Analysis of Photovoltaic Panel Integration for Achieving Net-Zero Energy in French Residential Retrofits in a Mediterranean Climate

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Abstract. The construction sector significantly contributes to global energy consumption, with 34% of final energy use and 19% of greenhouse gas emissions. In the EU, buildings account for 40% of total energy consumption and 36% of emissions. Most energy use in buildings (about 65%) comes from structures built before 2000. To save energy, it is crucial to assess and enhance the energy efficiency of existing residential buildings, aiming to streamline retrofitting, reduce consumption, and improve thermal comfort. This study aims to identify optimal passive solutions for renovating a traditional "Puccini" house in Nice, France, to boost energy efficiency and comfort, considering the Mediterranean climate. This study involves implementing passive strategies suitable for existing structures, including insulating external walls, roofs, and floors, upgrading windows, utilizing internal canopies, and minimizing air infiltration. By deploying these passive strategies, the house's energy demand could be slashed by approximately 50%, dropping from 112.16 to 52.34 kWh/m²/year. To meet the remaining energy needs, integrating photovoltaic panels into the building's shell as an active system on the roof is proposed. This design not only preserves the building's aesthetics but also covers a substantial portion of the electrical energy demand.

1 Introduction

Recently, the concept of net zero energy buildings (NZEB) has emerged as a promising solution for renewable energy generation, energy security, poverty alleviation, and indoor comfort benefits [1]. NZEBs are defined as buildings that generate at least as much energy as they consume on an annual basis [2]. The adoption of energy-efficient optimization (EER) measures utilizing passive, active, and renewable energy sources is essential for reducing energy consumption [3]. Therefore, it is critical to identify optimal strategies that incorporate passive, active, and renewable energy approaches for retrofitting existing residential buildings to enhance energy performance. Moreover, the incorporation of energy system technologies, such as photovoltaic (PV) system, into building design is a fundamental approach for achieving zero-energy buildings. PV panels, whether they are installed on

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rooftops or integrated into building components like walls and facades, have been extensively studied [4-11] for their ability to generate electrical power for buildings. However, a significant concern when utilizing photovoltaic technology in buildings is the need to maintain the aesthetic appeal of the structure. Preserving the visual attractiveness of building facades is essential, especially in tourist cities with historical significance. This study aims to investigate the application of the latest coloured PV panel technology and its potential integration into multiple buildings in the city of Nice, located in a Mediterranean climate. The assessment of these coloured PV panels seeks to strike a balance between energy efficiency and architectural aesthetics, taking into account the unique characteristics of the region.

2 Literature review

Numerous studies have been conducted, yet a comprehensive solution for implementing passive strategies in existing buildings remains elusive. While research has focused on presenting both passive and active solutions, it is crucial that these strategies are harmonious with the architectural characteristics of historic buildings. However, many of these solutions may prove unfeasible or impractical for implementation in such structures. Huang et al. [4] studied retrofitting strategies to improve energy efficiency and thermal comfort in a high-rise residential building in northern China. Using DesignBuilder software, they analyzed the building and implemented passive solutions like insulating liquid in walls, roof, and floor, multi-glazed windows, and awnings on external windows. Simulations showed a significant reduction in energy consumption, with heating decreasing by 96% and cooling by 8.7%, resulting in an overall reduction of 78.9%. Meeting the Passive House standard could lead to annual energy savings of 1147,957 kWh.

Foda et al. [5] investigated the energy and cost efficiency of renovation measures for a single-family house across four climate zones in France. Their analysis encompassed building fabrics, ventilation strategies, air-tightness levels, and various heating systems, revealing that external wall insulation emerged as the most effective method, yielding energy savings of 100 kWh/m^2/year. Qu et al. [6] examined passive retrofit measures in a late 19th-century Victorian house to improve energy efficiency and thermal comfort. They focused on interior wall insulation, window upgrades, and air sealing. The researchers recommended final passive retrofits like vacuum insulated windows, air infiltration reduction, and 2 cm polyisocyanurate panels. This integrated approach resulted in a 51.8% reduction in primary energy consumption. Imanloozadeh et al. [7] developed a sustainable smart residential energy hub and home energy management system aimed at reducing energy expenses, consumption, and greenhouse gas emissions by optimizing power output and scheduling based on users' uncertain behaviours. Their study highlights the significant impact of uncertainty in consumer behaviour and residents' activity profiles on energy consumption predictions. Thus, accurate modelling of consumer behaviour activity profiles in simulations is crucial for effective energy management.

