TRNSYS (Thermal Energy System Specialists, LLC, Madison, WI, USA). Gas and electricity consumption and internal parameters (temperature, relative humidity, and CO_2) were monitored for one year by García-Ballano et al. [11] in a residential complex in Zaragoza (Spain) after the renovation according to the nZEB target in order to verify the percentage of improvement in energy efficiency.

Three steps are generally used to achieve an NZEB [12]. These include the use of passive strategies, the use of energy-efficient technologies (HVAC, lighting, and appliances), and the integration of renewable sources. Sometimes a smart control can be added to obtain "Smart Sustainable Buildings" [13]. The level of performance varies based on the climate zone, the state of the buildings (new or existing), and the intended use (residential and non-residential). For example, a study conducted on the Member States of the European Union [14] shows that values for non-renewable primary energy for NZEBs in Europe vary from 20 to 150 kWh/m^2 year for new buildings, and from 20 to 157 kWh/m^2 year for existing buildings. In addition to energy savings, the high level of perceived comfort and satisfaction of occupants living in nZEB buildings should be highlighted [15].

The technical solutions for the building envelope mainly include the addition of thermal insulation and high-efficiency windows. Reference values report a thermal transmittance value for the external walls of 0.15–0.20 W/m^2 K for new buildings and 0.10–0.20 W/m^2 K for existing buildings. For the roof, 0.10–0.25 W/m^2 K was reported for new buildings and 0.10–0.20 for existing buildings. For window glass, 0.85–1.0 W/m^2 K was reported for new buildings and 0.9–1.15 W/m^2 K for existing buildings [14]. For a non-residential NZEB building in a Mediterranean climate, [16] obtained optimal transmittance values of 0.23 W/m^2 K for the external walls and roof, and 0.9 W/m^2 K for the windows. For a case study in Morocco, the optimal thermal transmittance values were 0.496 W/m^2 K for the external walls and 0.685 W/m^2 K for the roof. For the windows, double glazing with argon was used [17]. In a hot and humid climate, 6 mm single clear glass (U-value: 5.78 W/m^2 K) performs better than double and triple glass [18]. Passive strategies result in the highest percentage of energy savings in tropical climates [19]. Passive cooling solutions include the use of solar shading, natural ventilation and natural lighting, thermal mass, and night cooling.

The percentage of renewable energy sources used in NZEBs varies from 20 to 50% [14]. Photovoltaic is the most used renewable source and the heat pump is the most widespread generation system for heating and domestic hot water [14]. The variability in the size of the photovoltaic system significantly affects the ratio of renewable energy for heating, cooling, and domestic hot water [20]. Izadi et al. [21] explored the application of a hybrid renewable system for a medium three-story office in Iran. The hybrid system includes photovoltaic, wind and hydrogen storage. Between 35% and 49% of the electricity required by the building can be generated by photovoltaics and wind turbines and 70% to 88% can be covered by the combination of renewable sources and hydrogen storage. A total of 45% of the building's energy load is covered by renewable energy in a residential building in Morocco [17]. A newly built hotel in Croatia showed that 53.94% of the energy coverage was obtained from renewable sources [22]. The integration of renewable sources (photovoltaic and wind turbines) reduces the interaction with the grid [23]. The production of "distributed" renewable energy and the different forms of storage (heat, cold, and electricity) are crucial in the creation of nearly zero energy communities [24]. Huang and Sun [25] highlighted the advantages of grouping nZEB buildings to allow for them to share their energy generation and energy storage, and collaborate in load management, minimizing their interaction with the grid. Time-of-use energy management strategies help shift periods of peak power [26]. Storage solutions are also essential to obtain zero energy buildings in the case of "stand-alone" buildings [27]. For buildings connected to the grid, demand-side management can help optimize the load by decreasing the pressure on the network during peak hours [28]. However, this is not enough; in order to create the conditions for the large-scale diffusion of NZEB buildings, the flexible interaction of buildings and the grid must be improved, promoting the advancement of grid-friendliness indicators [29]. The development of advanced controls provides an additional opportunity to improve the behavior of each individual technical component, the environmental efficiency and energy-efficiency of buildings, and the interface with the energy grid [30]. In hot climates, solar energy can be optimized for the production of cooling energy through solar cooling systems [31]. However, the unpredictability of renewable sources and the variability of user loads can lead to a mismatch between energy supply and availability [32]. Furthermore, for multistory buildings, only the roof area is available to install photovoltaics on site, making it difficult to achieve energy self-sufficiency. D'Agostino et al. [33] have suggested that, as a preliminary design in a Mediterranean climate, square-plan buildings can achieve the NZEB target for a building height of up to seven stories. As buildings with a rectangular or L-shaped plan have a higher rate of energy consumption, energy self-sufficiency can be achieved for up to a maximum of six or five floors, respectively [33].

Few renovation studies conducted in buildings in a tropical climate can be found in the literature. Little attention is paid to the application of NZEBs in hot climates [34,35]. Renovation measures that include the improvement of the envelope and the use of active systems contribute to the decarbonization process. However, the objectives are still focused on reducing heating and DHW consumption, even in countries where the demand for cooling is important, such as those in Southern Europe. No specific indicators are used to limit cooling demand. This aspect should be regulated in view of climate changes that potentially increase cooling needs [36]. As pointed out by Cerezo-Narváez et al. [37], adaptation to the new standards produces significant energy savings (from 69% to 127%), which can be achieved with the restructuring of the envelope, and the installation of thermal and photovoltaic solar systems. However, these measures are effective for reducing heating demand, but do not produce significant effects mitigating cooling needs. The authors suggest that regulations should include proposals to alleviate climate consequences in locations with significant summer weather severity. An overview of the concept of zero energy buildings in Latin America was provided by Austin et al. [38]. Retrofit guidelines to obtain zero energy buildings in hot climates are defined by Costa et al. [34]. Kitagawa et al. [39] suggest the combination of ventilative cooling and radiant cooling to improve the cooling performance of buildings in hot and humid climates and improve the thermal comfort of the occupants. A combination of the variable thermal transmittance of the envelope (including phase-change materials), integrated photovoltaics, solar thermal systems, and solar greenhouses was explored by Buonomano et al. [16] for a non-residential building in the Mediterranean area. The integration of PCM into the envelope of a school in Catalonia has also been addressed by Berardi et al. [40]. A saving of 46% for the total final energy consumption was achieved for a four-story office in Brasilia [34]. To reduce energy consumption for air conditioning, a reduced WWR, a glass with reduced SHCG, the addition of solar shading, and natural ventilation are among the measures that were found to be most effective for reaching the NZEB goal. According to a study conducted by Abdou et al. [17], 40% of the total cooling energy can be saved by combining passive measures and renewable sources in Morocco. In hot and humid climates, passive strategies based on natural ventilation, solar shading, and the airtightness of the envelope allow for greater energy savings than thermal insulation [41]. In any case, occupant behavior and actual building use should be used as more realistic input parameters to avoid deviations between the design and the actual building performance [42]. In fact, occupant behavior can lead to discrepancies between expected consumption and actual consumption. Buildings designed to be nZEBs can show significantly higher consumption (up to double) under real operating conditions [15]. Nevertheless, some studies show a full correspondence between the calculated savings and those actually obtained after the renovation of buildings according to nZEB standards [11].

