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A French Residential Retrofit toward Achieving Net-Zero Energy Target in a Mediterranean Climate

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Abstract: Cities are paying more attention to building energy use and carbon footprint for attaining sustainability. Within this building sector, there is a growing attention toward development and adoption of energy efficient retrofit strategies. Plagued by the lack of efforts in achieving comprehensive energy efficient retrofit solution sets (passive, active, and renewable energy systems), the authors acknowledge the concept of NZEB toward achieving energy efficiency by 2050. Toward this end, a numerical energy simulation modeling is carried out to retrofit an existing French "Puccini house" using 'passive, energy efficient building systems and renewable energy' strategies toward an NZEB target in the Mediterranean climate of Nice. Using Design builder 7.0, the simulated baseline energy model (Case A) is retrofitted through variations in the proposed energy efficient retrofit measures using two case scenarios (Case B: passive retrofit; Case C: energy-efficient building) to achieve NZEB (Case D). Assessing the performance of energy efficient retrofits using % energy reduction, the implementation of a high-performance building envelope is achieved using a thermally insulated external wall (46.82%), upgraded airtightness (20.39%), thermally insulated pitched roof component (33.03%), and high-performance window type—a glazing system (3.35%) with maximized window-to-wall ratio (5.53%). The maximum energy-saving retrofit solutions provide an ambitious reduction in energy consumption by approximately 90% from the baseline. A deep retrofitting of the French house meets the NZEB targets, as it reduces the baseline energy consumption from 194.37 kWh/m^2/year to 23.98 kWh/m^2/year using both passive and active strategies. The remaining energy demand is met by the integration of on-site PV panels (EUI= −27.71 kWh/m^2/year), which achieve an increase in energy production by 15.5%, while returning energy back to the grid (−3.73 kWh/m^2/year). Findings of this study serve as a guideline for retrofitting traditional French single-family residences, while contributing toward the NZEB goal.

Keywords: energy efficiency; renewable energy; NZEB; Mediterranean climate; retrofitting; single-family housing

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) recognizes, summarizes, and justifies the implications of climate change on building heating, cooling, and ventilation demands [1]. The building construction sector accounts for about 34% of global final energy use and 19% of energy-related greenhouse gas (GHGs) emissions [2]. The EU building stock contributes to 40% of the total final energy use and 36% of energy-related GHGs emissions [3]. Toward this end, the European Union (EU) has presented the Energy Performance of Buildings Directives (EPBD) and Energy Efficiency Directives (EED) to improve energy performance while cost-effectively reducing the CO_2 emissions. Additionally, guided by the 2030 framework for climate and energy resilience, the EU has pledged to attain 40% reduction in GHGs emissions with a 27% minimum integration of renewable energy sources [4]. Addressing the importance of affordable and clean energy for all, the United Nations SDG7 urges to further reduce these GHGs emission by 2050 (by up to 80%). According to the European Commission [4], about 65% of the building sector's energy consumption is accounted for by 87% of existing buildings constructed before 2000. Existing EU building stock is characterized by old, insufficient, and minimally renovated structures, while 25% of the building stock for the 2050s is yet to be constructed. Consequently, upgrading the existing building stock serves as a significant energy-saving potential, when compared to constructing new buildings with improved energy performance strategies. Hence, significant energy savings must be realized by achieving these targets through long-term retrofitting of the existing building stock and implementing on-site renewables or smart technologies [5–8].

Retrofitting, renovation, and refurbishment through modifications may improve the energy performance or decrease the energy demand. According to the EPBD and European Economic Community (EEC), the most effective means to attain energy efficiency is through the integration of renewable energy sources on site [9]. Over the past decades, the net-zero-energy buildings (NZEBs) concept has shown great potential for renewable energy generation together with energy security, poverty alleviation, and indoor comfort benefits [10,11]. NZEBs are defined as "buildings that generate at least as much energy as they consume on an annual basis when tracked at the building site" [12]. Implementation of energy-efficient retrofit (EER) measures through passive, active, and renewable energy sources is an important adaptation measure in minimizing energy use [13]. Although the EPBDs highlight the importance of cost-effective retrofits, they do not prescribe guidelines for implementing residential NZEBs [14]. These frameworks offer flexibility to each individual state in setting the targets [11,15]. Even though addressing NZEBs is at the core of the EU's energy directives, variations are characterized by energy performance, energy balance calculations, condition boundaries, and primary energy factors. This diversity in benchmarks indicate that adopting the 'one size fits all model' proves insufficient for achieving the NZEBs [16]. In this context, review studies suggest that conventional design strategies may result in an unacceptable performance or outsizing of renewable energy management systems [17]. Therefore, it is necessary to identify the optimal 'passive, active, and renewable energy' strategies to retrofit existing residential buildings for improved energy performance.

1.1. Previous Studies: Retrofitting Approaches and Concepts

Since 2000, there has been a vital amount of research on energy-efficient retrofits. Ansstasiadou et al. [18] studied the energy consumption patterns and methods of retrofitting using machine learning and statistical techniques to analyze energy performance benchmarks and related data. By proposing an integrated key performance indicators (KPIs) framework, McGinley et al. [19] applied a pre- and post-retrofit assessment, evaluating the environmental, economic, and social implications of retrofitting residences in Ireland. Similarly, Lingard [20] used dynamic simulations on a semi-detached dwelling to reduce the energy use and electrical demand by adopting active measures (heat pumps). Studies using appropriate combinations of passive design strategies for deep and shallow retrofits showed a reduction of 77% in heating and 79% in cooling energy demands [21]. Ulu and Arsan [22] developed an integrated approach using building performance simulation (BPS) and numerical analysis to determine the passive and active measures for retrofitting historic buildings in the Mediterranean. A methodology proposed by Streicher et al. [23] experimented on integrating and assessing the space-heating demand of passive retrofit measures on 54 building archetypes representative of the Swedish building stock. Examining the potential of passive, active, and renewable energy in NZEBs, Buso et al. [24] assessed the retrofit performance of an Italian building against the local NZEB targets. By carrying out renovations of Swedish and Finnish residences, Liu et al. [25] and Niemelä et al. [26] successfully reduced the primary energy use (PE) to about 25–42% and 39–62%, respectively. Kuusk et al. [27] proposed renovation strategies and assessed the energy and economic savings for single- and multi-family residences using simulation studies. The retrofits included strategies related to enhancement of the building envelope and the HVAC efficiency improvement. Hence, cost effectively, the Estonian building stock was retrofitted to achieve a 50% reduction in the primary energy consumption. One major limitation in these studies is the possibility of performance gaps between the estimated and actual energy savings. The above literature focuses on residential typology while using simulations for analysis. Additionally, some studies have used field measurements for validations as well.

1.2. Challenges, Problem Statement, and Objectives

Previous studies suggest that residential NZEBs in Italy, Austria, Hungary, Croatia, Germany, and Slovenia are 74% more energy efficient in comparison to the national standards. Among the EU members, ongoing progress is being made by Denmark and Austria in achieving specific requirements for high-performance building envelopes [11]. Considering the growing focus on energy efficacy, the European building codes are regularly updated to meet these regional-specific requirements. Despite the relevance, all the countries in the EU do not have clear retrofitting regulations. Moreover, one of the primary challenges lies in the present estimated retrofit rate of 0.6%, which demands a substantial increase [28]. Among them, France (551,695 km^2) is the largest state anticipated to exhibit extreme heatwaves and temperature events (2100–2170) [29]. Troubled by diverse climates (arid, temperate, Mediterranean/oceanic, continental, and the tundra), a considerable performance gap is observed between the current regulations and the existing building energy requirements. Accordingly, clear strategies must be devised to address the building energy retrofits to meet a particular climate zone in France [30].

There is a considerable increase toward the development and adoption of comprehensive retrofitting strategies for energy-efficient planning [31]. Success of the adopted energy strategies depends to a great extent on the strict enforcement of regional regulations. Since single-family residences constitute about 80% of the existing building stock [32], addressing the retrofits within this sector makes a compound improvement in achieving the 2030 and 2080 targets set by the EU. However, this area is plagued by certain shortcomings that influence the selection of the retrofit strategies and their effectiveness [33]. These factors include:

(1) Lack of regional and national standard targets to retrofit existing building stock while allowing for comparisons among energy-efficient constructions;
(2) Significant burden considering the incurred cost for the use of energy-efficient technologies and renewable energy systems [34];
(3) Lack of appropriate knowledge and awareness by building professionals and the house owners;
(4) Lack of efforts in achieving comprehensive retrofit solution sets (passive, active, and renewable energy systems) toward realizing the NZEB goal by 2050 [35].

Although there are alternative methodologies and technologies for retrofitting, studies by Ruparathna et al. [36] suggest that the selection of optimal solution sets is highly complicated. This study attempts to bridge the existing gap by answering the following research questions:

(1) What is the current state of knowledge regarding the NZEB concepts?
(2) What is the most relevant energy-efficient retrofit (EER) measures for conceptualizing a residential NZEB under the Mediterranean climate in France?

To answer these questions, this paper carries out an experimental simulation study to retrofit an existing French Puccini house using ‘passive, energy efficient building systems and renewable energy’ strategies toward an NZEB target in the Mediterranean context.

The remainder of this paper is structured into four main sections. Section 2 describes the mixed-methods research design adopted by the study. The qualitative research includes a systematic study of literature case studies of NZEB (both renovated and constructed), while the quantitative research analyzes the case study, proposes the retrofit scenarios, and outlines the energy simulation modeling and validation process. Section 3 summarizes the final energy demands while discussing the individual and combined performance impact of the proposed retrofit strategies. Section 4 then compares the achievement of the NZE

Puccini house with the standard retrofit targets in France while highlighting the limitations of the study. Finally, Section 5 summarizes the findings and implications for future research.

2. Materials and Methods

To achieve the objectives of this study, a mixed-methods research design encompassing both descriptive (qualitative) and experimental (quantitative) approaches were adopted. The qualitative methods include a detailed analysis and in-depth understanding of energy-efficient retrofit (EER) solution sets for NZEBs, while the quantitative methods systematically integrate these resultant EER sets to simulate a selected building energy model. Accordingly, the efforts were directed toward optimizing the energy performance of a French Puccini house using selected retrofit solution sets. An energy-efficient retrofit refers to the process of installing and/or modifying parts of an existing building to make it more energy efficient or to reduce the energy demand. In addition, EERs play an important role in reducing the operational costs, especially in old buildings. Here, an EER solution set refers to the individual or combined passive-design building-envelope strategies, energy-efficient systems, and renewable energy generation strategies that may be implemented to achieve energy efficiency.

The proposed methodological framework toward achieving NZEB, while isolating and understanding the impact of individual and combined EER solution sets, is presented in Figure 1.

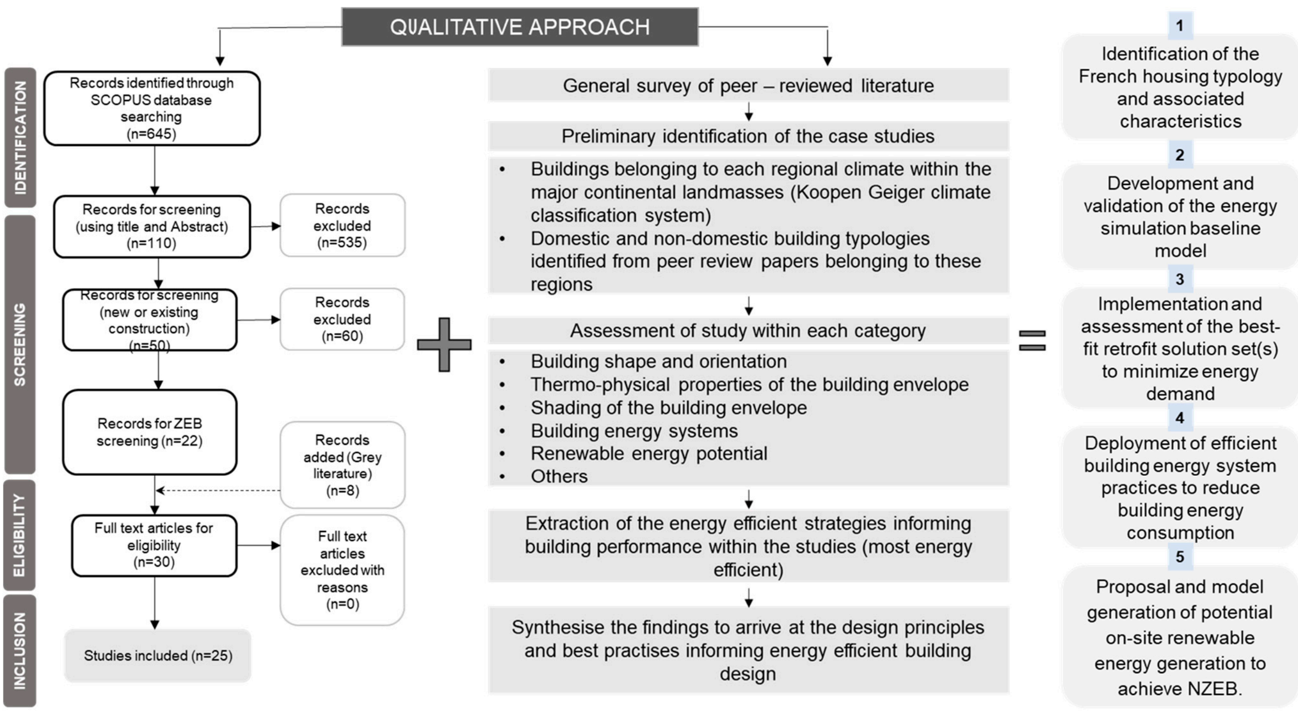


Figure 1. The research design depicting adopted methods and processes.