In a study by Sharma et al. [8], retrofitting strategies were evaluated using simulation methods. They conducted an energy audit and monitored an existing building to identify energy-saving opportunities through passive measures like insulation, window upgrades, and infiltration reduction. Results showed a 24.12% energy reduction and an 18.56% decrease in CO_2 emissions annually, with a 10.6-year return on investment. Passive solutions can significantly cut energy demand and improve comfort in older homes lacking proper insulation and ventilation. This study focuses on assessing the energy performance of historical houses in Nice, France, exploring the benefits of passive strategies and integrating photovoltaic panels for enhanced energy efficiency and sustainability. Lozoya-Peral et al. [9] studied energy performance in a traditional house on the Mediterranean coast in southeastern

Spain. They aimed to find passive solutions for renovating the house to improve energy efficiency and comfort. Their research focused on four strategies: better wall insulation, solar control glass with a movable canopy, larger windows, and natural ventilation with a ceiling fan. Simulations showed that combining these strategies could cut annual energy demand for cooling and heating by 87%. This study demonstrates the potential for creating a comfortable, energy-efficient home by implementing these strategies effectively. In another study, Hamzah et al. [10] conducted an experimental study on an iconic building, the Daya Bumi Building in Kuala Lumpur, Malaysia, evaluating the performance of an integrated photovoltaic system with colored building shell in a tropical climate region. While the study showcased the advantages of photovoltaic systems integrated with the building shell, it also highlighted limitations in terms of visual aesthetics, which were deemed unattractive for architecturally sensitive buildings such as historical and symbolic structures. Implementing photovoltaic systems integrated with the building shell in such buildings may pose significant challenges due to aesthetic considerations. In a recent study, Kutty et al. [11] conducted a comprehensive study on the renovation of an existing Puccini house in the Mediterranean climate of Nice, France, utilizing passive building systems and renewable energy strategies to achieve Nearly Zero Energy Building (NZEB) standards using Design Builder software. Their research demonstrated that the implementation of passive solutions, including thermal insulation in external walls (46.82% reduction), improved ventilation (20.39% reduction), sloping roofs with thermal insulation (33.03% reduction), high-performance windows (3.35% reduction), and maximizing the window-to-wall ratio (5.53% reduction), resulted in a substantial decrease in energy consumption from 194.37 to 23.98 kWh/m^2/year. To meet the remaining energy requirements, normal PV panels were integrated into the building's roof. However, their focus predominantly revolves around technical solutions, neglecting the crucial aspect of aesthetic considerations, particularly in the context of historical buildings. This oversight is evident in their research, highlighting a significant gap that needs to be addressed. Upon reviewing existing research, it becomes evident that a comprehensive approach to enhancing the efficiency of traditional buildings in historical areas of Southern Europe is lacking. The integration of passive and active solutions within these structures must be analyzed concurrently, taking into account factors such as functionality, societal acceptance of technology, aesthetic harmony with the urban environment, as well as the economic and environmental implications of technological implementation. This study addresses this gap by proposing and evaluating a holistic solution that considers all these aspects in a comprehensive manner.

3 Methodology

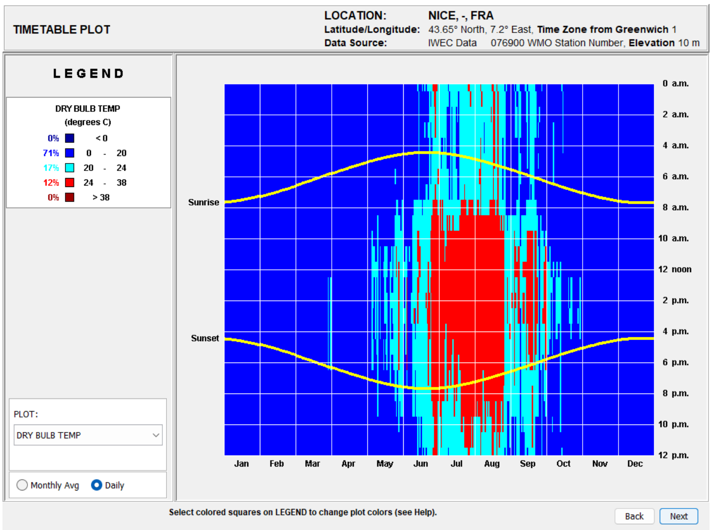
3.1 Case study of Nice, France

The city of Nice, located on the French Riviera at 43°7'N and 7°2'E, lies along the southeastern coast of the Mediterranean Sea (Fig.1). According to the Köppen climate classification system, the local climate is categorized as subtropical Mediterranean/summer dry (Csa), characterized by mild winters and hot summers [12]. The annual average temperature in Nice, France is mild at 15.1 °C, with average monthly temperatures showing a variation of 14 °C, which is relatively low. July stands out as the warmest month, with an average temperature of 22.5 °C, while January is the coldest month with a mean temperature of 8.5 °C [13]. August is recognized as the warmest month, with January being the coldest (Fig. 2). Therefore, effective cooling and ventilation strategies are crucial during the summer months (June to September), while heating strategies are essential in the winter months (December to March).