Several studies have addressed the problem of the optimization of zero-energy buildings, focusing on different objectives and adopting different methods. Energy conservation, carbon emissions, costs, and comfort were considered by Wu et al. [43] through an intelligent optimization process applied to a university building in Wuhan, China. Ecology, energy and economy were integrated into the multi-criteria optimization algorithm for zero-energy buildings developed by Zhu et al. [44]. The method aims to optimize the Life Cycle Energy and Life Cycle Cost and includes indices of different perspectives, such as the effectiveness of solar energy application, sociability, energy savings, and equipment economy. Energy savings, Life Cycle Cost, and thermal comfort were the subject of the optimization conducted by Abdou et al. [17] in the climatic zones of Morocco. A method for the integrated optimization of the envelope and the HVAC system for the nZEB refurbishment of a hotel in Croatia is proposed by Delač et al. [45]. The optimal solutions are achieved when the system meets the design load with adequate thermal insulation. Excessive thermal insulation and oversized systems have a negative impact on the cost.

Regarding investigations carried out in a hot climate, the reduction in the U-value of the external walls, the introduction of Energy Recovery Ventilation (ERV), the control of the ventilation rate, and the use of an HVAC system with a high SEER have been found to be significant factors that reduce the energy intensity of buildings and achieve NZEBs in tropical climate [46]. An optimization of the external Venetian blinds was conducted by Huo et al. [47] with reference to the inclination angle of the slats, the orientation, and the WWR ratio in different locations in China. The results demonstrated that solar shadings allow for the cooling load to be reduced and are useful for obtaining nZEBs. Ascione et al. [48] combined model predictive control with comfort models to optimize space cooling. Optimal control strategies allow the cooling load to be predicted and the hourly values of the set-point temperature to be optimized based on the weather forecast. This allows for savings of 28% to be obtained compared to the case in which a fixed set-point temperature is assumed. The economic optimization conducted by Usman et al. [49] for a zero-energy solar house in a subtropical climate showed that the Net Present Value of the solar house becomes lower than that of a conventional house in eight years. Li and Wang [50] highlighted the importance of coordinating the design process of the envelope and HVAC systems to optimize the performance of buildings in cooling-dominated subtropical regions.

Objective

The objective of this study is to propose an optimization procedure for the identification of the most effective building renovation measures to obtain Net Zero Energy Buildings in a tropical climate. The majority of optimization studies that can be found in the literature focus on objective functions that concern the minimization of energy demand, the minimization of emissions, the maximization of renewable energy, and the minimization of costs [51]. Few studies have addressed the problem of optimization from the perspective of comfort. Those that are available generally use PMV, and they are not applied in tropical climates. The current study aims to fill this gap by analyzing a case study set in Panama, characterized by a hot and humid climate. An optimization framework is proposed, aimed at reducing energy demand and, differently from other studies available in the literature, this work addresses the optimization of comfort not using the PMV index but the minimization of hours of discomfort inside the building.

2. Methodology

A case study is considered for the application of the methodology. First, possible energy renovation options are identified. Analysis variables corresponding to each measure are modeled. A parametric analysis is conducted for each variable in order to evaluate the impact, in terms of the extent of the achievable reduction in consumption and the effect produced. Subsequently, the sensitivity analysis allows for the identification of the variables with the greatest impact, in which it is convenient to invest to facilitate the achievement of the Zero Energy objective. Finally, an optimization study allows the optimal solution to be identified based on the minimization of Net Site Energy and discomfort hours, evaluated according to the ASHRAE with 55–80% acceptability [52]. Figure 1 schematizes the methodology's workflow.

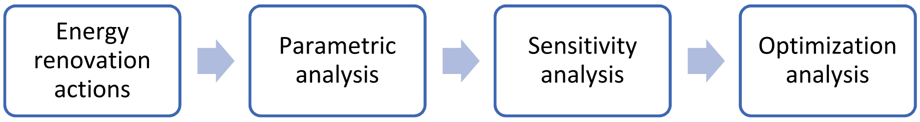

Figure 1. Workflow scheme.

2.1. Case Study Description

The case study building is a single-family house located in Panama City. The climate is identified as Aw according to the Köppen–Geiger classification (tropical wet and dry/savanna climate), with a pronounced dry season in the low-sun months, no cold season, and a wet season in the high-sun months [53]. According to historical data obtained from CLIMdata online platform from Solargis© (Bratislava, Slovakia), the climate of the case study is characterized by a dominant wind direction coming from the northwest, with a most frequent speed range between 1 and 3 m/s (annual average of 2.5 m/s) at 10 m. Two seasons are observed: dry (December to April) and rainy (May and November), where March is the hottest month and October is the rainiest month, with an annual average global radiation of 4.96 kWh/m^2 day and an annual rainfall of 580 kg/m^2. Moreover, the maximum temperature in a day is reached at 3:00 p.m. and the lowest at 6:00 a.m., with an annual average outdoor air temperature range between 22.2 °C and 35.6 °C near the ground. The annual average outdoor relative humidity ranges from 33% to 100%, with an average of 78%.

The software Designbuilder (Version 7.0.2.6, DesignBuilder Software Ltd., Stroud, Gloucs, UK) was used as the simulation tool. It is based on the EnergyPlus software (Version 9.4, Department of Energy, USA) as a Calculation Engine developed by the Department of Energy of the United States Government. This software has additional integrated modules for the easy-run calculation of a parametric analysis, a sensitivity analysis, and both single-objective and multiple-objective optimization analyses.

To perform thermal and energy calculations, the hourly weather data were implemented as site data to define the boundary conditions, which are normally included in the software or provided by the user. The following considerations are accounted for in the modeling approaches used by the software for each aspect of the model:

- The natural ventilation was set up as "calculated" in the software, which refers to the airflows at each opening, estimated via the airflow network method, which are already integrated in the software. This is implemented as the default by the software.
- Solar distribution modelling was set as the complete exterior.
- The Conduction Transfer Function (CTF) was left as default as the heat transfer solution algorithm with constant thermal properties, with no consideration of humidity movement.

- A constant infiltration rate of 0.7 ach was considered always available, considering the good crack state.
- Thermal bridges were not considered.
- The ground thermal behavior modeling was set by default because this study is interested in the comparison of designs where the ground modelling remains the same, among other characteristics. Any differences that are found are a result of the renovations only.

The building is on one floor, with a net surface area of 65.80 m^2. The house includes three bedrooms, a dining room, a living room, a kitchen, two bathrooms, and a storage room. The floor plan of the house is shown in Figure 2.

Figure 2. Floor plan of the analyzed case study building.

The roof is pitched, with a north–south orientation and an unconditioned space underneath. The house is considered representative of this category of buildings, based on a survey previously carried out in the research area [54].

Regarding the construction characteristics, the building envelope is not insulated. Table 1 reports the thermal transmittance values of the opaque elements of the construction.

Table 1. Thermal transmittance of the opaque elements of the building envelope.