The effectiveness and validity of these retrofit measures were then assessed through a comparison with the energy performance requirements for residential NZEBs in France. The adopted EERs addressing the building envelope, building energy systems, and on-site RE sources provide practical guidelines for retrofitting existing residences (Puccini typology) built before 1974, hence making a considerable contribution toward the attainment of the NZEB goal.

2.1. Qualitative Method—Case Study Review

2.1.1. Selection Criteria and the Review Process

A four-step process proposed by Xiao and Watson [37] was adopted as follows:

1. Identification—which included literature search and sampling;
2. Screening—performed by applying the predetermined inclusion–exclusion criteria;
3. Eligibility—application of quality assessment criteria and procedures;
4. Inclusion—adoption of appropriate data extraction, synthesis, and reporting.

Initially, the Elsevier's Scopus electronic database was queried, resulting in 645 peer-reviewed journal articles and those published in conference proceedings [37]. These sources were identified by using the following query: *"Energy Efficient buildings"* OR *"NZEB"* OR *"NZEB"* OR *"Plus EB"* OR *"Positive EB"* (thus identifying studies in which these terms were used in the keywords, title, or abstract). This initial set was then subjected to further scrutiny based on a three-stage procedure to exclude the articles that were unrelated to the research questions. Toward the end of this sequential process, the identified literature sources were subjected to "internal validity", whereby works directly related to residential NZEBs were retained. The final set of research studies was supplemented with 25 technical reports addressing the principles and practical applications of NZEBs (which were classed as gray literature), as outlined in Figure 1.

2.1.2. Conception of Energy-Efficient Buildings or NZEBs: Summary of the Solution Sets

The conception of NZEB is based on the suitability of adopted strategies. Accordingly, three categories were identified from the reviewed literature, as shown in Table 1. The impact of space conditioning and building energy loads can be lowered by sources of energy consumption (such as heating, cooling, lighting, etc.) or by building design incorporations. Hence, the studies were analyzed to include both residential (56%) and non-residential (office and educational) projects (44%), within different climatic zones (e.g., 48% in temperate climates (Cfb) and 28% in continental climates (Dfa)). Figure 2 provides a graphical representation of the adopted strategies.

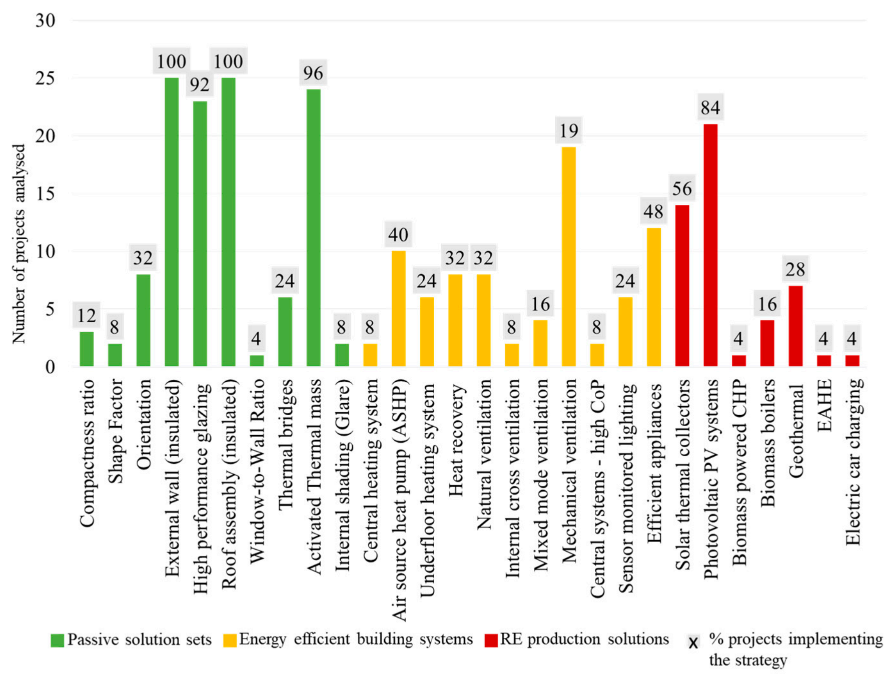


Figure 2. Frequency of the implemented energy-efficient solution strategies.

Table 1. Energy-efficient retrofit solution sets implemented toward achieving NZEB.

Project/Typology	Climate Zone	Passive Design Solutions										Active Energy-Efficient Building Energy System Solutions											Renewable Energy Production Solutions							PE Production (kWh/m²/year)	PE Consumption (kWh/m²)	Balance (kWh/m²/year)
		Building Form			High-Performance Building Envelope							Heating and Cooling				Ventilation Strategies					Lighting		On-Site Sources									
		CR	Shape Factor	Orinetation	External Wall	HPG	Roof Assembly	WWR	TB	ATM	Shading	CHS	ASHP	UH	Heat Recovery	NV	CV	MMV	MV	CS	SML	Efficient appliances	Solar TC	PV	Biomass-CHP	Biomass-boiler	Geothermal	EAHE	Electric car charging			
		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28			
The Botticelli Project (R)	Csa/Csb	✓			✓	✓	✓		✓	✓						✓	✓	✓	✓	✓	✓			✓				✓		−20.4	21.7	1.3
Efficiency House Plus (R)	Cfb			✓	✓	✓	✓		✓	✓		✓	✓	✓					✓			✓		✓					✓	−61.1	65.6	4.5
Grundschule Neuendorf (NR)	Cfb	✓		✓	✓	✓	✓		✓	✓						✓		✓	✓			✓		✓	✓					−20	20	0
Uhlandschule Stuttgart (NR)	Cfb			✓	✓	✓	✓		✓	✓			✓			✓			✓		✓	✓		✓						−24.1	42.9	18.8
Villa Isover (R)	Dfb			✓	✓	✓	✓	✓	✓	✓			✓		✓				✓			✓	✓	✓						−74	25.5	48.5
Šparna Hiža (R)	Cfa				✓	✓	✓			✓			✓						✓				✓							−40.4	40.4	0
Sems Have (R)	Cfb			✓	✓	✓	✓			✓					✓				✓			✓	✓	✓						−6.93	24.54	17.61
Rakvere Smart Building(NR)	Dfb				✓	✓	✓			✓									✓					✓		✓	✓			−13.3	86.3	73
Vallda Heberg (R)	Dfb				✓	✓	✓			✓				✓					✓				✓			✓				−55.7	55.7	0
Center for Sustainable Landscapes (NR)	Cfa				✓	✓	✓			✓						✓								✓			✓			−60	57.5	−2.5
Philip Merrill Center (NR)	Cfa		✓	✓	✓	✓	✓			✓			✓		✓	✓	✓	✓	✓	✓		✓	✓	✓						-	-	-
Adam Joseph Center (NR)	Dfa			✓	✓	✓	✓			✓			✓	✓		✓		✓	✓		✓	✓		✓						−47	97	50
The Cambria Building (NR)	Dfb		✓	✓	✓	✓	✓			✓			✓								✓	✓	✓	✓						-	-	-
Maison Doisy (R)	Cfb				✓	✓	✓			✓				✓					✓				✓							−36.8	7.7	29.1
Maison Hanau (R)	Cfb				✓	✓	✓			✓				✓					✓				✓	✓						−105.4	41.55	−63.85
Järvenpää Zero Energy House (R)	Dfb				✓	✓	✓			✓					✓							✓	✓	✓			✓			>−44	44	0

Table 1. *Cont.*

Project/Typology	Climate Zone	Passive Design Solutions						Active Energy-Efficient Building Energy System Solutions								Renewable Energy Production Solutions				PE Production (kWh/m²/year)	PE Consumption (kWh/m²)	Balance (kWh/m²/year)
		Building Form	High-Performance Building Envelope					Heating and Cooling				Ventilation Strategies		Lighting		On-Site Sources						
Villa Isover (R)	Dfb	✓	✓	✓		✓					✓		✓		✓	✓	✓		✓	−40.4	40.4	0
Efficiency House Plus (R)	Cfb	✓	✓	✓		✓		✓	✓		✓		✓				✓			−93.2	61.1	−24.1
Horizont-Building Strassen (NR)	Cfb	✓	✓	✓		✓											✓	✓		−37.6	75.6	38
Brabantwoningen (R)	Cfb	✓	✓	✓		✓			✓			✓	✓			✓	✓			−95.3	44.2	−51.1
Down 2-000 (R)	Cfb	✓		✓		✓					✓					✓	✓		✓	−111.4	78	−33.4
Powerhouse Kjørbo (NR)	Dfb	✓	✓	✓	✓	✓					✓		✓	✓	✓		✓		✓	-	19.4	−18.4
Solar XXI (NR)	Csb/Csa	✓		✓		✓	✓		✓			✓				✓	✓			−30	32	2
Väla Gård (NR)	Cfb	✓	✓	✓		✓							✓	✓	✓		✓		✓	−38.1	42.2	4.1
Vallda Heberg passive house (R)	Cfb	✓	✓	✓						✓			✓			✓		✓		−55.7	55.7	0

Note: R: residential; NR: non-residential; PE: primary energy; CR: Compactness ratio; HPG: High performance glazing; TB: Thermal Bridges; ATM: Activated Thermal mass; CHS: Central heating system; ASHP: Air source heat pump; UHS: Underfloor heating system; NV: Natural ventilation; CV: Cross ventilation; MMV: Mixed mode ventilation; MV: Mechanical ventilation; CS: Central System-high CoP; SML: Sensor monitored Lighting; Solar TC: Solar Thermal Collectors.

In projects relying on passive solutions, 10 different strategies were noted (Table 1). Although variable in their impacts, the passive strategies were shown to be the most effective in achieving the low/zero level of energy consumption. For example, in all 25 analyzed projects, a high-performance building envelope was employed, allowing the thermal mass of walls and ceilings to compensate for the heating/cooling requirements, and was further accompanied by high-performance glazing and airtightness (used in 23 and 6 projects, respectively). However, measures relying on the modifications of building form (such as shape and compactness ratios, window-to-wall ratio (WWR), and internal shading) were adopted in less than 12% of the projects.

The active energy-efficient category constitutes 11 strategies categorized under heating and cooling, ventilation, and lighting. For the heating and cooling systems, 40% of the projects relied on an air heat source pump, followed by heat recovery (32%) and underfloor heating (24%). For the ventilation category, 76% of the projects designed adopted an effective mechanical system, whereas natural ventilation and a mixed-mode ventilation system were adopted in 32% and 16% cases, respectively, and almost 50% of the project developers employed an efficient lighting system.

The renewable energy solutions category consists of only seven strategies used for energy production to ensure a zero-energy building balance, including a photovoltaic (PV) system, solar heating panels, thermal collectors, biofuel, geothermal, and earth–air heat-exchanger system (EAHE). As can be seen from Figure 2, PV systems were most prevalent at 84%, followed by solar thermal collectors at 54%, geothermal at 28%, and biomass boilers at 16%, whereas biomass-powered combined heat and power systems (CHP), earth–air heat-exchanger systems (EAHEs), and electric car charging were used in only 4% of the projects.

2.2. Quantitative Methods—Building Simulation

2.2.1. Case Study Context—Nice, France

The city of Nice is in the French Riviera at 43°7′ N: 7°2′ E along the southeast Mediterranean Sea coast. According to the Köppen climate classification system, the local climate is classified under hot Mediterranean/dry-summer subtropical climate (Csa), with relatively mild winters and very warm summers [38]. Belonging to the “Group C” zone, an average high and low temperature in the summer exceeds 27 °C and 17.3 °C, respectively, and these figures decline to 18 to −3 °C during winter [39]. August is the warmest month, while January is the coldest (Figure 3). Therefore, the summer months (June–September) require strategies for cooling and ventilation, while the winter months (December–March) require heating strategies.

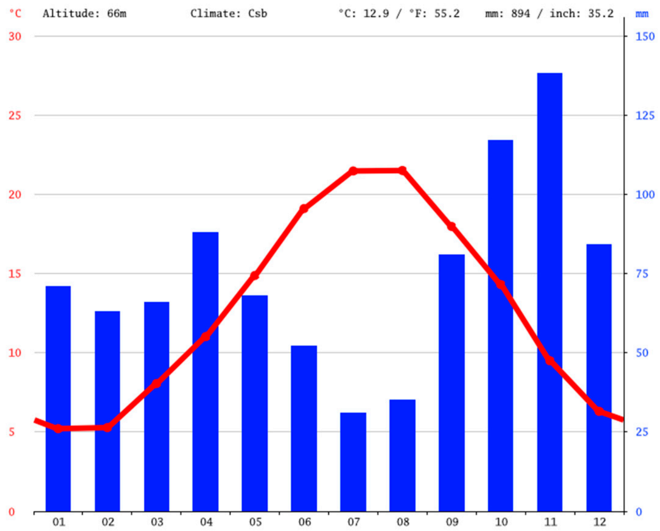


Figure 3. Nice (France) weather data: annual climate graph.

2.2.2. Bioclimatic Analysis—Psychrometric and Sun Shading Charts

A systematic procedure for thermal comfort assessment based on the external climate is provided by the combined analysis of the psychrometric chart and solar shading charts generated using Climate Consultant 6.0.