3.2 Climate simulation

In order to replicate the climate of Nice, the ClimateConsultant software was utilized. This software utilizes annual data from meteorological stations in EPW format, representing a 10-year average. Initially, a psychrometric diagram (Fig. 3) was generated based on this weather data, emphasizing key design strategies customized to the local climate to create comfortable living environments. Among these strategies, Internal Heat Gain emerged as the most influential, contributing 33.9% to overall comfort, followed by Heating and Humidification at 27.2% and Passive Solar Gain High Mass at 15.7%. These results highlight the significance of heating for comfort in Nice, as evidenced by the emphasis on heating-related strategies in the design recommendations. The visual depiction of these design strategies in Figure 4 is intended to facilitate their implementation for sustainable building construction. While the focus of the study is on existing residential structures, the suggested strategies can be easily integrated into established homes. Retrofitting measures in existing houses to reduce energy consumption include adding insulation to external walls and roofs, installing double-glazed windows, incorporating window awnings, and using indoor curtains to improve window insulation. An analysis conducted using DesignBuilder software further explored the energy implications of these design elements in traditional houses in Nice, demonstrating how these strategies can effectively enhance energy efficiency in pre-existing structures within a climate-specific context.

Fig. 1. The historical part of the city (https://en.wikipedia.org/).



TIMETABLE PLOT

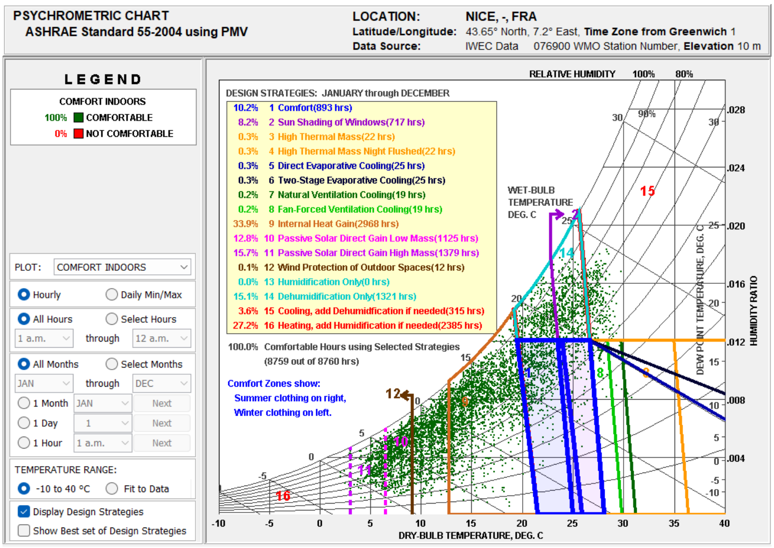
LOCATION: NICE, -, FRA
Latitude/Longitude: 43.65° North, 7.2° East, **Time Zone from Greenwich** 1
Data Source: IWEC Data 076900 WMO Station Number, **Elevation** 10 m

PLOT: DRY BULB TEMP

○ Monthly Avg ● Daily

Select colored squares on LEGEND to change plot colors (see Help).

Fig. 2. Timetable plot of Nice, France, ten-year average (ClimateConsultant Simulation).



PSYCHROMETRIC CHART
ASHRAE Standard 55-2004 using PMV

LOCATION: NICE, -, FRA
Latitude/Longitude: 43.65° North, 7.2° East, Time Zone from Greenwich 1
Data Source: IWEC Data 076900 WMO Station Number, Elevation 10 m

LEGEND
COMFORT INDOORS
100% 🟩 COMFORTABLE
0% 🟥 NOT COMFORTABLE

PLOT: COMFORT INDOORS
● Hourly ○ Daily Min/Max
● All Hours ○ Select Hours
1 a.m. through 12 a.m.
● All Months ○ Select Months
JAN through DEC
○ 1 Month JAN Next
○ 1 Day 1 Next
○ 1 Hour 1 a.m. Next
TEMPERATURE RANGE:
● -10 to 40 °C ○ Fit to Data
☑ Display Design Strategies
☐ Show Best set of Design Strategies