Building Element	Thermal Transmittance Value [W/m^2 K]
External walls	4.02
Roof	7.14
Dispersing ceiling	4.54
Ground floor	2.30
Windows	5.80

Only the three bedrooms are equipped with a cooling system, consisting of split units with a COP of 3. The cooling system is used in bedroom 1 from 7 p.m. to midnight, with a set point temperature of 23 °C. In bedrooms 2 and 3 it is used from 11 p.m. to 7 a.m. with a set point temperature of 23 °C. Occupation varies in the various rooms of the house, based on the typical profiles defined throughout the study [54]. The use of equipment and lighting was also defined based on the typical behavior identified in the same study. The hourly climate file used in the simulations was obtained based on real data recorded in the study area.

Regarding the comfort assessments, the following metabolic rate value was assumed in the environments: 90 W/person in the bedrooms, 110 W/person in the dining and living rooms, 120 W/person in the bathroom, and 160 W/person in the kitchen.

A clothing of 0.50 was assumed throughout the year, as there is no seasonal difference in the considered climate; rather, it is summer throughout the year.

2.2. Retrofitting Actions

The renovation interventions are primarily designed with reference to the minimum requirements defined by the standard [55]. This establishes the performance characteristics required for different construction elements to achieve an estimated level of energy saving. The rule actually refers to newly constructed buildings. However, as specific regulations on existing buildings are not available in Panama, it was deemed appropriate to refer to this source. Furthermore, in the hypothesis where an existing building is transformed into a Net Zero Energy Building, an extensive level of renovation is expected, which can potentially be assimilated into newly constructed buildings in terms of regulation. Table 2 summarizes the requirements for residential buildings, referring to "design option 3", provided by Regulation [55], which allows for energy savings of 16%.

Table 2. Target values for residential buildings (design variant 3) [55].

External walls U-value [W/m^2 K]	0.8
Windows U-value [W/m^2 K] g-value (SHGC)	 5.80 0.60
Exterior window shade Projection factor	0.30 South and West
Window-to-wall ratio	40%
Roof U-value [W/m^2 K]	1.04
HVAC COP	3.0

The present study intends to go beyond the performance required by law, identifying further renovation measures capable of bringing the building to have a zero or positive energy balance. In summary, the renovation actions include passive measures, active measures, renewable sources, and interaction with occupants.

Passive measures concern the improvement of the thermal performance of the building envelope. This is achieved through the thermal insulation of the opaque dispersing elements and the use of highly energy-efficient windows, with reduced thermal transmittance. The choice of the characteristics of the transparent surfaces, particularly the solar gain of the glass, is also one of the passive measures, as well as the use of solar shadings. The window-to-wall ratio can also be classified as a passive measure. However, this specific parameter was not analyzed in the present study, as it is difficult to change in the case of existing buildings. The size of the windows, in fact, is linked to the internal lighting requirements and the minimum ventilation required for the healthiness of the rooms. Furthermore, in the case of existing buildings, this could be prevented from modifying the extension and shape of the windows to avoid altering the façades. However, in the building under consideration, the WWR does not comply with the minimum imposed by the standard, as it is lower than 40% for all exposures.

The active measures concern the use of the cooling system, which is expected to improve its efficiency.

The efficiency of the building in relation to the interaction with the occupants is examined considering two parameters: the cooling set point temperature and the operation schedule of the cooling system.

Finally, the installation of a photovoltaic system on the roof of the building for the production of electricity on-site was planned. The system occupies the pitch of the roof facing south.

2.3. Modelling of the Design Variables

In relation to each analyzed aspect, a set of variables was defined in order to perform a parametric analysis to evaluate the impact of each single variable on the energy balance of the building. The variation ranges were defined with reference to the different technical solutions that can be adopted for the analyzed building. Uniform distributions were assumed for the different variation options. Table 3 shows the list of variables used and the minimum and maximum values containing the variation ranges. Discrete increments were assumed between the limit values, with variable steps. For photovoltaics, three options were analyzed, corresponding to 3 kW_p, 6 kW_p, and 9 kW_p. For the cooling set-point, the options are supported by the reported results from surveys found in [54,56]. For the cooling schedule, six options were defined, which are detailed in Table 4.

Table 3. Definition of the design variables.

Design Variable	Regulation Target Value (with Variant n°3)	Min	Max	Step
U external walls [W/m^2 K]	0.8	0.2	4	0.2
U windows [W/m^2 K]	5.8	1.8	5.8	0.2
U roof [W/m^2 K]	1.04	0.2	7	0.2
U ground floor [W/m^2 K]	-	0.2	4	0.2
U ceiling [W/m^2 K]	-	0.2	4.6	0.2
g-value [-]	0.6	0.35	0.6	0.025
Solar shading [%] of lit area	0.3	0	1	-
Cooling COP [-]	3	3	4	0.1
Photovoltaic [kW_p]	-	3	9	3
Cooling schedule	-	Off/24	On/24	-
Cooling set-point [°C]	[23.5–28.5]	16	28	1

Table 4. Cooling operation schedule options included in the parametric analysis.

Cooling Operation Schedule	Operation Hours	Description
C1	Always "Off"	Always "Off" 24/7
C2	"On" from 23:00 to 7:00	"On" eight hours during the night
C3	"On" from 8:00 to 17:00	"On" nine hours during the day
C4	"On" from 19:00 to 24:00	"On" five hours during the night
C5	"On" from 19:00 to 6:00	"On" eleven hours during the night
C6	Always "On"	Always "On" 24/7

3. Results

3.1. Energy Consumption at Current State

The baseline model was calibrated according to the ASHRAE Guidelines 14 [57]. The Mean Bias Error (MBE %) and Coefficient of Variation of Root Mean Square Error (CVRMSE %) indices were calculated considering the monthly metered electricity data, obtaining deviations lower than the limits allowed by the standard (±5% for the MBE and 15% for the CVRMSE).

The house, at present, has an energy demand of 75.55 kWh/m^2 year, which does not follow the base line proposed in [55] for Panama (60 kWh/m^2 year, although this proposed base line is only for new buildings). The graph in Figure 3 shows the monthly trend in electricity demand. There are no renewable systems, so all the necessary energy is taken from the grid. In the current state, the reference case shows 2431.17 discomfort hours, evaluated according to the ASHRAE 55 considering the 80% acceptability limit [52].

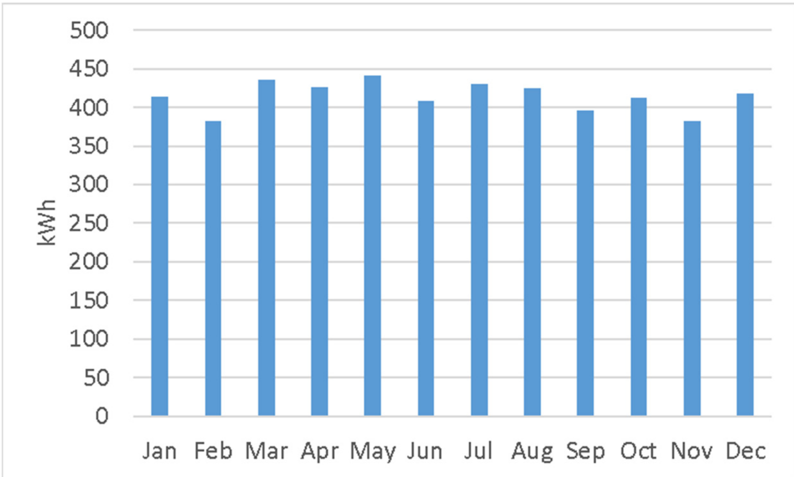

Figure 3. Monthly electricity consumption for the analyzed building in its current state.