The chart shown in Figure 4 outlines the following zones: a comfort zone (1), passive heating zones (9, 11, 12, 16), and passive cooling zones (2, 14). As noticed in Figure 4, strategy 2 outlines the provision of window shading taking up to 8.2%, which amounts to 717 uncomfortable annual hours. Hence, 717 h of comfort may be provided through implementation of appropriate shading devices. Only 0.3% of annual comfortable hours is achieved through direct evaporative cooling (strategy 5), adding up to 25 comfortable hours. About 33.9% of the thermal occupant comfort is achieved by harnessing the potential of internal heat gained (strategy 9) within the building through artificial lighting, electric equipment, or occupant internal activities. This includes about 2968 h annually. Using strategy 11, thermal comfort is achieved through passive solar gains. This includes about 1379 h (15.7%). For about 1321 h, thermal comfort is achieved through strategy 14, dehumidification only (3.7%). A 3.7% level of discomfort (320 h) may be removed using both the cooling and dehumidification (strategy 15) at the same time. To achieve thermal comfort, strategy 16 requires both the increase in air temperature through mechanical heating along with humidification to achieve 2624 h of comfort (30.0%). Clearly, a relatively small comfort zone (10.2%) for the building implies that both passive and active design strategies are needed to meet the heating and cooling requirements.

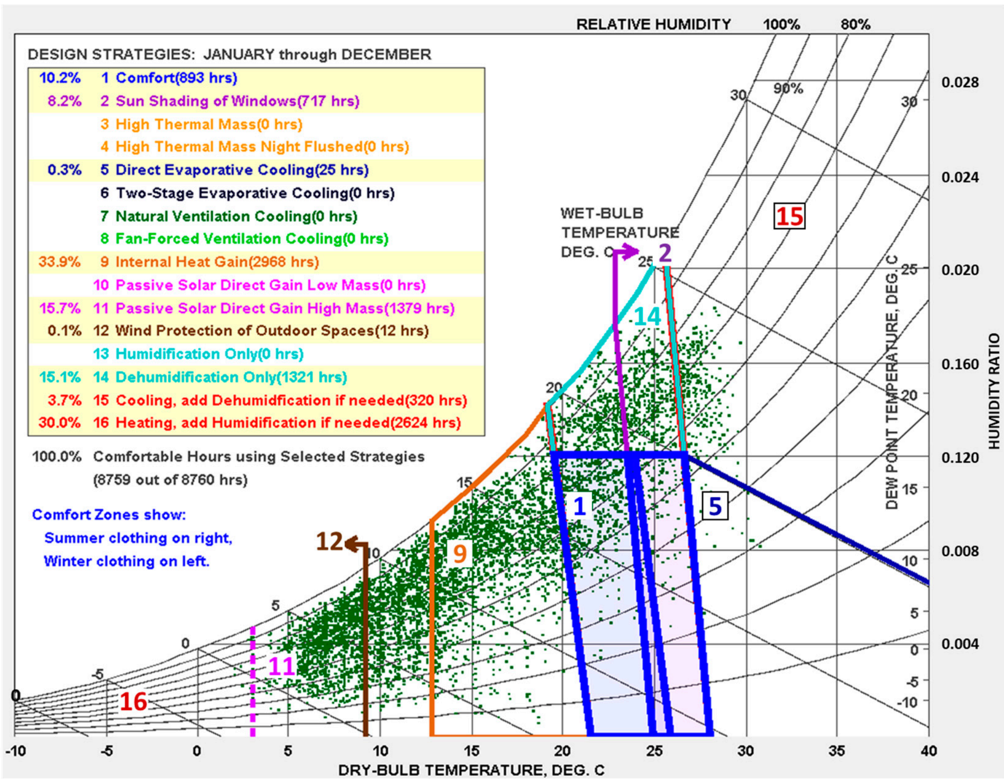
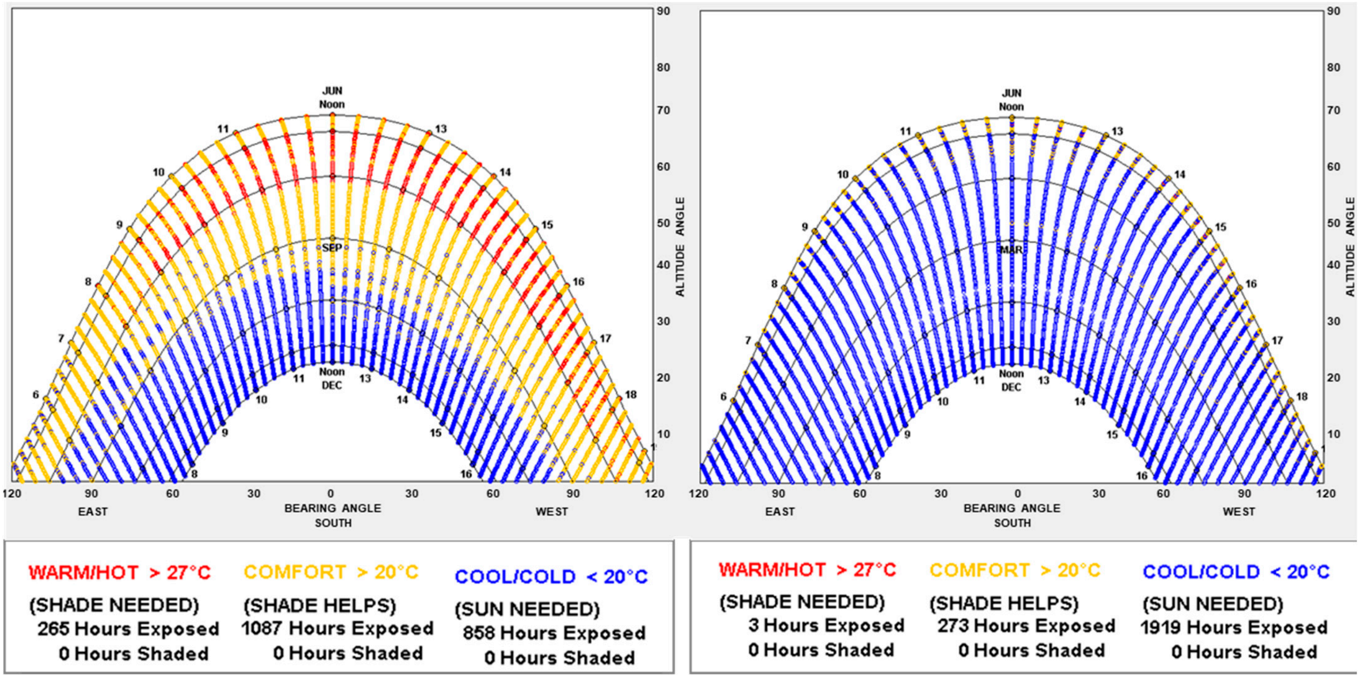


Figure 4. Psychrometric chart depicting the passive design strategies across the year for Nice, France.

During the winter and spring months, the sun is needed for 1919 h, along with 273 comfortable hours, whereas only 265 h of shading and 858 h of direct radiation are needed during summer (Figure 5). Hence, buildings in Nice require shading for only 268 h, while the availability of 2777 h of solar exposure must be ensured to maximize the solar heat gains during winter. Furthermore, the solar charts justify the need for passive heating at temperatures below 20 °C. Therefore, with these low ambient temperatures requiring direct solar radiation even during summer, it is imperative that greater efforts be concentrated on developing passive heating strategies.



(**a**) (**b**)

Figure 5. Solar radiation in Nice, France: (**a**) sun-shading chart for summer; and (**b**) sun-shading chart for winter.

The global horizontal solar irradiation is the most intense in the Provence–Alpes–Côte d'Azur (Nice) regions of France [40]. A high solar radiation is correlated with the high photovoltaic potential of Nice, which is estimated to exceed 1607 kWh/kWp [41]. In addition, the residential solar photovoltaic power capacity generated in France has gradually risen from 361 MW in 2010 to 1193 MW in 2018 [42]. Clearly, solar energy should serve as the alternate source of RE generation in Nice.

2.2.3. Residential Building Stock

While reviewing the impact of microclimatic variables on energy use, Ko [43] identified housing type and size as among the most important criteria influencing residential energy use. Based on the TABULA/EPISCOPE residential building typology studies by Intelligence Energy Europe (IEE), four typologies of residences are identified within the French national building stock [44]. They are categorized as (a) single-family house, (b) single-family terraced house, (c) multi-family house, and (d) apartment blocks [44,45]. Documenting these typologies for the CIMBETON project, the CSTB (Centre Scientifique et Technique du Bâtiment) studied these single-family homes under subcategories, namely, (a) "Mozart" (single-family house) and (b) "Puccini" (terraced single-family house) [35,45,46]. Statistical data of the building-type frequencies in 2013 report that 65% of the housing stock were built before 1974, of which approximately 90% are single-family homes [44]. Notably, the "Puccini" house constitutes 21% of this single-family housing stock [44]. Since a high percentage of the existing French building stock was constructed before 1974 with non-insulated construction [35], retrofitting is one of the most cost-effective measures to reduce energy consumption while improving indoor comfort.

Based on age band and sub-types, a medium-sized single-detached two-story "Puccini" house was chosen for modeling the baseline energy consumption representing the French housing stock [45,47] (Figure 6). This simple house designed for a medium-sized family of three to six members consists of the main living room, three bedrooms, one shared bathroom, and a kitchen. Since the French thermal regulations were not implemented until 1974 [35], the Puccini (built pre-1974) building layout was considered equivalent to non-insulated construction, as detailed in Table 2 [35,45].

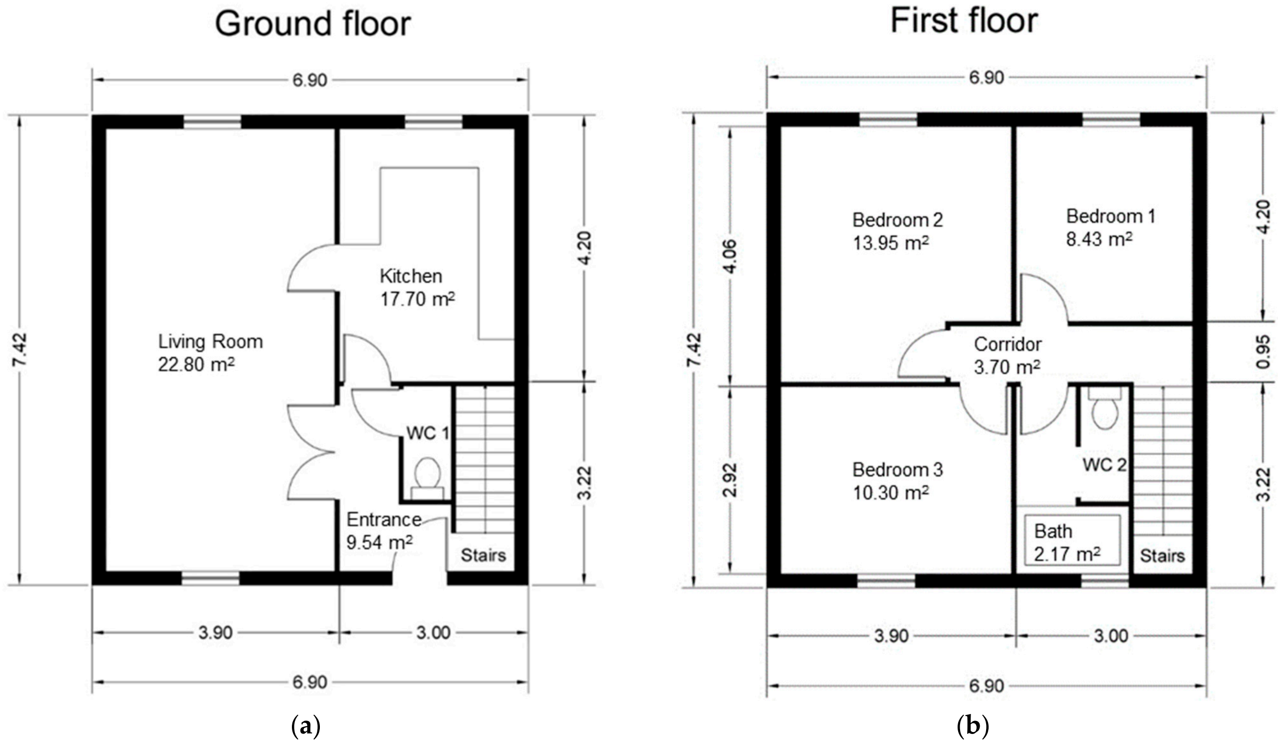


Figure 6. The layout of a single-family detached Puccini housing unit: (**a**) ground floor and (**b**) first floor.

Table 2. The Puccini typology building details (adapted from [35]).

Building Information	Description
Project and typology	A 'Puccini' typology of a detached single-family French residence in Nice, France
Total area of building (net and gross area)	102.4 m^2;115.52 m^2
Climatic region	Group C: temperate climates; Csa = hot-summer Mediterranean
Levels above the ground	G + 1
Window openings (WWR%)	5%
Construction type	Typical detached house before 1974 with non-insulated solid wall, ground flooring, and flat roof
External wall construction (in m)	(0.01) Gypsum board + (0.11) brick + (0.01 m) timber sliding
Floor construction (in m)	(0.05) Soil—leveling layers + (0.2) cast concrete + (0.2) timber floor
Roof construction (in m-flat roof)	(0.013) Plaster board + (0.2) wooden roof floor
Window type and glazing (in m)	Single-glazed (0.006) clear glass with wooden frame vertical divider
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

2.2.4. Building Simulation Software

A computationally simulated energy model together with its validation is the most efficient approach to study building form–energy relations [48]. Among the different tools developed to run the simulations, studies in this field have emphasized the validity and suitability of the Design Builder (DB) software [49–51]. Although several scientifically validated building-performance simulation (BPS) tools are currently in use, two distinct analysis programs were chosen for this study: the EnergyPlus calculation engine and the Design Builder graphical user interface (GUI). Accordingly, Design Builder 7.0 software was used to run a one-year simulation, the input parameters and data of which are detailed in the coming sections (Figure 7).