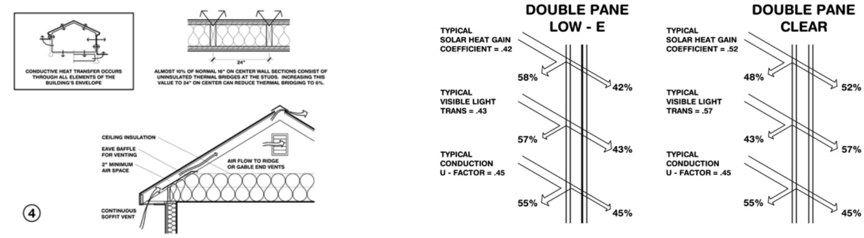
DESIGN STRATEGIES: JANUARY through DECEMBER

10.2%	1	Comfort(893 hrs)
8.2%	2	Sun Shading of Windows(717 hrs)
0.3%	3	High Thermal Mass(22 hrs)
0.3%	4	High Thermal Mass Night Flushed(22 hrs)
0.3%	5	Direct Evaporative Cooling(25 hrs)
0.3%	6	Two-Stage Evaporative Cooling(25 hrs)
0.2%	7	Natural Ventilation Cooling(19 hrs)
0.2%	8	Fan-Forced Ventilation Cooling(19 hrs)
33.9%	9	Internal Heat Gain(2968 hrs)
12.8%	10	Passive Solar Direct Gain Low Mass(1125 hrs)
15.7%	11	Passive Solar Direct Gain High Mass(1379 hrs)
0.1%	12	Wind Protection of Outdoor Spaces(12 hrs)
0.0%	13	Humidification Only(0 hrs)
15.1%	14	Dehumidification Only(1321 hrs)
3.6%	15	Cooling, add Dehumidfication if needed(315 hrs)
27.2%	16	Heating, add Humidification if needed(2385 hrs)

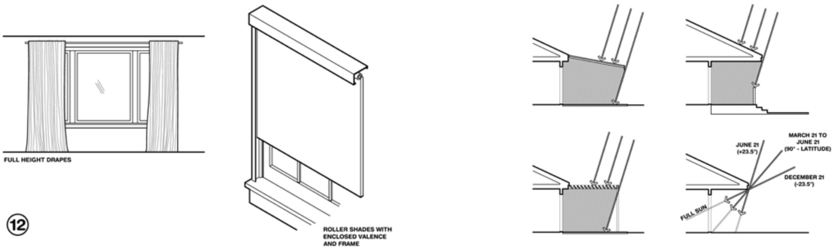
100.0% Comfortable Hours using Selected Strategies (8759 out of 8760 hrs)

Comfort Zones show:
Summer clothing on right,
Winter clothing on left.

Fig. 3. Psychrometric table of Nice, France (ClimateConsultant Simulation).



(a) Extra Insulation (b) Double pane high performance glazing



(c) Window shading (c) Window blind

Fig. 4. Visual depiction of the design strategies proposed by Climate Consultant Simulation.

3.3 Typology of houses in Nice

French housing is categorized into detached houses and apartment blocks. Research shows that 55% of housing in France consists of detached houses, with 63% built before 1974 without insulation due to the lack of thermal regulations. Retrofitting these homes can significantly enhance energy efficiency [14]. The two main styles of French individual houses are the single-story Mozart House and the two-story Puccini House, with the majority being two-story or Puccini houses. This study uses the floor plan of a pre-1974 Puccini house (refer to Fig. 5) as a model for French house architecture, featuring a main living room, three bedrooms, a shared bathroom, and a kitchen for families of three to six individuals (refer to

Fig. 6) [15]. The construction design of the Puccini house, lacking insulation due to pre-1974 regulations, serves as a basis for this study [5].

3.4 Building simulation

In this study, the DesignBuilder software was utilized to create the foundational model of the house based on specifications provided in references [14] and [15], These specifications are shown in Table 1. The house is designed to accommodate a family of four and is a two-story standalone residence primarily constructed with solid brick exterior walls, a non-insulated sloping roof with roof tiles, single-pane glass windows, wooden flooring between floors, light plaster interior walls, and an exterior floor made of solid concrete with wooden flooring. The occupancy schedule and associated activities for the main living areas (living room, bedroom, kitchen, and bathroom) were derived from a time use survey, while occupancy for other areas like toilets and corridors was obtained from the DesignBuilder library. Common household appliances, including kitchen appliances, audio/visual equipment, and personal computers, were considered based on modern technology available in the market [16]. The lighting design and power specifications were adopted from the DesignBuilder library. A standard ventilation rate of 0.5 air changes per hour (ACH) was used as a fixed input, accounting for intentional window opening or mechanical ventilation operation. The base model assumed an air permeability of the house due to leaks and cracks at 1.0 ACH. The heating system in the base model was electric with an efficiency of 1.0, and the transparency of the facades was set to 5% [5]. Puccini's house in DesignBuilder is modelled in Fig. 7.

