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Research Article

The Role of Passive Design Strategies in the Optimization of Energy Performance in Algerian Social Housing : A Case Study Application in Bordj Bou Arreridj Using Dynamic Simulation and Uncertainty Analysis

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Abstract:

This research presents a comprehensive examination of the various passive design strategies and their impact on energy efficiency in social housing situated in Bordj Bou Arreridj, Algeria. Dynamic thermal simulation studies were carried out, calibrated with measured consumption data, to disaggregate monthly consumption patterns by end-use type (heating, cooling, lighting), thus giving more focused information as to the efficacy of interventions. It was found that energy consumption varies seasonally, with heating demand predominant from November to March at 86.5kWh/m²/year, closely followed by cooling in July and August at 50kWh/m²/year, and lighting consumption is stagnant throughout the year at 16.2 kWh/m²/year. Upon applying climate-responsive passive strategies, overall energy savings of 47.9% were achieved. The reduction in energy consumption was, however, not evenly spread over all categories, with heating showing a reduction of 46%, cooling 54%, and lighting 04%. The statistical analysis has shown that the most effective single measure in this climate characterized by highland is thermal insulation while the combined measures act synergistically to realize a non-linear enhancement of winter thermal performance. This study thus provides empirical evidence in support of Algerian housing policy for climatic-specific architectural interventions and also outlines a methodology for disaggregated energy analysis applicable to similar highland contexts.

1. Introduction

The challenges of sustainability, particularly those involving energy conservation and environmental preservation, are extremely imperative in today's world and require a concerted human effort to curtail energy consumption and ensure the provisioning of sustainable energy sources [1-5].
Global, The building sector is the most final energy consumer and always above 40% out of the total consumption [6,7]. This trend can be experienced intensely in Algeria, indicated by the recent data from the 2022 Annual Energy Report, which shows that buildings now account for 47% of the nation's final energy consumption, thus an increase of 7.6% from 2021. The surge is mainly from the residential sector, which accounts for 36% of the national total and has rebounded by 4.4% [8], as shown in figures.1 . This consumption can be aggravated by a standard building practice under which the disparate climatic conditions in the country are not adequately addressed for optimal thermal performance but allow heavy reliance on the mechanical heating and cooling systems [9,10]. The main cause given is the underexposure to energy-saving considerations in house design, across different typologies, as a result of meeting numerical targets, in addition to following unsuitable models [11-13].This is what the Algerian government undertook as a national energy management policy, ECO-BAT, through which, since 2011, the program has been increasing the number of new high-energy performance housing units in all climate zones to 600 [14]. Besides

building new high energy performance houses, the energy efficiency gains must also come from upgrading existing stock of residential buildings (RBS) to improve their performances. This is the thrust of the 2030 energy efficiency program, which has for its target improving thermal insulation on buildings [15]. To this end, thermal insulation and the integration of renewable energy sources, which is the overall objective, has the aim of making all buildings, whether or not existing, achieve better energy performance through concerted multisectoral intervention. In-depth studies exist around the globe on the significant potential that passive design concepts can have for achieving energy savings in different climatic conditions coupled with indoor temperature reductions. As such, an intelligent prioritization of such design paradigms is crucial in minimizing the adverse environmental footprint created by an expanding Algerian building sector in the road towards sustainable energy efficiency in the residential context of the built environment [11,16-20]. Unfortunately, academic literature on optimization of energy performance fails to address real empirical markers regarding the efficacy of such strategies in Algeria's highland regions, despite accounting for 17% of total housing stock in Algeria. This research fills a critical gap that exists in sustainable architecture by associating the quantitative effects of passive design strategies on the efficiency of energy consumption in Algerian collective residential buildings expressed in kWh/year/m2 and analyzed in detail per end-use category. It relies on a rigorous quasi-experimental methodology, calibrated computational simulations of verified occupancy scenarios against real energy consumption data, analyses of monthly and seasonal patterns of energy consumption, and statistical tests of the effectiveness of passive design strategies for every end-use category. Evidence-based interpretations from the findings are intended to yield recommendations for climate-responsive housing design in the Algerian highlands. The results can feed into creating guidelines for collective residential building design, which aims to increase energy functionality, minimize costs, and lessen environmental impacts. This applies both for new projects and renovations of existing buildings, thus contributing to national sustainability aspirations.