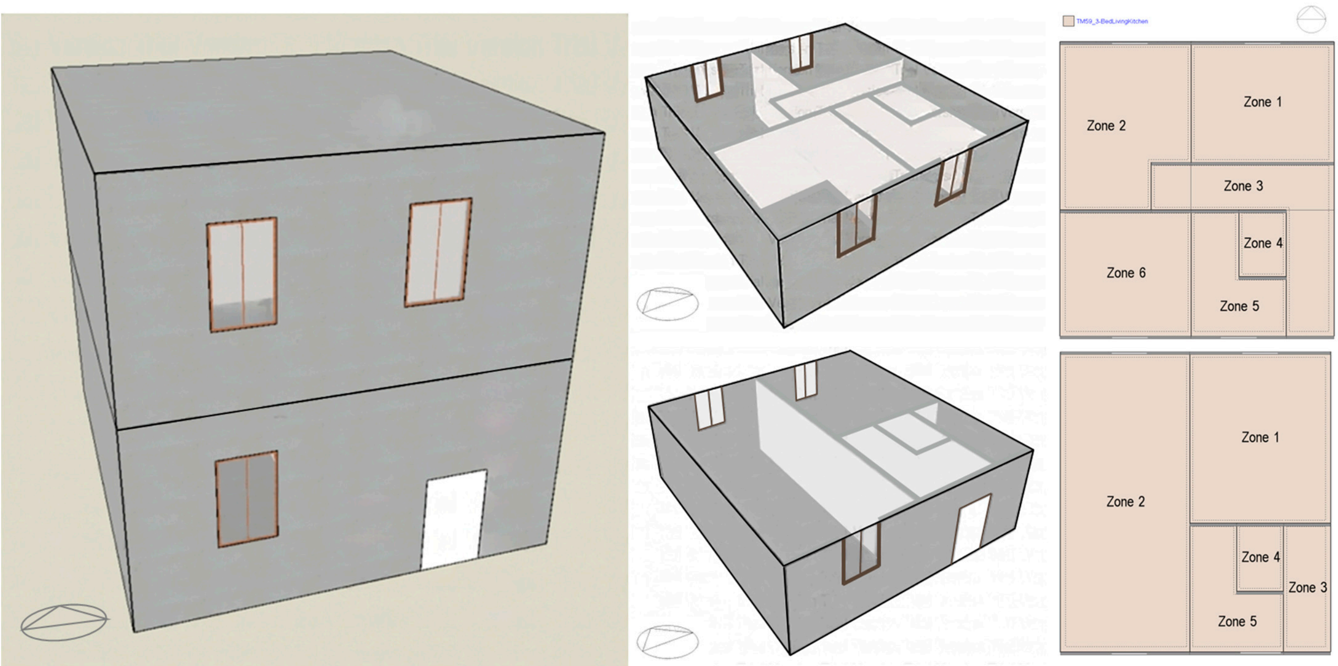


Figure 7. The baseline single-family residential "Puccini" house simulated using Design Builder software.

2.2.5. Model Implementation Process and Input Data

To set up and generate the energy models, the following design parameters were considered:

1. Climate and outdoor environment;
2. Construction materials;
3. Building schedules (occupancy and domestic hot-water use) and load (lighting, plug-outs, heating, cooling, and natural ventilation).

The climate data was provided by Energy Plus in .epw format, while the outdoor environment parameters were defined by the DB library based on the climate of Nice. The set-point internal temperatures and the indoor air temperature during the heating periods are set at 21 °C during morning and 18 °C at night for maximum occupancy with minimum air change per hour (ACH).

Occupant-related design parameters and activities were based on the general occupied zones, while other zones were based on Design Builder 7.0 domestic schedules (Table 3). Additionally, domestic appliance usage for each zone was based on the data yielded by the survey conducted by Noel [45]. The energy profile for the skin load-dominated building included the power released by a person (estimated at 140 W), and other relevant details that were not available were estimated as follows: activity level—110 W/person, and a typical indoor winter and summer clothing combination type of 1.0 clo and 0.5 clo, respectively (Table 3).

Table 3. Baseline building schedules for load calculations.

<table>
<tr><th>Function</th><th colspan="3">Occupancy Schedule</th></tr>
<tr><td rowspan="4">Residential</td><td>Occupancy density (p/m^2)</td><td>0.04</td><td>All year round [1]</td></tr>
<tr><td>Equipment power density (W/m^2)</td><td>4</td><td rowspan="3">Morning—7:00—9:00; 16:00–22:00
Night—22:00–7:00</td></tr>
<tr><td>Lighting power density (W/m^2)</td><td>3</td></tr>
<tr><td>Illuminance (lux)</td><td>200</td></tr>
</table>

[1] Occupancy rate is based on the Puccini housing typology, whereas assumptions are made accordingly for unknown data.

To further explore the relationship between building form and thermal behavior, layered details of both opaque and transparent components were specified according to the existing visual data and EPBD codes [35]. Oriented at 0° with respect to the N–S cardinal axis, model setup for the baseline included a single-family detached dwelling unit constructed mainly of solid-brick external walls, flat wooden roof, single glazing, light construction partition walls, and concrete ground slab (Table 4). Each material is characterized by inertia levels, the fixed heat capacity of 1000 J, and convective exchange coefficients (U values). Furthermore, the transparency rate of the facades is set at 5%, with the E–W walls set at a zero flux on the exterior wall surface.

Table 4. Baseline material properties and construction details (adapted from [35]).

Construction	Materials Layers (from Outside to Inside)	U Values (kWh/m^2/year)
Exterior Wall	0.01 m gypsum board + 0.11 m brick + 0.01 m timber sliding	2.326
Ground Floor	0.05 m soil—leveling layers + 0.2 m cast concrete + 0.2 m timber floor	1.602
Interior Floor	0.2 m wooden	1.961
Partitions	2 mm × 25 mm lightweight gypsum	1.639
Roof	0.013 m plaster board + 0.2 m wooden roof floor (flat roof)	2.08
Windows	Single-glazed 0.006 m clear glass + wooden frame	5.77
Structure	Wooden structure with concrete flooring	
Floor-to-Floor Height (FFH)	3.0	
Window-to-Wall Ratio (WWR)	0.05	

The building systems consist of electric radiators for heating the designated zones with a performance coefficient of 1.0. The required heating energy is obtained from the district heating system, whereas a cooling system was absent for this housing typology (Table 5). Using a default lighting schedule, an illuminance of 200 lux was considered for the lighting systems. Additional details of the domestic use schedules and powers were also prescribed by the Design Builder 7.0 objects library. Yet, the natural ventilation standard rate of 0.5 ACH was applied as a constant input, implying the intentional opening/closing of windows based on the requirements (Table 5).

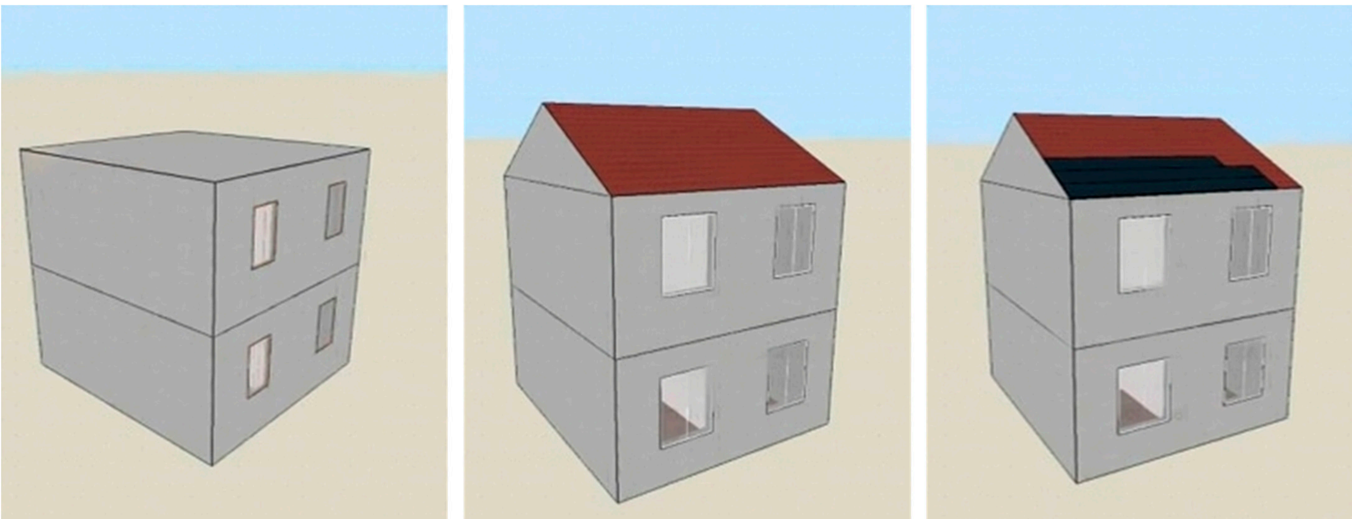
According to the Belgian studies on the existing EU building stock conducted by the Buildings Performance Institute Europe (BPIE) [52], old building stocks aim to meet the set renovation targets at the rate of 5–5.5% by 2030. The authors support the notion of increasing the energy efficiency of the old components by simultaneously offering energy conservation and energy generation solutions with resultant net-zero energy. Upholding retrofitting as a cost-effective approach, four different simulation case scenarios were developed (Table 6) (Figure 8).

Table 5. Zone information details—heating, ventilation, domestic hot water.

	Zone Information	Details
Heating	Heating setpoint (°C)	21 °C morning, 18 °C night
	CoP	1.0
	Maximum supply air temperature (°C)	35.0
	Maximum supply air humidity ratio (g/g)	0.0156
Ventilation	Infiltration rate (ACH)	1.0
Domestic hot water	Supply temperature (°C)	65
	Inlet temperature (°C)	10
	CoP	0.8
Windows	Operable area (%)	0.24

Table 6. Building simulation case scenario details and purpose (authors, 2021).

	Scenarios	Purpose
Simulation Retrofit cases	Case A: Baseline	Define the actual existing level of energy consumption.
	Case B: Passive retrofit	Define the level of energy consumption and % reduction after implementing building envelope (passive) retrofit strategies.
	Case C: Energy-efficient building	Define the level of energy consumption met by efficient building energy system (active) retrofit strategies.
	Case D: Net-zero-energy building (NZEB)	Define the level of primary energy consumption (energy-efficient systems + passive strategies) and primary energy generation (RE generation) to achieve net-zero-energy or plus-energy building.



(**a**) (**b**) (**c**)

Figure 8. The simulated "Puccini" house case scenarios to achieve n-ZEB/NZEB of French residential stock—(**a**) Case A: baseline; (**b**): Case B: passive retrofit; (**c**) Case D: n-ZEB/NZEB.

2.3. Retrofit Measures

Based on the findings yielded by the case studies, the following energy-efficient retrofit design solutions were proposed as the simulation retrofits:

1. Passive design solutions: optimized building form (orientation); thermal insulation of building envelope components (external wall, roof assembly, and ground slab construction); high-performance window types and glazing (window-to-wall ratio, WWR); and airtightness and permeability represented by infiltration rate.
2. Energy-efficient building system solutions: ventilation strategies (mechanical ventilation and mixed-mode ventilation); efficient heating systems and connection to the grid; and adjustable interior operable shading systems.
3. Renewable energy production solutions: application of on-site solar PV power system and solar thermal collectors.

3. Results

3.1. Baseline Energy Consumption

The baseline simulated energy consumption ($E_{puccini}$) of the Puccini house with the original building envelope, natural ventilation strategy, and a radiator heating system connected to the grid is 194.37 kWh/m^2/year. Using the baseline, the breakdown of the annual space heating, cooling, and lighting consumption was estimated at 181 kWh/m^2/year, 0 kWh/m^2/year, and 6.21 kWh/m^2/year, respectively. The site energy of 194.37 kWh/m^2/year denotes the energy consumed by the building that is reflected in the utility bills, while the source energy of 699.55 kWh/m^2/year represents the contribution of the district heating system. With a net conditioned area of 89.23 m^2, the breakdown of the monthly energy use reflecting the heating, cooling, lighting, domestic hot water, appliances, and plug loads is displayed in Figure 9.

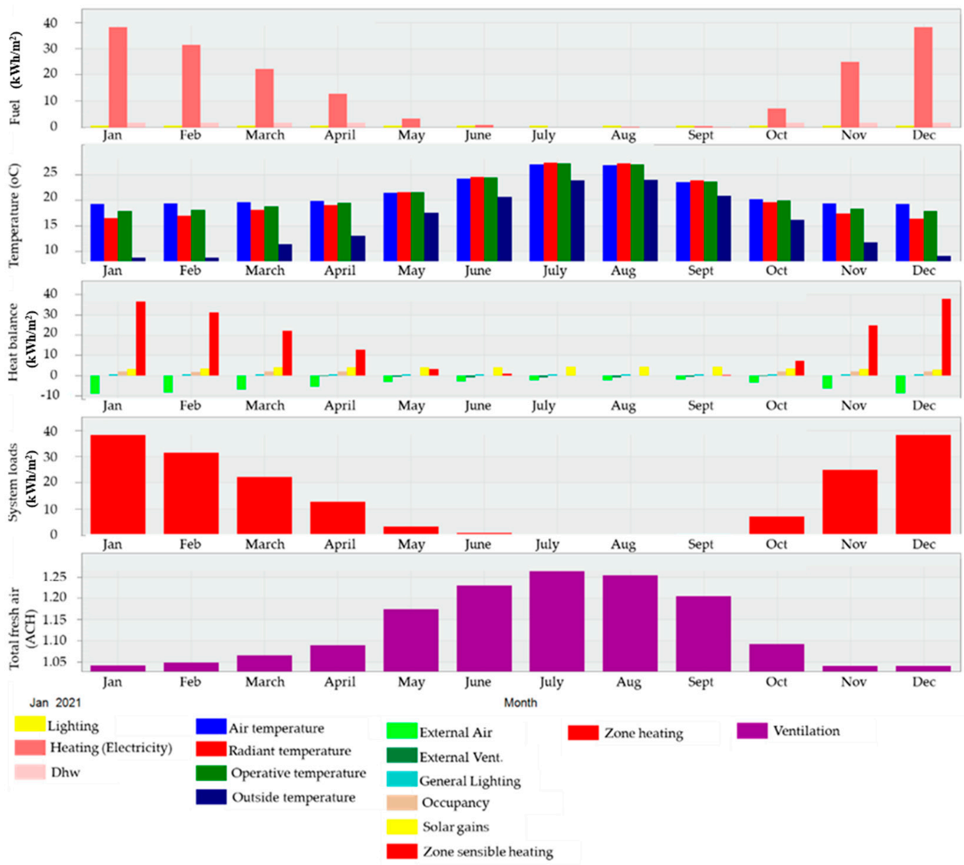


Figure 9. Baseline monthly breakdown simulation results: energy consumption, temperature, heat balance, and ventilation for the Puccini house.