Figures 8 and 9 illustrate the zoning plan found in the Residential folder within the Activity header, accurately assigning each section to its corresponding application. Defining activities in simulation is crucial as it helps segment different areas of a building based on cooling, heating, and lighting system usage, allowing for more precise determination of energy requirements aligned with the structure. This process helps to delineate the different spaces within a building based on the utilization of cooling, heating, and lighting systems. This enables a more precise determination of the energy required by the building, aligning it with the specific characteristics of the structure. Incorrect zoning can result in inaccurate assessments of the building's energy demand. In the study conducted by Kutty et al. [11], the building's zoning was initially established using default values in the software. However, this article emphasizes that all areas within the floor plan were assigned to specific templates within the activity section, and the spatial division of the house was simulated accordingly. It was observed that this zoning led to errors in the energy analysis of Puccini's house. Therefore, this study aims to rectify these previous errors by meticulously defining the zoning plan.

Fig. 5. Puccini houses in the Nice (Google Earth Software).

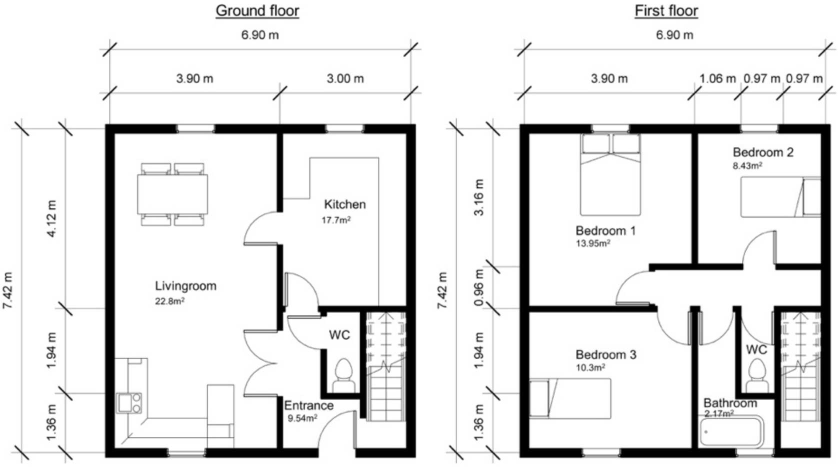


Fig. 6. Puccini house floor plan (Revit Simulation this study).

In this study, each area of Puccini's house is individually zoned, with appropriate activities selected for each section (Living room, Kitchen, Corridors, Bedrooms, Bathroom, and WC) within the Design Builder program, as depicted in Figures 8 and 9. Errors in zoning can lead to inaccuracies in analyzing the building's energy demand [7]. The simulated energy consumption of Puccini's base house with the main building envelope, natural ventilation strategy, and grid-connected radiator heating system is 112.16 kWh/m²/year. Using the baseline, the breakdown of annual consumption for heating, cooling, and lighting was estimated as 86.17, 0, and 25.97 kWh/m²/year, respectively. After creating the initial model of Puccini's house in DesignBuilder and calculating its annual energy demand using ClimateConsultant's tools, the next step is to explore passive solutions to reduce energy consumption towards achieving near-zero energy usage. These solutions include strategies like installing internal awnings (curtains), upgrading windows, improving wall insulation, enhancing roof insulation, optimizing floor insulation, and improving building ventilation systems.

Table 1. Details of Puccini's typology building.

Building Information	Description
Total area of building	102.4 m^2 ;115.52 m^2
Window openings (WWR%)	5%
External wall construction (in m)	(0.3) brick + (0.013 m) Plasterboard
Floor construction (in m)	(0.02) Soil—levelling layers + (0.2) Cast concrete + (0.02) Timber floor
Pitched Roof (in m)	(0.025) Clay tile+ (0.02) Air gap + (0.2) Timber flooring + (0.02) Plasterboard
Window type and glazing (in m)	Single-glazed (0.006) clear glass with wooden frame
Ventilation	Natural ventilation using operable windows
Heating system	Electric radiators with CoP 1
Cooling system	Not used
Lighting system	General lighting system provided
Domestic hot water system	As part of the heating system
Shading devices	No external shading devices provided
Infiltration	1.0 air change per hour (ACH)

Fig. 7. 3Dimentional view of Puccini house modelled in DesignBuilder software.