Electricity consumption includes, in addition to cooling, electricity for the operation of household appliances and lighting, deriving from the modeling of the typical occupancy profiles of the considered area. On average, cooling consumption takes up approximately 50% of the total electricity consumption assessed for the home.

With the aim of finding the best combinations of measures capable of obtaining Net Zero Energy Buildings in a tropical climate, the net energy at the site was considered as the output of the analysis. This is calculated as the difference between the electricity demand and the renewable electricity generated on site by the photovoltaic system. The balance is calculated at the site. The lower the net site energy, the more energy-efficient and independent the building. Negative net site energy values indicate that the generated energy is greater than the demanded energy, with the surplus resulting in a positive energy building. Surplus electricity is assumed to be fed into the grid. There are no storage systems.

3.2. Parametric Analysis

The results of the parametric analysis allow for first idea to be obtained of intervention methods that are suitable for pursuing the goal of Zero Energy. Regarding the thermal insulation of the opaque envelope, the observed trend is that the addition of a layer of thermal insulation and the consequent reduction in thermal transmittance leads to a decrease in cooling energy demand. This is true for the external walls, for which a more significant decrease in energy needs is recorded as the thermal insulation thickness increases, going from 4973.27 kWh/year to 4216.47 kWh/year, and also for the ceiling and roof, which produce less significant reductions. The opposite trend is instead observed for the ground floor slab. In this case, the positive effect is registered as the thermal insulation thickness decreases. The higher the thermal transmittance of the floor in contact with the ground, the lower the net site energy. This behavior is explained by the fact that, in a hot climate, such as the tropical climate of Panama, heat losses towards the ground favor the passive cooling of internal environments, with a consequent reduction in the required energy. The graphs in Figures 4 and 5 show the results of the parametric analysis conducted for the net site energy as a function of the thermal transmittance of the external walls and the ground floor, respectively.

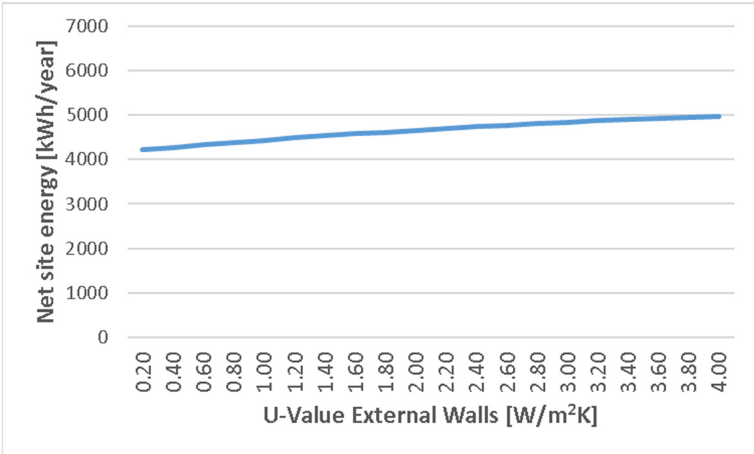

Figure 4. Parametric analysis of the net site energy during variations in the thermal transmittance of the external walls.

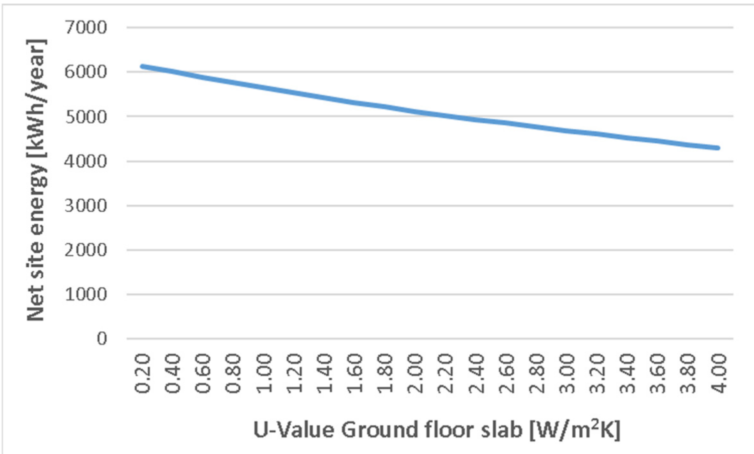

Figure 5. Parametric analysis of the net site energy during variations in the thermal transmittance of the ground floor slab.

Regarding windows, the variation in thermal transmittance does not produce significant variations in energy demand. The net site energy remains almost constant using windows with different thermal transmittance values. This is due to the limited extension of the openings compared to opaque surfaces. Furthermore, the solar gain factor of the glass and the different solar shading levels that are analyzed do not appreciably change the energy requirements. This is assumed because, for the specific case in question, the windows are already in the shade due to the geometry of the construction itself, so the impact of solar radiation is already reduced, even in the current configuration.

Regarding the efficiency of the cooling system, the energy demand decreases as the cooling efficiency increases. The graph in Figure 6 shows the trend of the net site energy upon variations in the cooling COP.

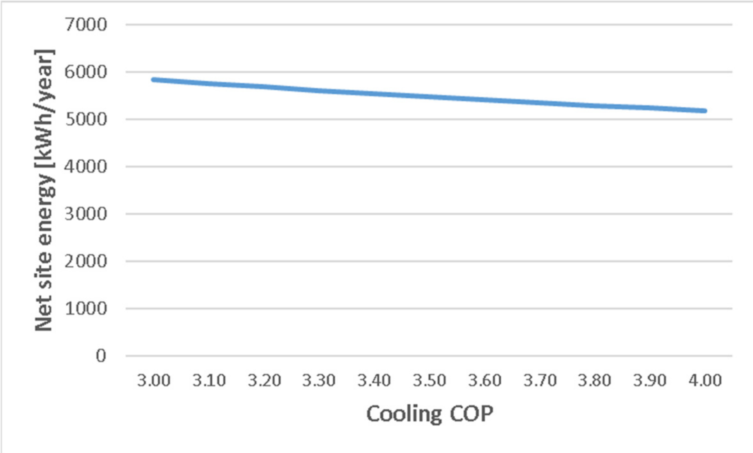

Figure 6. Parametric analysis of the net site energy at variations in the cooling COP.

The operation schedule of the cooling system has a significant impact on the energy demand. The lowest consumption is obtained with the C1 schedule (always "Off"). In this case, the energy demand is attributed only to the use of electrical appliances. The maximum value is instead reached by considering the cooling always "On" (C6 option) in the rooms where it is present. The other schedules that were considered produce an energy demand between these two extremes, as illustrated in Figure 7.