The simulation was able to capture the increase in energy consumption during the winter months (October to April) because of the use of a radiator heating system connected to the district heating network. Clearly, most of the total energy consumed during this period is attributed to heating loads, whereas lighting, domestic hot water, cooling, and appliances consume almost negligible amounts of energy. This assertion may be verified by negatively correlating air temperature and dry bulb temperature with the heating electricity consumed. In simple terms, the coldest month of January with low dry-bulb (3 °C) and ambient air temperatures (18 °C) demands more energy for heating (38 kWh/m^2/year). In contrast, the warmest month of July with high dry-bulb (24 °C) and ambient air (27 °C) temperatures demands less energy for heating (0.5 kWh/m^2/year). The favorable air movement promoted by natural ventilation for thermal comfort will not provide the desired results, as shown in Figure 9. Here, the warm months (May–September) with high infiltration rates (approx. 1.0 ACH) negatively impact heating system efficiency. Moreover, variations in the thermal balance between the zone heating and external air throughout the winter months justify the use of interal heating.

Model Validation

Model validation ensures the objectivity and accuracy of the produced simulation data. As the "Puccini" house represents one of the traditional French residential stock, governmental documentation of utility bills, as well as consumer electricity bills, is lacking. Consequently, the space heat conditioning requirements of 188.16 kWh/m^2/year obtained in this study are compared with the findings reported previously for a Puccini house in the Mediterranean climate [35]. Using dynamic thermal modeling (DTM) coupled with optimization algorithms executed using the finite element plus (FE+) tool [39], a value of 181 kWh/m^2/year was obtained as the space-heating energy requirement for the baseline Puccini house. Using Equation (1) below, an error ratio of 3.805% is obtained. Hence, the simulated results of the heating energy and, hence, the total final energy of the Puccini baseline are validated.

$$\text{Error \%} = \left[\frac{\text{Reference} - \text{Simulated}}{\text{Reference}}\right] \times 100 \quad (1)$$

3.2. Impact of Retrofit Measures on Energy Demand and Consumption Reduction

The final energy demand using the proposed variants of the 10 individual retrofits in terms of percentage energy reduction is summarized in the following sections. In this study, all the scenarios are investigated based on the same ACH for ensuring accurate comparisons.

3.2.1. Individual Performance of Passive Strategies for Reducing the Energy Demand

Optimized building form through orientation: the building orientation affects the choice of the passive retrofit measures that would be appropriate for the high-performance building envelope or shading strategies [52]. Although orientation is a low-cost measure applicable only at the initial project stage, its impact on the baseline has been explored by the authors with the view of optimizing energy consumption [52]. A building oriented at 0° with respect to the N–S axis is rotated at 45° increments to obtain four variants (O_1, O_2, O_3, and O_4) along the NE–SW, SE–NW, SW–NE, and the NW–SE directions (Table 7).

Among the different variants considered, except for the initial 0° orientation to the N–S axis, all other orientations increase energy demand by 0.5–1.15%. Hence, the best orientation for reduced energy demand for the building is 0° along the N–S axis.

Thermal insulation of external wall component: the authors explored five insulated external wall constructions (W_1, W_2, W_3, W_4, and W_5) and compared them against the non-insulated baseline (W_0). These construction variants were obtained by changing the type, thickness, or placement of the insulation material incorporated into the inner layers of the external wall. The base wall and the variants were assigned a common outer wall layer of 0.11 m brick, 0.20 m cement render, and 0.01 m timber sliding, while the inner layer was assumed to comprise 0.01 m gypsum board. Three common insulation materials preferred by homeowners in the French market—namely, glass fiber, expanded polystyrene, and mineral wool of 0.1 m, 0.15 m, and 0.12 m thickness, respectively—were considered for all variants. Additionally, the wall retrofits were externally insulated to reduce the thermal bridges that would minimize the impact on internal floor areas and openings (Table 8).

Table 7. High-performance building through orientation.

Variants (n)	Orientation (Degrees)	$E_{puccini}$ (kWh/m^2/year)	% Reduction $E_{puccini}$
O_0	0°	194.37	-
O_1	45°	196.62	-
O_2	90°	197.03	-
O_3	135°	197.49	-
O_4	180°	195.27	-

Table 8. High-performance building envelope through the insulated external wall.

Variants n	Material Description (In m)	U W/(m^2.K)	U_{max} W/(m^2.K)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
W_0	(0.01) Gypsum board + (0.11) brick + (0.01 m) timber sliding	2.326	0.45	194.37	-
W_1	(0.01) Gypsum board + (0.11) brick + (0.10) glass fiber + (0.01) timber sliding	0.341	0.45	106.69	45.11
W_2	(0.01) Gypsum board + (0.11) brick + (0.15) glass fiber + (0.01) timber sliding	0.239	0.45	103.37	46.82
W_3	(0.01) Gypsum board + (0.11) brick + (0.12) expanded polystyrene + (0.2) cement render + (0.01) timber sliding	0.270	0.45	111.59	42.59
W_4	(0.01) Gypsum board + (0.11) brick + (0.2) cement render + (0.12) expanded polystyrene + (0.01) timber sliding	0.270	0.45	110.93	42.93
W_5	(0.01) Gypsum board + (0.11) brick + (0.2) cement render + (0.12) mineral wool + (0.01) timber sliding	0.259	0.45	110.32	43.23

Insulation of the building envelope plays a major role in passively reducing the energy demand in the old Puccini house. It is observed that the addition of insulation to the external wall can reduce the energy consumption by 45.11–46.82%. Moreover, all considered variants equally enhanced the resistance of the wall toward heat loss or heat gain through lower transmittance values when compared to the extreme high U value of the baseline (2.326 W/m^2.K). As expected, all considered wall retrofit variants provided a U value that was 0.2–0.3 W/m^2.K below the standard U_{max} value of 0.45 W/m^2.K. For example, W_2 (with the addition of 0.15 m glass fiber as the insulation material toward the outer wall layer) reduces the energy consumption by 46.82% with an improved transmittance of 0.239. In W_3, an increase in the thickness of the same insulation material from 0.10 m to 0.15 m further improved the energy reduction potential by 1.7% (Figure 10). Previous research emphasized the energy reduction potential of placing an insulating material within the outer walls to develop thermally activated building systems (TABS) [32]. However, the variants W_3 (42.59%) and W_4 (42.93%) based on the TABS principle failed to show significant variation in the percentage of the energy reduced (Figure 10).

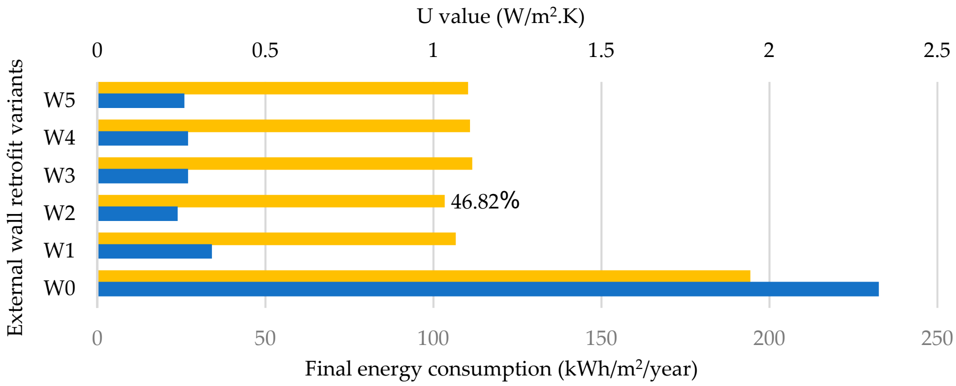


Figure 10. Insulated external wall retrofit variants with % reduction in the final energy consumption and corresponding U values.

Thermal insulation of the roof component: five roof component variants (R_1, R_2, R_3, R_4, and R_5) were compared with the baseline condition (R_0). To explore the potential benefits of increased thermal mass and insulation, different roof constructions were obtained by varying the roof type (lightweight pitched roof), and the type, thickness, or placement of the insulation within the roof floor. As an additional component in DB, the common layers were designated as 0.013 m plasterboard, 0.2 m wooden roof floor, and 0.005 m roofing felt finished with 0.025 m clay tiling. Insulation materials included 0.12 m expanded polystyrene, 0.9 m, 0.14 m glass fiber quilt, and 0.18 m mineral wool (MW) stone rolls (Table 9).

Table 9. High-performance building envelope through the insulated roof.

Variants n	Material Description (m)	U W/(m^2.K)	U_{max} W/(m^2.K)	k W/(m·K)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
R_0	(0.013) Plaster board + (0.2) wooden roof floor (flat roof)	2.08	0.25	0.44	194.37	-
R_1	(0.013) Plaster board + (0.2) wooden roof floor + roofing felt (0.005) + (0.09) glass fiber quilt + (0.025) clay tiling (lightweight pitched roof)	2.79	0.25	0.93	154.80	20.34
R_2	(0.013) Plaster board + (0.2) wooden roof floor + roofing felt (0.005) + (0.14) glass fiber quilt + (0.025) clay tiling	0.125	0.25	0.05	131.86	32.15
R_3	(0.013) Plaster board + (0.2) wooden roof floor + roofing felt (0.005) + (0.12) expanded polystyrene + (0.025) clay tiling	0.149	0.25	0.05	130.17	33.03
R_4	(0.013) Plaster board + (0.2) wooden roof floor + (0.12) expanded polystyrene + (0.005) roofing felt + (0.025) clay tiling	0.132	0.25	0.05	132.60	31.76
R_5	(0.013) Plaster board + (0.2) wooden roof floor + roofing felt (0.005) + (0.18) MW stone wool (rolls) + (0.025) clay tiling	0.108	0.25	0.05	132.59	31.77

A similar trend to the external wall insulation was observed with the thermally insulated roof retrofit variants. Not only did the addition of roof insulation decrease the energy consumption (R_1), but an additional change of roof typology to lightweight pitched profile brought about a 33.03% energy reduction. This improvement may be attributed to the increase in thermal mass with an unconditioned space providing an unchanged volume for space conditioning. All the roof retrofits provided a U value that was 0.03–0.15 W/m^2.K below the standard U_{max} value of 0.25 W/m^2.K. Among the variants, an R_3 pitched roof with the use of 0.12 m expanded polystyrene reduced the energy consumption the most (by 33.03%) with an improved U value of 0.149 W/m^2.K (Figure 11).

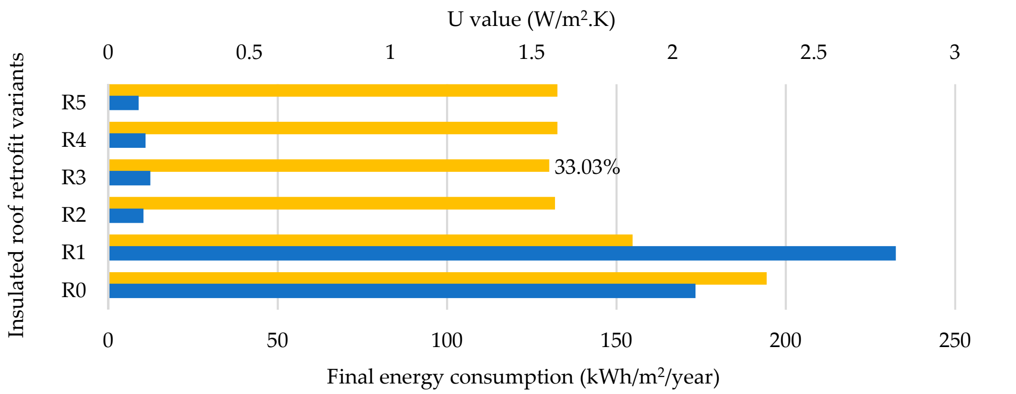


Figure 11. Insulated roof retrofit variants with % reduction in the final energy consumption and corresponding U values.

Ground slab construction and insulation: the authors considered five variants (GF_1, GF_2, GF_3, GF_4, and GF_5) based on the same design principles as in the case of the wall and roof component variants. Progressive variants were developed by adding air-spacing layers sandwiched between the cast concrete and 0.1 m wood fir pine topped by 0.14 m mineral wool (G3), 0.05 m glass fiber batt (G4), and 0.05 m MW stone wool (rolls) (G5) (Table 10).

Although similar principles were implemented, none of the variants significantly reduced energy consumption. For example, GF_3 with both 0.1 m air spacer and 0.14 m mineral wool showed a 0.52% reduction in energy consumption and resulted in the lowest transmittance of 0.15 W/m^2.K. The U values for all the variants declined from the baseline of 1.602 W/m^2.K by 0.15–0.34 W/m^2.K (Figure 12).