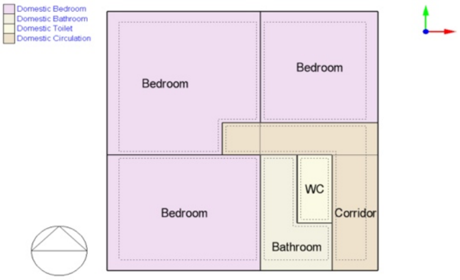


Fig. 8. First floor plan (DesignBuilder Simulation).

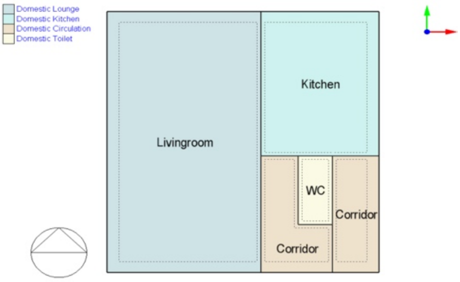
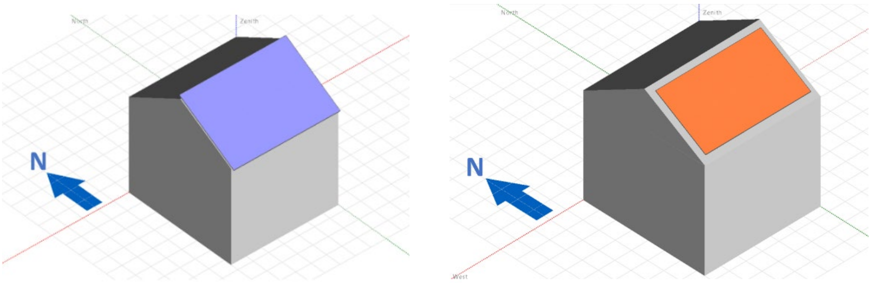


Fig. 9. Second floor plan (DesignBuilder Simulation).

Two common types of photovoltaic (PV) systems used in buildings are building attached PVs (BAPVs) and building integrated PVs (BIPVs) [17]. BAPVs are not integrated into the building structure, while BIPVs are PV modules that can replace conventional materials on the roof or building facade, making them an integral part of the building's energy system [18]. BIPV technology includes solar cell roofs, canopies, facades, and glass, and has gained popularity for meeting high standards of building thermal comfort and reducing energy consumption for heating, ventilation, and air conditioning (HVAC) [19] and [20]. This strategy is a viable option for enhancing the energy efficiency of buildings. When integrated into roof systems, photovoltaic panels can replace traditional roofing materials and function seamlessly as part of the roof structure. They offer the same performance as conventional roofing materials while generating electricity for the building [21].

To design a BIPV system for Puccini's house, suitable panels and an inverter must be selected. A hybrid inverter, a modern type of uninterruptible power supply (UPS), can store excess energy generated during the day for later use, especially at night [22]. Solar panels typically produce electricity during daylight hours, with peak production around noon, leading to fluctuations in energy generation that may not align with household consumption patterns. To address this issue, surplus energy needs to be stored for later use. A buck-boost converter is used to stabilize the voltage output from solar panels to ensure consistent levels, considering the natural fluctuations in solar and wind power sources [23]. After selecting the inverter, the next step is to choose the right solar PV panels for the roof. Manufacturers like Aiko, Sun Power, Jinko Solar, Canadian Solar, and LONGi Solar are recognized for their extensive research and development efforts [24]. LONGi Solar, in particular, has become the world's largest manufacturer of monocrystalline cells, with the Hi-MO 5m LONGi panels being well-suited for residential buildings. To enhance the aesthetics and seamless integration of integrated photovoltaic systems with the building shell, options include using monochromatic dark panels or coloured panels with a dark cellular layer.

Another approach is to incorporate semi-transparent and coloured layers in front of the cell layer to improve the facade's visual appeal. High transmittance of colour layers is crucial to minimize efficiency impacts and optimize energy efficiency. This can be achieved by applying a pigment layer in specific areas or making the colouring layer transparent [25]. Given the traditional location of the selected house in Nice, it is essential to use panels suitable for traditional buildings to preserve the city's aesthetic appeal. Futurasun offers coloured panels in red and orange designed for roofs and facades of traditional houses. While these coloured panels have lower strength and efficiency than normal panels, the coloured panel is chosen for simulation based on the colour of the Puccini houses' roofs in Nice. The simulation was conducted using PVsyst software with both the coloured panel and the normal panel (refer to Fig. 10).