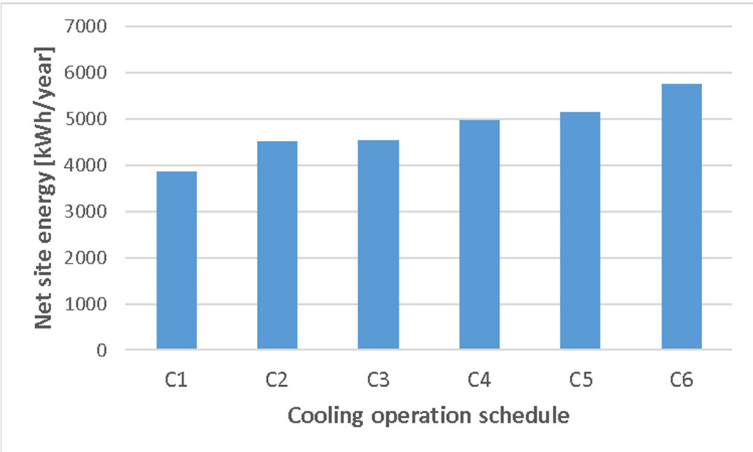

Figure 7. Parametric analysis of the net site energy upon variations in the cooling operation schedule.

The cooling set-point temperature also has a significant impact. The net site energy is halved, passing from a set-point temperature of 16 °C to 28 °C (Figure 8).

The measure that most affects the energy balance is the integration of the photovoltaic system. This, at the smallest size, allows for an energy balance close to zero. By using the medium and large sizes, the balance becomes that of a positive energy building, with generation being greater than consumption.

A parametric analysis was also conducted to explore the combined effect of the set-point temperature and the cooling schedule (Figure 9). As expected, the highest consumption is associated with the lowest cooling temperature (16 °C) and the most prolonged use of the cooling system (Always "On" operating schedule). Turning the cooling on all night (option C5—"On"—for eleven hours during the night: from 19:00 to 6:00) also involves high consumption. Consumption progressively decreases for all operating modes by increasing the set-point temperature. Maintaining a temperature of 20 °C, the most convenient operating schedule is C4 ("On" for five hours during the night: from 19:00 to 24:00). If the set-point temperature is higher than 20 °C, the most convenient operating schedule becomes C3 ("On" for nine hours during the day: from 8:00 to 17:00). Options C2 and C3 show similar consumption levels. At a temperature of 28 °C, cooling for five hours during the night (from 19:00 to 24:00—C4) involves the same net site energy demand as cooling for 24 h (C6: always "On"). By selecting a temperature of 20 °C, the C3, C2, and C4 operating modes are equivalent, approximately 40% lower than what would be achieved if cooling always in "On" mode.

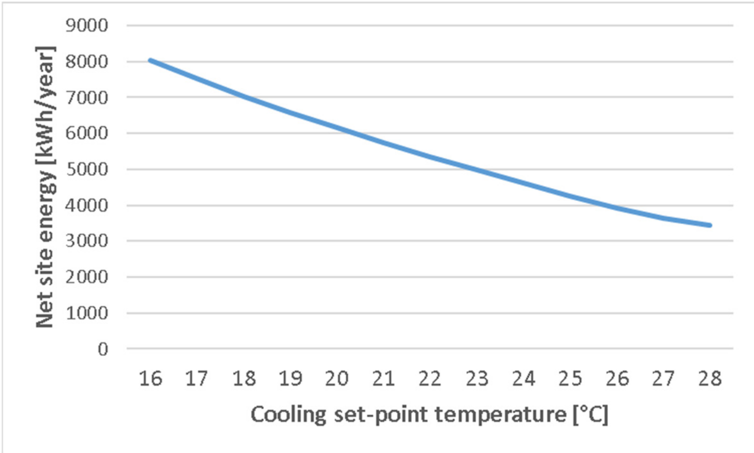

Figure 8. Parametric analysis of the net site energy upon variations in the cooling set-point temperature.

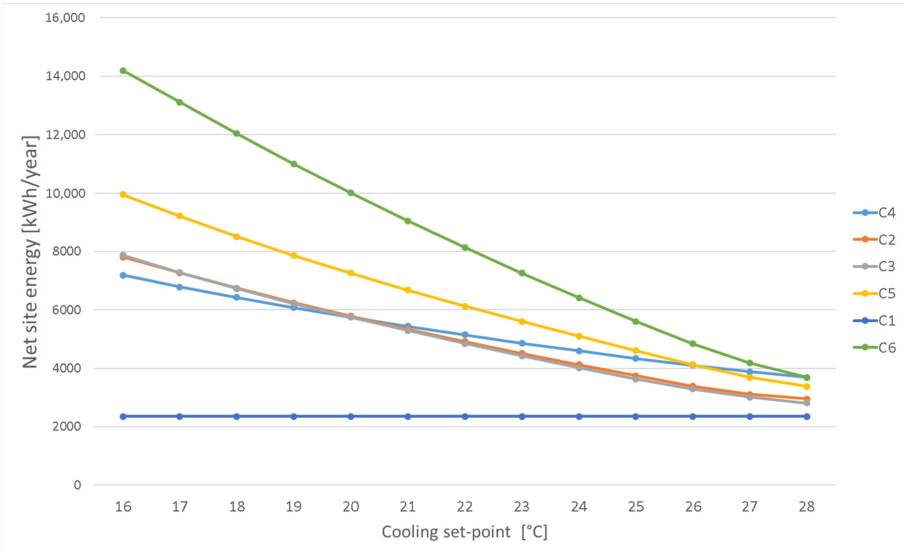

Figure 9. Parametric analysis of the net site energy upon variations in the cooling set-point temperature and cooling schedule.

3.3. Sensitivity Analysis

The sensitivity analysis identified the variables that had the highest impact on the net site energy requirement, which should be considered when renovating buildings in a hot–humid climate.

The LHS method was used to sample the variables, setting a number of iterations equal to 300. All the options defined for the different variables were uniformly sampled. This means that, during the various iterations, combinations of variables were explored using the different options defined for each variable.

The multiple linear regression method was used for the sensitivity analysis. This statistical method estimates the relationships between input variables. A regression analysis helps to understand how the typical value of the output changes when any one of the input variables is varied (assuming that the input variables are independent of each other). The Standardized Regression Coefficient (SRC) indicates the sensitivity of each input variable, thus identifying the most and least important variables. Other regression outputs, like "Adjusted R-squared" value and "*p*-value", help to determine the level of confidence and the reliability of the results.

Figure 10 reports the Standardized Regression Coefficient for each variable. The colors indicate the importance of the variables (High Importance: red; Medium Importance: blue; Low Importance: green).

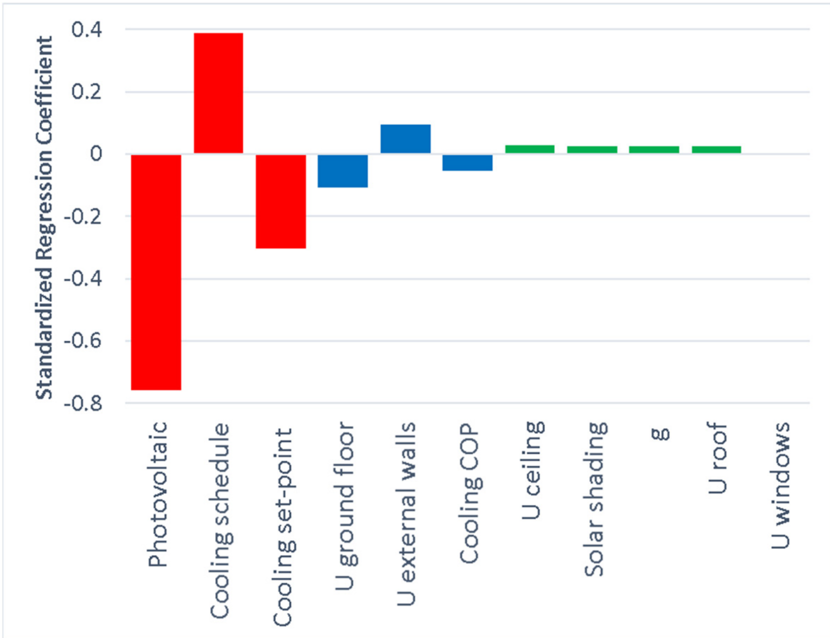

Figure 10. Standardized Regression Coefficient for each variable.