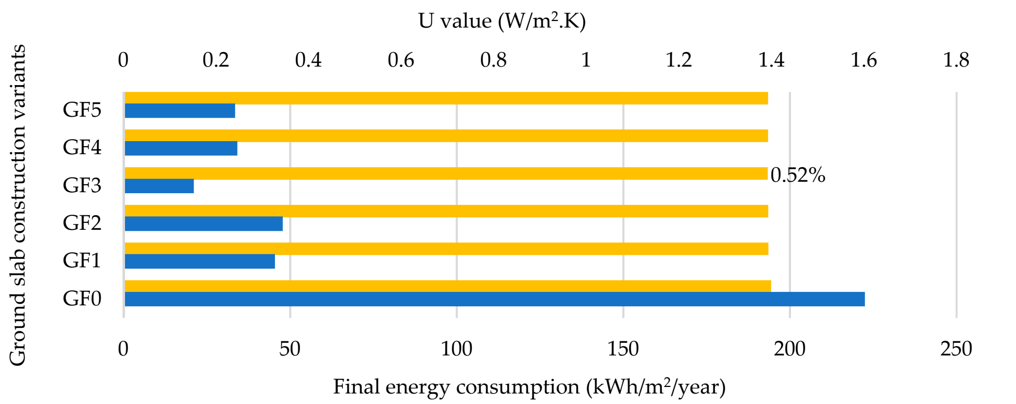


Figure 12. Insulated ground slab construction variants with % reduction in the final energy consumption and corresponding U values.

High-performance window types, glazing, and window-to-wall ratio (WWR): considering the window glazing available in the French market [53], a clear glass window type (Wn_0) was adopted as the baseline. All considered variants (Wn_1 and Wn_2) were based on the thickness, presence, or absence of an air spacer and associated properties of the glass used within the common wooden frame, as shown in Table 11.

Table 10. High-performance building envelope through the insulated ground floor.

Variants n	Material Description (m)	U W/(m^2.K)	U_{max} W/(m^2.K)	k W/(m.K)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
GF_0	(0.05) Soil—leveling layers + (0.2) cast concrete + (0.2) timber floor	1.602	0.19	0.72	194.37	-
GF_1	(0.05) Soil—leveling layers + (0.2) cast concrete + (0.05) glass fiber batt + (0.1) reinforced concrete + (0.2) timber floor	0.327	0.19	0.20	193.56	0.42
GF_2	(0.05) Soil—leveling layers + (0.2) cast concrete + (0.1) wood fir pine + (0.1) air gap + (0.2) timber floor	0.344	0.19	0.22	193.51	0.42
GF_3	(0.05) Soil—leveling layers + (0.2) cast concrete + (0.1) wood fir pine + (0.1) air gap + (0.14) mineral wool + (0.2) timber floor	0.152	0.19	0.12	193.36	0.52
GF_4	(0.05) Soil—leveling layers + (0.2) cast concrete + (0.1) wood fir pine + (0.1) air gap + (0.05) glass fiber batt + (0.2) timber floor	0.246	0.19	0.17	193.43	0.48
GF_5	(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	0.241	0.19	0.17	193.43	0.48

Table 11. High-performance building through high-U-value windows.

Variants n	Material Description (m)		U (W/m^2.K)	Umax (W/m^2.K)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
Wn_0	Type	Single-glazed (0.006) clear glass	5.77	1.9	194.37	-
	Frame	Wooden frame				
	WWR (%)	5%				
Wn_1	Type	Double-glazed, LowE (e3 = 0.1) (0.003) generic clear glass + (0.013) argon spacer + (0.003) clear glass	1.512	1.9	187.86	3.35
	Frame	Wooden frame				
	WWR (%)	5%				
Wn_2	Type	Triple-glazed, LowE (e2 = e5 = 0.1) (0.003) clear glass + (0.013) air gap + (0.013) air gap + (0.003) clear glass	0.982	1.9	189.26	2.63
	Frame	Wooden frame				
	WWR (%)	5%				

The double-glazed low-emissive 0.003 m clear glass with 0.013 m argon spacer decreases energy consumption by 3.35%. However, the variant (Wn_2) with a low transmittance showed a much lower energy reduction potential when compared to Wn_1 with a higher transmittance value of 1.512 W/m^2.K. Nonetheless, the two variants led to a significant reduction in the U value compared to the baseline 5.77 W/m^2.K (1.512 W/m^2.K and 0.982 W/m^2.K, respectively), as shown in Figure 13.

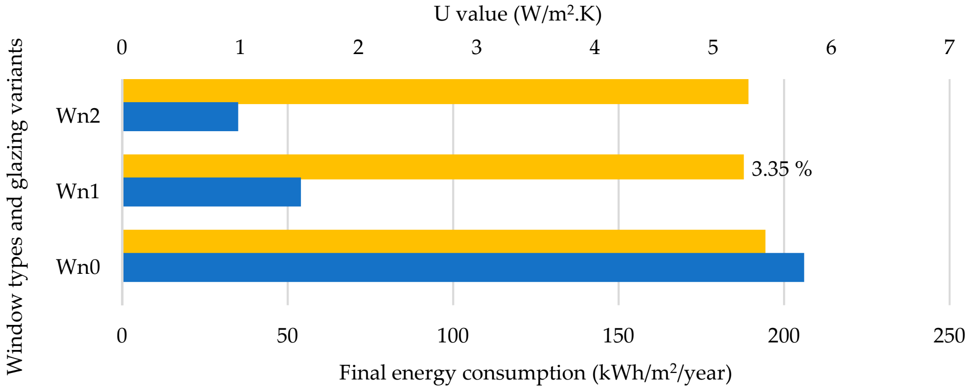


Figure 13. High-performance window types, glazing variants with % reduction in the final energy consumption, and corresponding U values.

Apart from the type of glazing and thickness, the glazing percentage of the total façade area influences the heat transfer rate through the windows. With a window-to-wall ratio of 5%, only 10 m^2 of the façade is glazed. Accordingly, the authors proposed two variants to achieve the ASHRAE 90.1-2007 standard of 24% WWR [54]. The variants were determined based on the location, window size, daylight penetration potential (6 m), and plan depth of the lit room. Considering the 24% WWR, horizontal (WWR_1: 0.9 m) and vertical (WWR_2: 1.8 m) dimensions of the windows were altered to obtain maximum WWR without compromising the interior daylit areas (Table 12).

Table 12. High-performance building through window-to-wall ratio.

Variants n	Material Description (%)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
WWR_0	5%	194.37	-
WWR_1	24% Horizontal (0.9)	185.43	4.60
WWR_2	24% Vertical (1.8)	183.63	5.53

Most importantly, the improvement in WWR to 24% was achieved with the increase in window height to 1.8 m when compared to the depth. Aligned in proportion to the spatial dimensions of the room, the variant WWR_2 resulted in a reduction in energy consumption by 5.53%. This result may be attributed to the improvement in daylighting provisions, which help to reduce the lighting or heating loads (Figure 14).

Upgraded airtightness and air permeability: many old houses have a weak airtight layer that is broken around the construction floor–wall joints and opening–wall joints. To mitigate the reduction in insulation performance, heat resistance, and increased heat losses, several arbitrary values less than 0.6 (due to infiltration) were considered and compared with the poor baseline value of 1.0. Three variants with gradually lower infiltration rates (in 0.2 decrements) were adopted for the external wall and window retrofits (Table 13).

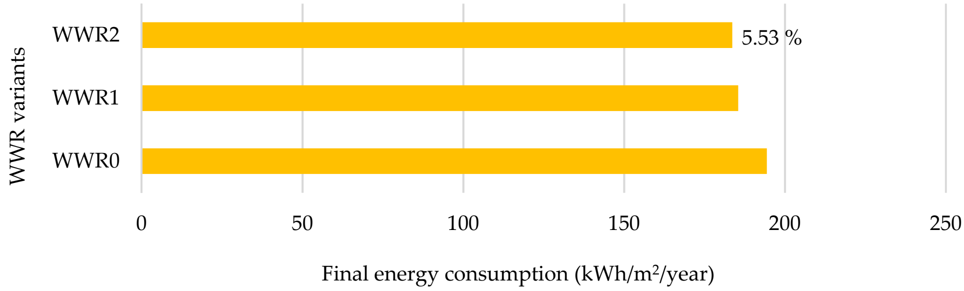


Figure 14. WWR variants with % reduction in the final energy consumption.

Table 13. High-performance building through the airtightness.

Variants n	Infiltration Rate (m^3/h-m^2)	Performance Rating (@4Pa)	IR_{max} EPBD (m^3/h-m^2)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
A_0	1.00	Loose	<0.6	194.37	-
A_1	0.8	Loose	<0.6	182.09	6.32
A_2	0.6	Medium	<0.6	172.91	11.04
A_3	0.2	Tight	<0.6	154.74	20.39

The lowest air infiltration rate of 0.2 $m^3/h.m^2$ was most beneficial as it minimized cracks and air leakages and led to the highest energy reduction (20.39%). Due to the old construction type, the baseline type exhibited an extremely poor infiltration rate (1.0 $m^3/h.m^2$) because of loose joints.

3.2.2. Combined Performance of Passive Strategies

Based on the analyses, combining seven energy-saving retrofit solutions that yielded the most optimal results would provide the most suitable passive retrofit solution set. Adoption of these strategies led to approx. 90% energy consumption reduction compared to the baseline (Table 14). Moreover, a passive retrofit with a final energy demand of 20.27 kWh/m^2/year ($E_{passive}$) was achieved by combining the following measures (Figure 15).

1. Thermally insulated external wall (46.82%);
2. Upgraded airtightness and air permeability (20.39%);
3. Thermally insulated roof component (33.03%);
4. Maximized WWR to meet standards (5.53%);
5. High-performance window type and glazing system (3.35%);
6. Insulated ground slab construction (0.52%).

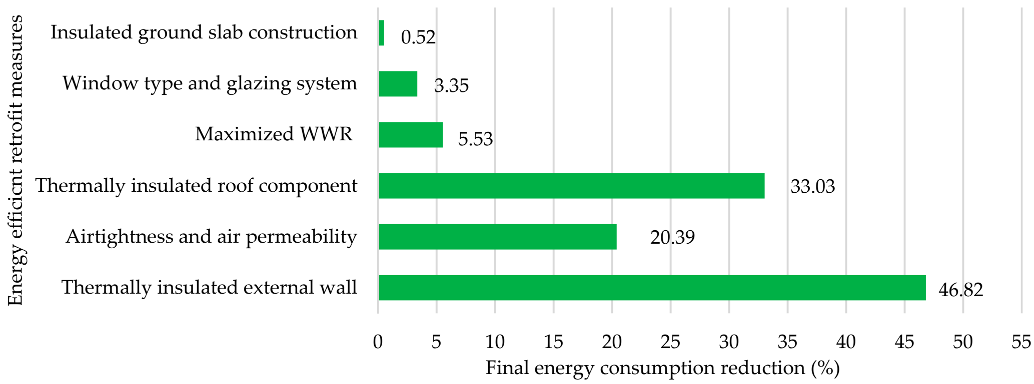


Figure 15. Combined impact of passive retrofit strategies based on % of energy reduction.

Table 14. Combined performance of passive retrofit strategies.

Variants n		Material Description (m)	U W/(m^2·K)	U_{max} W/(m^2·K)	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
W_2		(0.01) Gypsum board + (0.11) brick + (0.15) glass fiber + (0.01) timber sliding	0.239	0.45	103.37	46.82
R_3		(0.013) Plaster board + (0.2) wooden roof floor + (0.005) roofing felt + (0.12) expanded polystyrene + (0.025) clay tiling	0.149	0.25	130.17	33.03
GF_3		(0.05) Soil—leveling layers + (0.2) cast concrete + (0.1) wood fir pine + (0.1) air gap + (0.14) mineral wool + (0.2) timber floor	0.152	0.19	193.36	0.52
Wn_1	Type	Double-glazed, LowE (e3 = 0.1) (0.003) generic clear glass + (0.013) argon spacer + (0.003) clear glass	1.512	1.9	187.86	3.35
	Frame	Wooden frame				
	WWR	5%				
WWR_2		24% vertical (1.8)			183.63	5.53
A_3		0.2 m^3/h.m^2	Tight	<0.6	154.74	20.39

A comparison of the monthly energy consumption loads for the Case A and Case B scenarios shows a 90.8% (17.7 kWh/m^2/year) reduction in heating demand with a similar lighting demand as that presented in Figure 16. During this stage, overheating (with the rise in the temperature above 28 °C) during the warm months was one of the major drawbacks.