(a) (b)

Fig. 10. Standard (a) and coloured PV panels (b) on roof of Puccini house (PVsyst Simulation).

4 Results and discussions

The findings are detailed in Table 2, illustrating a noteworthy decrease in overall energy usage to 111.75 kWh/m²/year through the implementation of diverse passive strategies. As indicated in Table 2, the substitution of windows with Low-E double-glazed windows containing argon filling proves particularly effective in lowering both total energy consumption and heating energy usage in the structure. Enhancing the thermal efficiency of the building's envelope via insulation is pivotal for achieving passive energy reduction in Puccini's House.

This study examined various wall configurations, with external insulation demonstrating the most substantial energy conservation. Among the wall models assessed, the one incorporating a 0.15-meter expanded polystyrene insulation layer displayed the greatest reduction in energy consumption, as depicted in Table 2. Various roof models with different insulation levels were examined to improve energy efficiency. By incorporating insulation layers on top of the wooden roof structure, energy usage can be further diminished. This holistic approach to insulation for walls and ceilings aids in decreasing overall energy consumption in the structure.

The study evaluated insulation materials such as glass fiber, phenolic foam, expanded polystyrene, and PVC. Among these options, it is clear that the roof with expanded polystyrene insulation provides the most substantial decrease in total energy consumption and heating energy usage in the building. Many older homes suffer from poor airtightness at the junctions between floors and walls, resulting in energy inefficiency. To tackle this issue, simulations were carried out using three arbitrary values (0.8, 0.4, and 0.2) representing air changes per hour (ACH) less than 1, compared to the base value of 1.

Table 2. The energy consumption in Puccini Building considering passive strategies.

	Passive Strategy	Total Energy kWh/m²/year	Heating kWh/m²/year
Internal shading	High reflectance - Low transmittance shade	111.75	85.97
Windows	Double-glazed, LowE (e3 = 0.1) (0.003) generic clear glass + (0.013) argon spacer + (0.003) clear glass	109.53	83.50
	Triple-glazed, LowE (e2 = e5 = 0.1) (0.003) clear glass + (0.013) argon spacer + (0.013) argon spacer + (0.003) clear glass	110.68	84.70
External wall	(0.013) Cement plaste + (0.1) Glass fiber quilt + (0.3) brick + (0.013 m) Plasterboard	81.90	55.45
	(0.013) Cement plaste + (0.1) Phenolic foam+ (0.3) brick + (0.013 m) Plasterboard	81.19	55.20
	(0.013) Cement plaste + (0.1) Expanded polystyrene + (0.3) brick + (0.013 m) Plasterboard	81.19	55.20
	(0.013) Cement plaste + (0.1) PVC + (0.3) brick + (0.013 m) Plasterboard	91.60	65.62
	(0.013) Cement plaste + (0.15) Expanded polystyrene + (0.3) brick + (0.013 m) Plasterboard	78.83	52.84
Roof	(0.025) Clay tile+ (0.02) Air gap + (0.15) Glass fiber quilt + (0.2) Timber flooring + (0.02) Plasterboard	111.97	85.98
	(0.025) Clay tile+ (0.02) Air gap + (0.15) Phenolic foam + (0.2) Timber flooring + (0.02) Plasterboard	111.97	85.98
	(0.025) Clay tile+ (0.02) Air gap + (0.15) PVC+ (0.2) Timber flooring + (0.02) Plasterboard	113.73	87.75
	(0.025) Clay tile+ (0.02) Air gap + (0.15) Expanded polystyrene + (0.2) Timber flooring + (0.02) Plasterboard	110.74	84.75
Insulated airtightness	ACH 0.8 –Bad	107.49	81.50
	ACH 0.4 – Good	98.19	72.21
	ACH 0.2 – Very good	93.57	67.58
Ground	(0.02) Soil—leveling layers + (0.2) Cast concrete + (0.05) Glass fibre + (0.1) Concrete 1% reinforced + (0.02) Timber floor	114.42	88.43
	(0.02) Soil—leveling layers + (0.2) Cast concrete + (0.1) Expanded polystyrene + (0.02) Timber floor	114.69	88.71
	(0.05) Soil—leveling layers + (0.2) Cast concrete + (0.1) Wood fir pine + (0.1) Air gap + (0.05) MW stone wool + (0.2) Timber floor	113.99	88.00
	(0.02) Soil—leveling layers + (0.2) Cast concrete + (0.2) Air gap + (0.02) Timber floor	112.05	86.07

The outcomes in Table 2 also indicate that reducing ACH leads to a notable drop in energy consumption in the Puccini building, with total energy usage reaching 93.57 kWh/m²/year. Additionally, the study found that alterations in floor composition have minimal impact on energy consumption, except for the inclusion of an air gap which marginally decreases overall energy usage to 112.05 kWh/m²/year, as illustrated in Table 2.