The results highlight that the net site energy demand is most strongly influenced by the photovoltaic size; however, there is an inverse relationship. This implies that increasing the PV size leads to a decrease in net site energy consumption. The net size energy is also strongly influenced by the cooling operation schedule and cooling set-point temperature. A moderate influence is obtained for the thermal transmittance of the ground floor slab, external walls, and the cooling COP. The U-value of the semi-exposed ceiling, the roof and windows, the solar shadings, and the window g-value do not have a notable influence on net site energy consumption.

The adjusted R-squared value represents the goodness of fit of the complete model. This indicates how much variation in the output is explained by the input variables.

For the analyzed output (net site energy), the adjusted R-squared value of 0.9151 is obtained, suggesting that most of the key sensitive input variables were identified.

Table 5 reports the Standardized Regression Coefficient, standard error and the *p*-value of the variables included in the analysis. The color of the variables listed in Table 5 corresponds to their importance (High Importance: red; Medium Importance: blue; Low Importance: green).

The *p*-value expresses whether the input variable has a statistically significant effect on the output. Some input variables have a *p*-value greater than 0.05, indicating that there is a low level of confidence in their respective regression result values. These are as follows: thermal transmittance of semi-exposed ceiling, shadings, windows' g-value, thermal transmittance of the roof, and thermal transmittance of the windows.

Table 5. Standardized Regression Coefficient, standard error, and the *p*-value of the analyzed variables.

Design Variables	Standardized Regression Coefficient	Standard Error	*p*-Value
Photovoltaic	−0.7587	97.5714	0.0000
Cooling schedule	0.3867	70.7853	0.0000
Cooling set-point	−0.3046	21.1847	0.0000
U ground floor	−0.1084	13.9192	0.0000
U external walls	0.0949	14.0195	0.0000
Cooling COP	−0.0543	25.4718	0.0019
U ceiling	0.0283	11.9863	0.0984
Solar shading	0.025	71.5164	0.1476
G	0.0237	25.1695	0.1672
U roof	0.0235	7.8552	0.1700
U windows	−0.0037	13.1753	0.8283

3.4. Optimization Analysis

3.4.1. Optimization of Net Site Energy

The optimization analysis was conducted in two stages. In the first phase, the optimization was carried out only as a function of the net site energy, searching for the lowest achievable value. The minimum value of −10,144.89 kWh/year was obtained, corresponding to point 1, highlighted in Figure 10, with the combination of variables illustrated in Table 6. Since the net site energy is negative, this indicates that, regarding the balance between energy consumed and energy produced on-site, the energy produced with renewable sources is greater than the energy consumed. In this configuration, the cooling system is always off and the largest photovoltaic system is used.

Table 6. Optimal solution minimizing net site energy.

Optimal Point	**n°**	**1**
Net site energy	[kWh/m^2 year]	−154.18 *
U-value external walls	[W/m^2 K]	0.8
U-value roof	[W/m^2 K]	7.0
U-value ground floor slab	[W/m^2 K]	3.8
U-value semi-exposed ceiling	[W/m^2 K]	0.8
U-value windows	[W/m^2 K]	3.0
g-value windows	[-]	0.35
Shadings	[%] of lit area	50
Cooling set-point temperature	[°C]	26
Cooling operation schedule	[-]	C1
Photovoltaic size	[kW$_p$]	Large
Cooling COP	[-]	3.5

* The electricity generation is higher than the electricity consumption. Convention of signs used: energy consumption is always positive.

Looking at the solutions that are closest to zero (indicated with the yellow band in the graph in Figure 11), it is possible to see that a balance close to zero can be achieved by turning on the cooling system with different schedules and by installing a small or medium-size PV system.

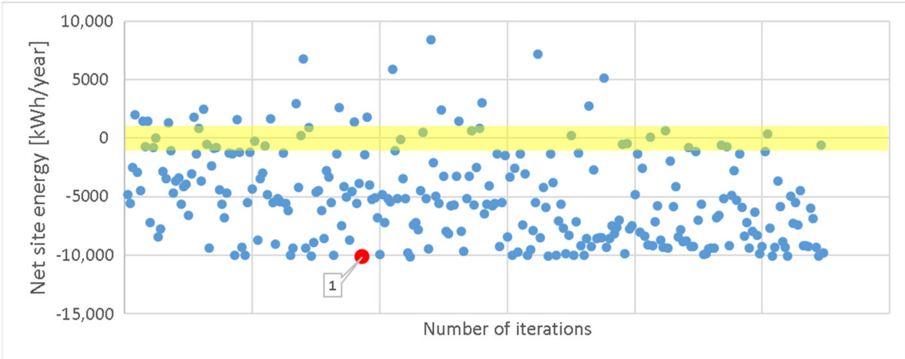

Figure 11. Single-objective optimization based on the minimization of the net site energy. The point n°1 indicates the optimal solution. The combinations closest to net "zero" site energy are highlighted with a yellow band.

3.4.2. Optimization of Net Site Energy and Discomfort ASHRAE 80% Acceptability

In the second phase, the optimization was conducted based on two objectives: minimizing the net site energy and minimizing the hours of discomfort calculated according to the ASHRAE 55, considering 80% acceptability. The point cloud obtained for the various combinations of measures is shown in Figure 12.

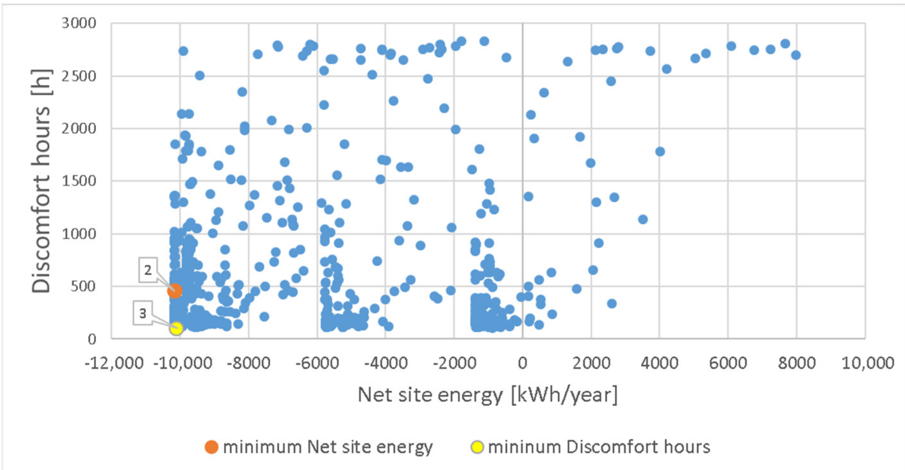

Figure 12. Optimization based on the minimization of the net site energy and minimization of discomfort hours ASHRAE 55 Adaptive 80% Acceptability. The points n°2 and n°3 correspond to the solutions with minimum net site energy and minimum discomfort hours, respectively.