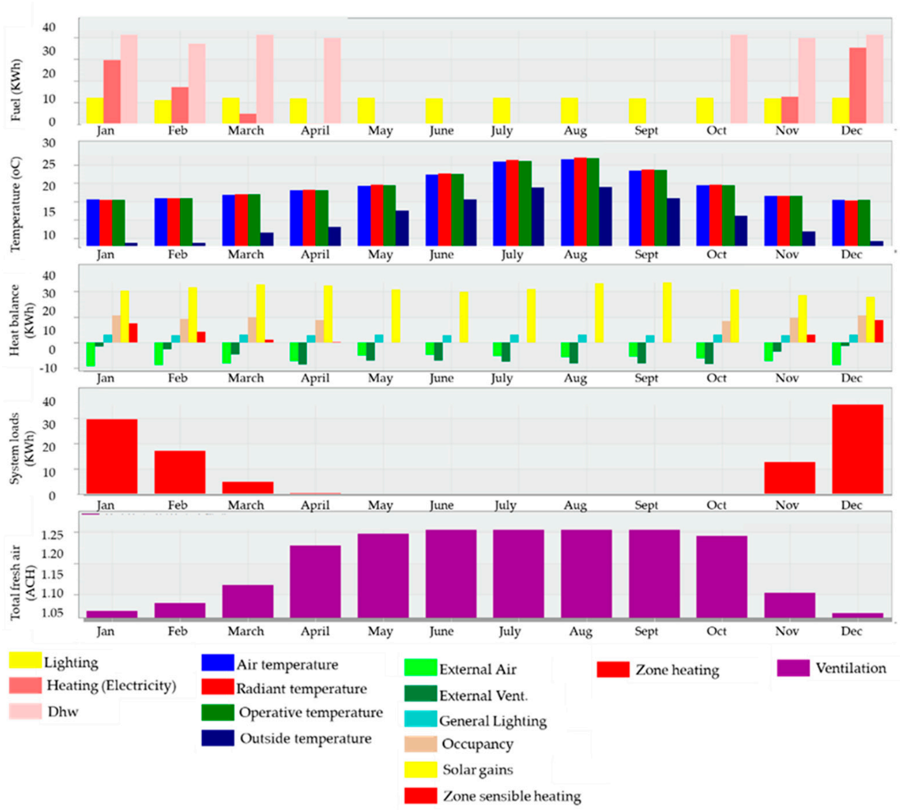


Figure 16. Passive retrofit, monthly breakdown of the simulation results: energy consumption, temperature, heat balance, and ventilation for the low-energy Puccini house.

This low-energy retrofit obtained by making improvements relative to the baseline ($E_{puccini}$) was then subjected to similar scrutiny of energy-efficient system selection based on the maximum energy savings (E_{enef}). Here, the authors relate to research experiments where the efficiency of the building relies on the bioclimatic and passive design solutions, as well as the adoption of efficient building systems.

3.2.3. Energy-Efficient Building System Performance

Provision of interior shading systems: the authors proposed automatic/switchable shading devices with designated control types. The baseline (S_0) simulated in the absence of any shading systems was compared to four shading variants (S_1, S_2, S_3, and S_4) operable under two conditions. The former control type was activated when the outside night temperatures were lower than the set-point temperatures, while the latter was activated when the day zone-cooling rate from the previous time step was non-zero (Table 15).

Table 15. High-performance building through shading component.

Variants n	Shading Description (Type)	Position	Control Type	Operation	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
S_0	None	-	-	-	20.27	-
S_1	Movable Venetian blinds Light	Inside	Night outside low air temp + day cooling	Occupancy	20.13	0.69
S_2	Movable Venetian blinds Light	Inside	Night outside low air temp + day cooling	Schedule	19.91	1.78
S_3	Roller Shades	Inside	Night outside low air temp + day cooling	Occupancy	20.13	0.69
S_4	Roller Shades	Inside	Night outside low air temp + day cooling	Schedule	19.91	1.78

Our analyses demonstrate that the addition of internal shading devices leads to an almost negligible reduction in the final energy consumption (in the 1–2% range). Among the considered variants, movable Venetian blinds and roller shutters positioned in the interiors operated under the S2 and S4 schedules were the most beneficial with a maximum reduction of 1.78%.

Ventilation strategy and heating system design: the old Puccini house relies on a natural ventilation strategy (V_1) whereby windows are manually opened and closed by the inhabitants. Due to the lack of any air-driving energy consumption or control, this system may be noncompliant with the standard minimum rate of 0.5 ACH. Additionally, as manual operation brings unconditioned outdoor air into the house, this strategy alone negatively impacts heating system efficiency. Hence, the authors propose the ventilation variants along with the HVAC system design.

Heating system efficiency plays a dominant role in meeting the energy demand of a typical residential unit [36]. Moreover, climatic variations, building insulation levels, and air permeability or tightness influence the viability of the combined HVAC systems. Hence, two variants ($HVAC_1$ and $HVAC_2$) were proposed based on the combined effect of ventilation strategies applied alongside different systems for heating, ventilation, air conditioning, and domestic hot water (DHW) provisions. Accordingly, the mechanical ventilation (MV) or mixed-mode ventilation (MMV) retrofit variants were considered. Additionally, air to the water heat pump (ASHP) or gas boiler were the two DHW alternatives considered as part of the heating system. All simulated retrofit variants were compared with the baseline strategy, as outlined in Table 16. The comparisons were carried out using corresponding efficiency values for the system, emissions, and carrier factors.

Table 16. Active energy-efficient building through HVAC components.

Variants n	HVAC Description (Type)	CoP	$E_{puccini}$ kWh/m^2/year	% Reduction $E_{puccini}$
HVACo	Natural ventilation (NV) + radiator heating + DHW gas boiler	H_e = 0.85; H_c = 0; DHW = 0; NV (ACH) = 0.5	20.27	-
$HVAC_1$	Air-to-water heat pump (ASHP) + gas boiler DHW + NV	H_e = 1.8; H_c = 0; DHW = 0.8; NV (ACH) = 0.5	25.25	−24.56
$HVAC_2$	Radiator heating + DHW gas boiler + mixed-mode NV + local comfort cooling	H_e = 0.85; H_c = 1.80; DHW = 0.8; NV (ACH) = 0.5	23.93	−18.06

The variants added to reduce the energy demand proved to reverse the impact by increasing the energy consumption. This may be attributed to the fact that a minimal cooling load was introduced along with the heating, lighting, and DHW loads. Moving toward adopting cost-effective systems, an $HVAC_2$ variant inclusive of radiators and gas boilers for the heating system, combined with mixed-mode ventilation (NV+ MV) ensuring thermal comfort cooling (H_e = 0.85; H_c = 1.80; DHW = 0.8), offered minimal energy consumption (18.06 % increase). Finally, the total primary energy consumption of the Puccini house (E_{enef}) is 23.98 kWh/m^2/year.

3.2.4. Renewable Energy Production

To achieve the NZEB energy-efficiency level, the roof of the Puccini house is equipped with PV panels for on-site renewable energy production. Using the solar PV energy output of a photovoltaic system, the approximate roof area available for integration along with the number of panels are identified as follows:

$$E = A \times r \times H \times PR \tag{2}$$

where E = energy (2769.50 kWh), A = area of the solar panel (7.94 m^2), r = solar panel yield (estimated as 22.8 %), H = annual average irradiation on tilted panels (assumed as 1800 unit), and PR = performance ratio, the coefficient for losses (0.75).

As a result, five panels of monocrystalline solar PV panels were proposed to meet the primary energy consumption (Table 17). With an installed power of 440 Wp and 22.8 % efficiency, two variants (PV_1 and PV_2) of monocrystalline solar-cell types differing in the number of panels are proposed, as shown in Table 18 [55].

Table 17. SunPower PV panel description and details.

Component Materials	
Cells per module	72
Cell type	66 Maxeon Gen 6
Cell dimensions	166 mm × 166 mm
Panel dimension	1872 mm × 1032 mm
Front	High-transmission tempered glass with anti-reflective coating
Frame	Class 1 black anodized (highest AAMA rating)
Weight	21.8 kg
Maximum power	440 Wp
Maximum efficiency	22.8%

Table 18. Renewable energy production through on-site photovoltaic (PV) system.

Variants n	PV Description (Type)	No. of Panels	Tilt Angle (Degrees)	Power (W)	E_{final} kWh/year	EPV kWh/year	% Reduction $E_{puccini}$
PV_0	None	-	-	-	2769	-	-
PV_1	Monocrystalline	4	33.65	440	2769	−2559.4	92.4
PV_2	Monocrystalline	5	33.65	440	2769	−3199.2	115.54

The very low primary energy of the building (E_{enef} = 23.98 kWh/m^2/year) is balanced by 7.94 m^2 of south-facing PV panels tilted at an angle of 33.65° from the horizontal axis. The total PV electricity produced using five panels is calculated as 3199.245 kWh (E_{pv} = 27.69 kWh/m^2/year), satisfying 446.32% of the total building electric loads. Thus, the electricity produced not only meets the low primary energy of 23.98 kWh/m^2/year but also yields surplus energy of −3.714 kWh/m^2/year to be returned to the utility grid. Hence, the integration of on-site RE in the form of PV panels achieves an NZEB, while increasing the energy production of the Puccini house by 15.5%. Therefore, the authors are successful in achieving a variant of the NZEB concept—i.e., the plus-energy Puccini house.

4. Discussion

4.1. NZEB Performance and Comparison with the Standard Targets in France

An NZEB is developed with the primary energy generation of −27.69 kWh/m^2/year to meet the primary energy demand of 23.98 kWh/m^2/year as plotted in the ZEB challenge graph (Figure 17). A graphical representation of the total energy breakdown of the energy uses—heating, cooling, ventilation, lighting, and PV generation—shows that maximum final energy reduction of 90% is obtained in Case B, followed by an increase of 15.47% in Case C where the energy consumption is met by PV production. Accordingly, the heating energy shows the largest reduction by 90.8%, with constant lighting energy demand for all the cases. The contribution of heating system demand is reduced from 97% to 72%, while the remaining 26% and 2% are occupied by the lighting and cooling-ventilation energy demands respectively (Figure 18).

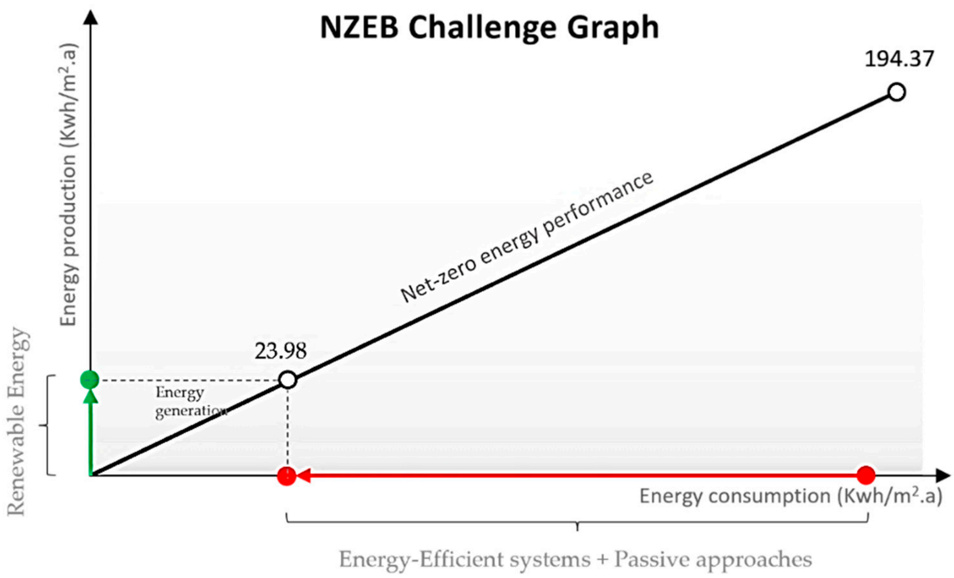


Figure 17. The NZEB Puccini house within the NZEB challenge graph.

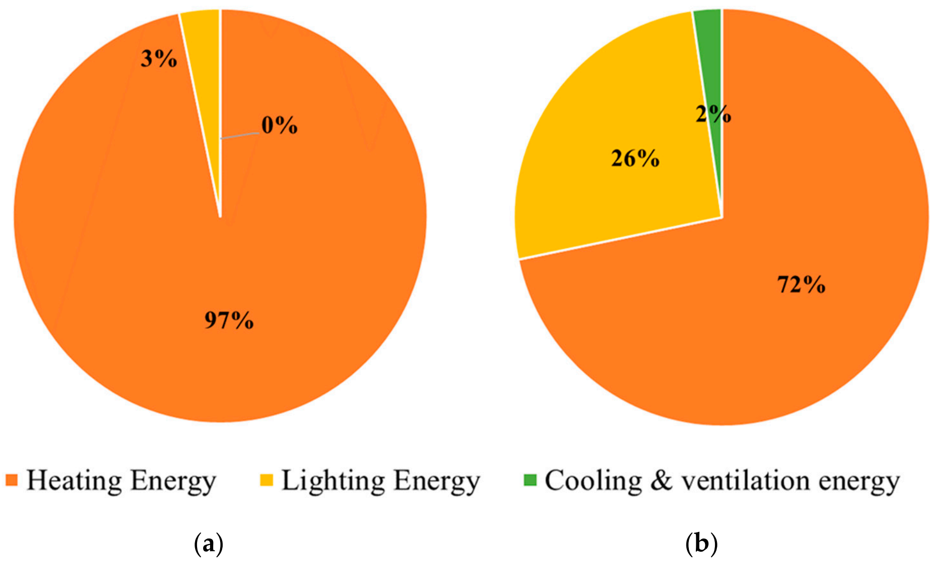


Figure 18. Comparative distribution of energy use: heating, cooling and ventilation, lighting: (**a**) $E_{puccini}$; (**b**) $E_{passive}$.

For this study, the retrofitted NZEB is compared to the benchmarks adopted in France for low-energy performance, plus-energy buildings, or nZEBs. These include thresholds set by Effinergie+ and BBC Reno standards, as shown in Table 19.

Table 19. Comparative analysis of NZEB with French standards—Effinergie+ and BBC Reno.