By implementing all the aforementioned solutions simultaneously in the Puccini house, the total energy consumption decreases from 112.16 kWh/m²/year to 52.34 kWh/m²/year. Additionally, the heating energy demand drops from 86.16 kWh/m²/year to 26.36 kWh/m²/year, as illustrated in Table 3. This indicates that passive measures and tailored solutions for existing buildings can lead to a substantial reduction of approximately 50% in total energy demand for a passive house in Nice, France. Based on energy-saving solutions and passive measures implemented to reduce energy consumption in buildings, these strategies successfully led to a significant 50% reduction in energy usage compared to the baseline, resulting in a final energy requirement of 52.34 kWh/m²/year.

Table 3. Energy reduction in Puccini's house.

	Total Energy [kWh/year]	**Energy Per Total Building Area [kWh/m²/year]**	**Heating [kWh/m²/year]**
Old House	9322.29	112.16	86.18
Modified	3917.38	52.34	26.36

Overall, implementing each passive strategy can result in energy savings as outlined below:

1. Insulated external walls (29.7% reduction)
2. Enhanced ventilation and air permeability (18.59% reduction)
3. Insulated ceilings (1.2% reduction)
4. Utilization of high-performance windows and glazing systems (2.3% reduction)
5. Incorporation of internal shading (0.3% reduction)
6. Construction of insulated ground slabs (0.11% reduction)

To achieve Nearly Zero Energy Building (NZEB) efficiency at Puccini's house, PV panels are installed on the south-facing roof with a 30-degree slope. Despite a slight 0.9% energy loss due to the angle not being ideal for the city, this is negligible, and the same angle is used for panel installation. The south-facing roof has been maximized for panel coverage without shading, allowing for the installation of 12 panels in two rows. Normal PV panels generate 9373.38 kWh/year, while coloured panels produce 4765.12 kWh/year, translating to 101.06 kWh/m²/year and 51.37 kWh/m²/year, respectively. With passive design solutions, the energy demand of the Puccini building decreased from 112.16 kWh/m²/year to 52.34 kWh/m²/year. Using normal PV panels yields 101.06 kWh/m²/year, meeting energy needs with surplus for grid return. However, coloured panels produce only 51.37 kWh/m²/year, falling short of the building's energy requirements. According to Table 4, in the case of using normal PV panels, the amount of energy produced by photovoltaic panels is more than the amount of energy demanded in the Puccini building, and in the case of using coloured PV panels, this amount is slightly less than the required energy.

Table 4. The energy demand of Puccini's house and the energy produced by the PV panels.

Parameter	**Value [kWh/m²/year]**
Energy consumption of modified Puccini's house	52.34
Energy production by standard PV panels	101.06
Energy production by colored PV panels	51.37

5 Conclusion

In this study, the energy efficiency of the Puccini house was evaluated through passive strategies, focusing on heating, lighting, and hot water consumption on an annual and monthly basis, given that electricity is the sole energy source used in the residence. The potential of PV panels installation on the roof as a means to reduce electricity consumption was also examined. Furthermore, the feasibility of integrating colored panels alongside passive energy solutions to decrease annual electrical usage was explored. The results indicated that by implementing passive design strategies, the total energy demand of the Puccini house could be reduced from 112.16 to 52.34 kWh/m²/year. Normal PV panels were found to generate 101.06 kWh/m²/year, while colored PV panels produced approximately half that amount at 51.37 kWh/m²/year due to their lower efficiency. Despite this reduction in efficiency, both types of panels were able to exceed the house's energy requirements. The integration of photovoltaic panels presents a technically feasible solution to achieve Zero Energy Building (ZEB) status. However, in historically significant European locations like old Nice, aesthetic considerations are paramount. The use of colored photovoltaic panels on a building's facade or roof can effectively address energy needs while enhancing visual appeal. Our analysis suggests that installing colored PV panels on a 100 m^2 roof of a traditional Puccini-style house can adequately meet its energy demands. For urban planners seeking to incorporate PV panels while preserving the architectural charm of historic structures, the adoption of colored panels emerges as a viable option. Future research avenues could explore the implementation of off-grid and standalone Microgrids tailored for Puccini houses, with a focus on integrating energy storage elements to enhance sustainability and resilience.

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