The combinations of measures that generate the lowest net site energy (point 2) and the fewest hours of discomfort (point 3) are highlighted. The details of these two solutions are specified in Table 7.

Both optimal points were obtained by using the largest photovoltaic size and lead to a positive balance, with a notable energy surplus.

The graph in Figure 13 shows the grouping of points according to the size of the photovoltaic system. The figure highlights that a balance close to zero can be achieved by using a small photovoltaic system.

Table 7. Optimal solution minimizing net site energy and hours of discomfort.

Optimal Point	**n°**	**1**	**2**
Net site energy	[kWh/m^2 year]	**−154.50**	−153.80
Discomfort hours	[h/year]	462.6	**101.9**
U-value external walls	[W/m^2 K]	0.4	2.4
U-value roof	[W/m^2 K]	0.2	0.2
U-value ground floor slab	[W/m^2 K]	3.2	3.8
U-value semi-exposed ceiling	[W/m^2 K]	3.8	4.4
U-value windows	[W/m^2 K]	3.0	3.2
g-value windows	[-]	0.4	0.375
Shadings	[%] of lit area	30	30
Cooling set-point temperature	[°C]	27	26
Cooling operation schedule	[-]	C1	C1
Photovoltaic size	[kW$_p$]	Large	Large

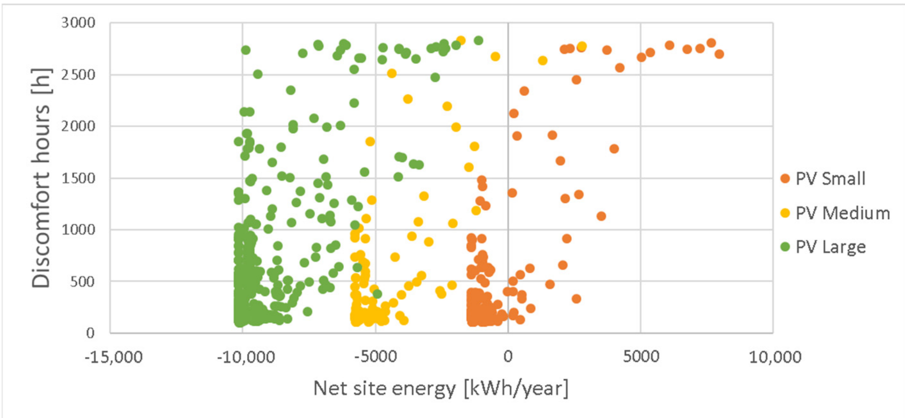

Figure 13. Optimization results grouped by PV size.

By limiting the search to a small photovoltaic size, the optimal solution can be identified at point 4, as indicated in the graph in Figure 14, which has the characteristics specified in Table 8.

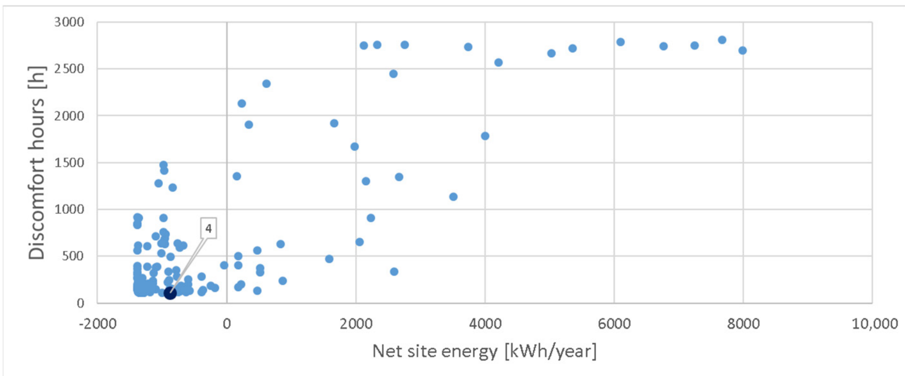

Figure 14. Optimal point considering only the combinations using small-sized photovoltaics. The point n°4 indicates the optimal solution.

Table 8. Optimal solution for minimum net site energy and fewest hours of discomfort using the small photovoltaic size.

Optimal Point	**n°**	**4**
Net site energy	[kWh/m^2 year]	−13.36
Discomfort hours	[h/year]	105.6
U-value external walls	[W/m^2 K]	2.2
U-value roof	[W/m^2 K]	0.4
U-value ground floor slab	[W/m^2 K]	3.8
U-value semi-exposed ceiling	[W/m^2 K]	4.0
U-value windows	[W/m^2 K]	3.0
g-value windows	[-]	0.375
Shadings	[%] of lit area	0
Cooling set-point temperature	[°C]	28
Cooling operation schedule	[-]	C2
Photovoltaic size	[kW$_p$]	small
Cooling COP	[-]	3.8

The graph in Figure 15 shows the optimization results, grouped based on the cooling schedule. The points are quite spread out and it is not possible to identify precise groupings. The points at the top, highlighted with the red band, are those that present the greatest number of discomfort hours, despite having the cooling schedule always "On". The high number of discomfort hours obtained for these points is due to the excessively low set-point temperature and the inadequate characteristics of the building envelope. On the other hand, the green band identifies points with the lowest number of discomfort hours. Among these, there are many combinations in which the cooling schedule is always "Off". In this case, despite not using the cooling system, comfort is guaranteed by the good performance of the building envelope.

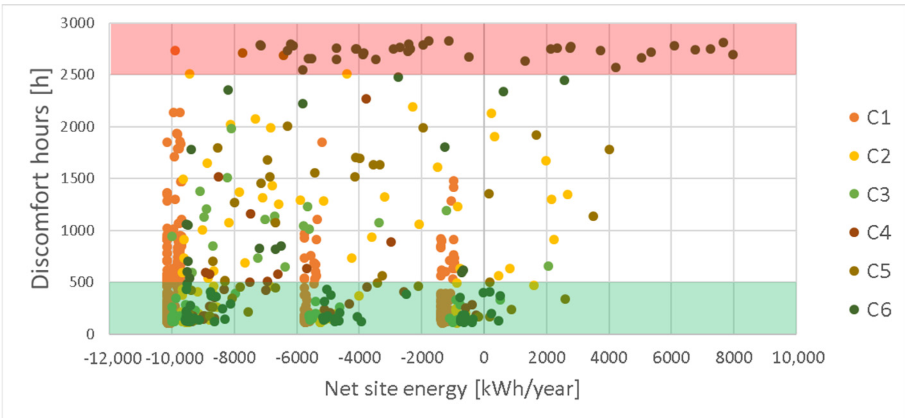

Figure 15. Optimization results grouped according to the cooling schedule. The red and green bands represent the solutions with greater and fewer discomfort hours.