	Case A	Case B	Case C	Case D	Effinergie+	BBC Reno
Heating Energy (in kWh/m^2/year)	188.16	17.18	17.74	17.16	35.4	64.9
Lighting Energy (in kWh/m^2/year)	6.21	6.21	6.21	6.21	4.1	6.6
Cooling and ventilation energy (in kWh/m^2/year)	0.00	0.55	0.28	0.61	3.6	7.1
Final energy (in kWh/m^2/year)	194.37	20.27	23.98	−27.71	43.2	78.60
C_{pemax} (in kWh/m^2/year)				23.98	50–65	-
Renewable energy production (in kWh/m^2/year)				27.71	5.00	-

As per the Effinergie+ standards, the simulated 23.98 kWh/m^2/year primary energy consumption (C_{pe}) is lower than the maximum primary energy consumption (C_{pemax}) value of 50–65 kWh/m^2/year by at least 49% (Figure 19). Accounting for the breakdown of the final energy consumption, heating energy (17.16 kWh/m^2/year) and cooling and ventilation energy (0.61 kWh/m^2/year) are well below the set thresholds of 35.4 kWh/m^2/year and 3.6 kWh/m^2/year, respectively. Most importantly, the renewable energy production exceeds the set threshold by 22.71 kWh/m^2/year through a surplus production of $E_{pv} = -3.71$ kWh/m^2/year. The BBC Reno standards are prescribed for existing buildings undergoing renovations (Figure 20). Table 20 summarizes all the retrofit strategies adopted to obtain the NZEB.

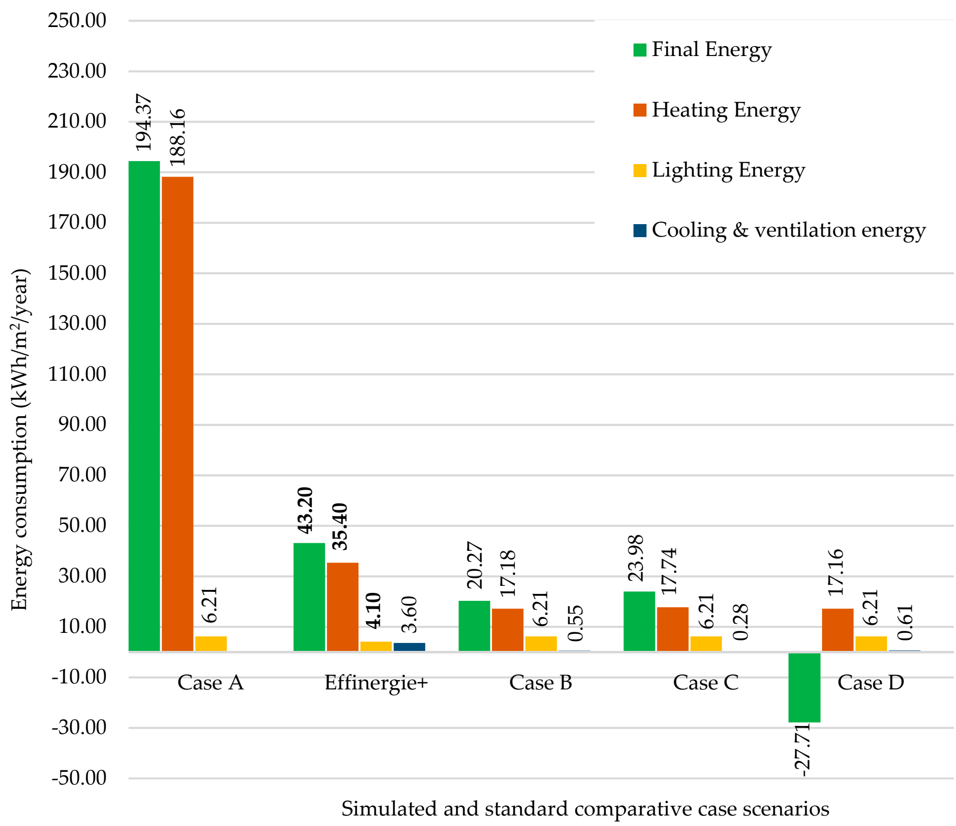


Figure 19. NZEB performance and comparison with the standard targets of Effinergie+.

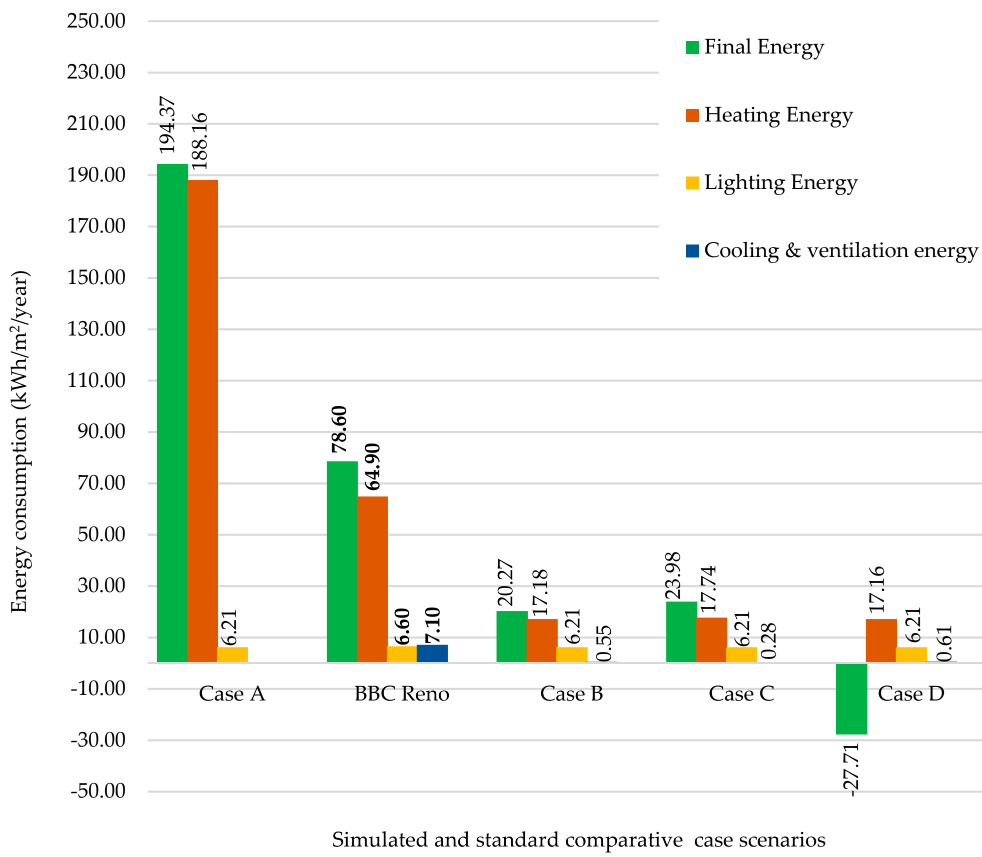


Figure 20. NZEB performance and comparison with the standard targets of BBC Reno.

Table 20. Retrofit strategies adopted to achieve NZEB in single-family terraced residences in France.

<table>
<tr><th>Variants n</th><th colspan="3">Material Description (m)</th><th>U W/(m²·K)</th><th>Umax W/(m²·K)</th><th>$E_{puccini}$ kWh/m²/year</th><th>% Reduction $E_{puccini}$</th></tr>
<tr><td>W_2</td><td colspan="3">(0.01) Gypsum board + (0.11) brick + (0.15) glass fiber + (0.01) timber sliding</td><td>0.239</td><td>0.45</td><td>103.37</td><td>46.82</td></tr>
<tr><td>R_3</td><td colspan="3">(0.013) Plaster board + (0.2) wooden roof floor + roofing felt (0.005) + (0.12) expanded polystyrene + (0.025) clay tiling</td><td>0.149</td><td>0.25</td><td>130.17</td><td>33.03</td></tr>
<tr><td>GF_3</td><td colspan="3">(0.05) Soil—leveling layers + (0.2) cast concrete + (0.1) wood fir pine + (0.1) air gap + (0.14) mineral wool + (0.2) timber floor</td><td>0.152</td><td>0.19</td><td>193.36</td><td>0.52</td></tr>
<tr><td rowspan="3">Wn_1</td><td>Type</td><td colspan="2">Double-glazed, LowE (e3 = 0.1) (0.003) generic clear glass + (0.013) argon spacer + (0.003) clear glass</td><td rowspan="3">1.512</td><td rowspan="3">1.9</td><td rowspan="3">187.86</td><td rowspan="3">3.35</td></tr>
<tr><td>Frame</td><td colspan="2">Wooden frame</td></tr>
<tr><td>WWR</td><td colspan="2">5%</td></tr>
<tr><td>WWR_2</td><td colspan="3">24% vertical (1.8)</td><td></td><td></td><td>183.63</td><td>5.53</td></tr>
<tr><td>A_3</td><td colspan="3">0.2 m³/h.m²</td><td>Tight</td><td><0.6</td><td>154.74</td><td>20.39</td></tr>
<tr><td>$HVAC_2$</td><td colspan="3">Radiator heating + Dhw gas boiler + mixed-mode NV + local comfort cooling</td><td>H_e = 0.85; H_c = 1.80; Dhw = 0.8; NV (ACH) = 0.5</td><td></td><td>23.93</td><td>−18.06</td></tr>
<tr><td rowspan="2">S_2 & S_4</td><td>Movable Venetian blinds Light</td><td>Inside</td><td colspan="2">Night outside low air temp + day cooling</td><td>Schedule</td><td>19.91</td><td>1.78</td></tr>
<tr><td>Roller shutters</td><td>Inside</td><td colspan="2">Night outside low air temp + day cooling</td><td>Schedule</td><td>19.91</td><td>1.78</td></tr>
<tr><th>Variants n</th><th>PV Description (Type)</th><th>No. of Panels</th><th>Tilt Angle (Degrees)</th><th>Power (W)</th><th>E_{final} kWh/year</th><th>EPV kWh/year</th><th>% Reduction $E_{puccini}$</th></tr>
<tr><td>PV_2</td><td>Monocrystalline</td><td>5</td><td>33.65</td><td>440</td><td>2769</td><td>−3199.2</td><td>115.5</td></tr>
</table>

4.2. Limitations and Future Work

One of the major drawbacks identified is the overheating scenario that has not been mitigated using appropriate strategies. Moreover, retrofitting projects are characterized by not only energy reduction, but also cost effectiveness [49]. Despite efforts by organizations for environmental awareness, decision makers are bound by the main criteria of cost. This creates a dilemma for the decision makers. Therefore, an optimal balance should be achieved between the investment costs for installing the retrofit measures and the yearly energy consumption. To substantiate the high cost of the retrofit process of any existing building stock, it is advisable to carry out a detailed cost analysis while comparing the percentage of energy savings obtained over a decade. Hence, future implications for research may include computing the cost of retrofits while simultaneously addressing the challenge of reducing the cost of the proposed retrofits. In addition, since the NZEB strategies efficient in the Mediterranean climates may not necessarily be beneficial for other climatic conditions in France, studies may be directed toward experimenting on the other four climates to derive a general framework for achieving residential NZEBs through retrofitting in France—furthermore, studying more options for renewable energy production in terms of building-integrated photovoltaics (BIPV) compared to the two variants of roof PV installation used in the study.

5. Conclusions

In this era of climate change, cities are paying more attention to building energy use and carbon footprint for attaining sustainability. Recalling the UN-Habitat's initiative for achieving the Sustainable Development Goals (SDGs 7, 11, and 13), several initiatives launched by the EU governments focus on achieving energy efficiency by integrating passive, efficient building systems and on-site renewable energy solutions.

One method to achieve the EU's ambitious target of reduced ecological footprints is to retrofit existing building stock to meet the NZEB goals. Accordingly, this study discusses the different retrofit strategies suitable for reducing the energy demand for space conditioning (heating and cooling), reducing the electric energy consumption of building systems to be balanced by the primary energy production (renewable energy sources) in the French context.

This simulation-based study presents a simple experimental approach for the efficient retrofit of a French Puccini house located in the Mediterranean climate of Nice in France. The passive solution sets were categorized to include seven optimized building forms and high-performance building envelope design strategies along with 27 variants. The maximum energy-saving retrofit solutions provided an ambitious reduction in energy consumption by approximately 90% from the baseline ($E_{puccini}$ = 194.37 kWh/m^2/year). The passive retrofit with the final energy demand of 20.27 kWh/m^2/year ($E_{passive}$) energy demand is met through a group of energy-efficient building systems with eight variants. The very low primary energy of the building (E_{enef} = 23.98 kWh/m^2/year) is balanced by 7.94 m^2 of south-facing PV panels with a total PV electricity production of 27.69 kWh/m^2/year. Thus, the electricity produced not only meets the low primary energy of 23.98 kWh/m^2/year but also yields surplus energy of -3.714 kWh/m^2/year to be returned to the utility grid. Hence, the integration of on-site RE in the form of PV panels achieves an NZEB, while increasing the energy production of the Puccini house by 15.5%. Therefore, the authors are successful in achieving a variant of the NZEB concept—i.e., the plus-energy Puccini house. This study draws some general conclusions and suggestions for improving the energy consumption of the existing building stock toward achieving NZEBs:

(1) Implementation of high-performance building envelope through a thermally insulated external wall (46.82%), upgraded airtightness (20.39%), thermally insulated pitched roof component (33.03%), and high-performance window type—glazing system (3.35%) with maximized WWR (5.53%);
(2) Implementation of a standard building code based on energy-efficient retrofits of residential building typologies, especially applied in the existing old building stocks for historic conservation and preservation;
(3) Integration of the occupant behavior through building performance simulation as part of the design process to enhance the potential savings.

Conceptualizing an NZEB presents both unique opportunities and challenges. The NZE concept through an integrated holistic approach combining all the aspects of environmental sustainability ensures resource, energy, and economic efficiency. This simple study indicates that the NZEB challenge is achievable in existing old building stocks. Furthermore, efforts may be directed toward quantifying and bridging the energy balance, financial and environmental gaps between optimal combinations of passive, energy-efficient, and renewable energy solution sets.

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