4. Discussion

Building performance optimization studies generally are based on objective functions that include economic aspects (e.g., minimizing Life Cycle Costs, overall investment costs, or building operation costs, or maximizing Net Present Value), energy aspects (e.g., minimizing overall primary energy, total electrical load, etc.), and environmental aspects (minimizing life cycle environmental impact, carbon emissions, etc.). Optimization studies focused on comfort, particularly in Zero Energy buildings, are not widespread and typically consider parameters such as minimizing the Predicted Mean Vote (PMV) or Predicted Percentage of Dissatisfaction (PPD) [12]. Boutet et al. [58] conducted an optimization in a hot and humid climate but focused specifically on hygrothermal and daylighting behavior in a school in Argentina. The procedure developed by Chen and Yang [59] was aimed at finding the optimal solution as a function of cooling and lighting. Visual comfort was also the subject of optimization in the work carried out by Rabani et al. [60] for an office building in Norway. Differently from the studies available in the literature, the present research aimed at investigating the optimization of Net Zero Energy Buildings in tropical climate, with respect to building renovation, considering the combination of two objective functions, which are the minimization of energy demand and minimization of hours of discomfort, evaluated according to ASHRAE 55 Adaptive 80% Acceptability. Other studies in the literature have investigated the feasibility of Zero Energy Building renovations in tropical climates. An example is provided by Ohene et al. [41]; however, they only conducted a parametric analysis and not an optimization, concluding that retrofitting existing buildings into Net Zero Energy Buildings in a tropical climate is feasible by applying passive strategies to the envelope and installing renewable energy systems. The results obtained from the present study indicate the PV size, the operating schedule of the cooling system, and the cooling set-point temperature as the most influential variables for minimizing the net site energy and hours of discomfort in the considered building. The thermal transmittance of the floor and external walls and the cooling COP were found to be moderately influential. The thermal transmittance of the windows, roof, and ceiling, together with the windows' solar factor and the shading type, were found to be the least influential variables. Giouri et al. [61] found that cooling set-point temperature and PV output are among the factors with the highest impact on annual energy demand and adaptive thermal comfort by evaluating a high-rise office building in a Mediterranean climate. Furthermore, it is possible to observe that occupancy hours are among the most influential variables on electricity consumption, as assessed by Chacón et al. [62]. Chen et al. [63] obtained a low influence of cooling COP. In contrast to the results obtained in the present study, Chen et al. [64] reported the thermal transmittance of windows and the level of exterior window shading as variables that have a great impact on building energy demand in a hot and humid climate. However, in this case, the analyzed building is a high-rise residential building for 30–40 story apartments.

As was also found by Al-Saadi and Al-Jabri [35], in warm climates, the largest share of consumption is related to cooling (up to 70%). Based on the results reached by Al-Saadi and Al-Jabri [35], optimal envelope solutions include single glazing for windows and thermal insulation ranging from 5 to 10 cm in the walls and roof. For a building in a Mediterranean climate, high thermal insulation was used for the walls and roof (U = 0.23 W/m^2 K), and low-transmittance glass (U = 0.9 W/m^2 K triple low-e glass with Krypton filling) was used for the windows [16]. In contrast, in the present study, the optimal solution involves low insulation for opaque structures and double glazing for windows. Among the envelope elements, floor thermal transmittance has the greatest impact on energy demand. In particular, cooling energy decreases as floor thermal insulation decreases. Similar outcomes were obtained by Gou et al. [65], who highlighted that improving ground thermal insulation can diminish the heat exchange between the building and the ground, resulting in a decrease in the building's energy performance. Abdou et al. [17] achieved the optimal solution for a building in Morocco using a ground floor with high thermal transmittance (U = 2.875 W/m^2 K). The optimal solutions identified in the current study involve a cooling set-point temperature of 26 °C or 28 °C, which is higher than that obtained by Hwang et al. [66] for a school building in a hot and humid climate, for which the analysis returned cooling set-point temperature values between 23 and 25 °C. The use of a photovoltaic system can produce surplus energy, which, in this case, was estimated at about 13.4 kWh/m^2 year. Similarly, Acar and Kaska [23] obtained excess energy of up to 23 kWh/m^2, 9 kWh/m^2, and 3 kWh/m^2 for a hot, semi-arid climate, Mediterranean climate, and cold, semi-arid climate, respectively.

The application of the renovation measures makes it possible to reduce the energy consumption of the case study by approximately 29%, over the 16% indicated by the regulations in force for newly constructed buildings [55].

The present study shows some limitations. First, the analysis conducted at this stage only focused on a single-family house. Other building types (e.g., apartment buildings) were not considered, nor were other uses, which could significantly change the results of the analysis. The thermal mass of the structure was not considered in the optimization parameters, because this is difficult to change in existing buildings. The interaction of the Net Zero Energy Building with the grid was not considered, and consequently the aspects of optimal load management and possible income from the sale of surplus energy are neglected. Furthermore, the environmental aspects, in terms of CO_2 emissions, were not evaluated, nor were the cost issues, which could be useful in assessing the economic viability of the renovation interventions. Finally, the study is limited to the climatic conditions of the analyzed site, and the effects of future climate change are not examined. As noted by Chai et al. [67], climate change could alter NZEBs' performance over their life cycle. Plant size, cost, and comfort satisfaction levels could show differences that occur under climate change.

5. Conclusions

The present study explored strategies for renovating existing buildings into Net Zero Energy Buildings in a tropical climate and proposed a methodology that can be followed for renovations to NZEB in a hot and humid climate. The analysis, conducted for a single-family house, allowed for the definition of some guidelines. The most important role is played by renewable energy. The installation of a photovoltaic system makes it possible to cover the cooling energy demand and the energy demand other uses of the dwelling. In the case of single-family houses, it is possible to exploit the entire roof area to place photovoltaic panels, reaching a size that allows for more energy to be produced than is required. It would be worthwhile to extend the study with a view to sharing the excess energy that is produced with other buildings. Regarding active measures, the use of a high-efficiency system is recommended. In the examined case, an electric heat pump was used, which works efficiently in combination with the photovoltaic system. With reference to passive measures, the analysis in a warm climate showed the need to carefully consider the thermal insulation of the envelope. In particular, optimal solutions were found with low external wall insulation. In addition, floor slab insulation is critical. This element, by allowing heat exchange with the ground, should be poorly insulated or uninsulated to favor heat losses and the consequent reduction in cooling requirements. Passive measures also include window shading. Finally, with regard to occupant behavior, a set-point temperature of 28 °C and nighttime operation were identified as optimal solutions that can reduce energy consumption and ensure comfort.

Future studies will be directed to the analysis of other types of residential buildings and buildings with different uses (e.g., office, commercial, education). The interaction of the building with the grid is worthy of further investigation, depending on the interchange that can take place between multiple NZEB buildings connected in energy communities, with the integration of storage systems with the energy produced by photovoltaics. After analyzing optimization from the perspectives of energy and comfort, the next step certainly requires economic optimization in terms of Life Cycle Costs, as well as the achievement of zero-emission buildings, including at the construction and operational phases. Finally, evaluation under different climatic conditions is required to expand the range of possible solutions, and studies under different climate evolution scenarios would also increase the validity of the results.

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Conflicts of Interest: The authors declare no conflicts of interest.

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