2. Materials and Methods

The procedures that are laid out in this research methodology are to allow a quantitative and analytical evaluation of heating/cooling energy demand in Algerian multi-family social housing buildings. The approach incorporates a dynamic building performance simulation applied to a calibrated model of multi-family social housing buildings. The entire detailed conceptual framework depicted in Figure.2, gives a descriptive breakdown of the sequence of stages of the research methodology. This methodology is segmented into six major phases, each of which will be detailed in subsequent sections.

- ➢ Description of the Case Study (Detailed climatic analysis, Characterization of building typology).
- ➢ Establishment of baseline performance metrics through calibrated simulation.
- ➢ Systematic implementation and evaluation of discrete passive design interventions.
- ➢ Statistical analysis of intervention efficacy by energy end-use category.
- ✓ Economic feasibility assessment.

2.1 Case Study ; Climate Data and Reference Model Creation

2.1.1 Site Characteristics and Climatic Analysis

Bordj Bou Arreridj is in northern Algeria, at approximately 900 meters above sea level, located at 36.07°N, 4.76°E. It represents the highland climates of Algeria in classifying it under the Köppen-Geiger system as BSk (cold semi-arid). This climate is characterized by [21-23] :

- Cold winters though the average January minimum is -1.2°C
- Hot, dry summers with moderate cooling requirements (average July maximum: 33.7°C)
- Great daily temperature swings (average annual amplitude: 12.8°C)
- Moderate annual precipitation (384mm) concentrated during winter months
- Relatively low average relative humidity (annual average: 57%).

Decided energy demands are characterized by seasons, with well-marked heating requirements in winter and moderate cooling needs in summer. The high diurnal temperature range offers possibilities for passive design strategies based on thermal mass and night ventilation, which are often neglected in standard ways of constructing buildings.
The climate data used for this simulation were imported from the Meteonorm software_package as standard weather, bringing with it all the monthly climatic data, and we validated this against 10 years' (from 2013 to 2023) record from the Algerian National Office of Meteorology.

2.1.2 Reference Building Characteristics

The chosen model building for the application of our methodology represents a typical multi-family social housing residential building, F3-type apartment (three rooms 68 m²), Figure.3, selected as the reference model because this distribution is statistically common in the social housing program of Algeria [24] Table.1. conformance to the Standards stipulated in the Algerian thermal regulation (DTR).

2.1.3 Heat Transfer Coefficient (U) (W/m2k)

The next step in the building performance modeling process is to assign appropriate structural configurations for each component of the building envelope, considering especially the overall heat transfer coefficient (U-value). This is important because it directly influences the energy demand necessary for maintaining the desired indoor air temperature within each thermal zone [11]. A complete view of the envelope composition and corresponding thermophysical properties of its constituent materials is summarized in Table.2.

2.2 Simulation Methodology and Validation

Simulation methodology and validation have undergone major developments. Today, a number of validated Building Performance Simulation (BPS) tools are available quite globally. The advancement of these software tools has increased their working capabilities over the years, to the extent of offering in-depth insights into building design, operational efficiency, maintenance, and whole life assessments [25]. These software programs offer energy performance assessments for existing buildings and proposed buildings by employing an occupancy profile, thermal comfort and visual comfort assessments [26, 27]. Earlier studies [28, 29] established the great benefits of computer-based simulation and modeling. A study by [25] ranked Design-Builder among the most recognized BPS tools among architects and engineers based on user needs and functional specifications. This software was intended specifically for running EnergyPlus simulations on virtual building models [27] Figure.3. The validity and applicability of Design-Builder for assessing performance of buildings have been studied and proved in an ample number of studies [25-29]. Consequently, for this research, Design-Builder shall be set as the main BPS application.The following were simulation parameters defined for this study:-

- Weather data: Typical Meteorological Year (TMY) Weather data for Bordj Bou Arreridj.
- Simulation duration: Hourly simulations for a complete annual cycle to capture seasonal variations.
- Simulation period: January 1st to December 31st.
- Reporting intervals: Monthly and yearly.
- Output variables: Heating energy, cooling energy, and lighting energy.

2.2.1 Modeling End-Use Energy Consumption

Energy consumption in the residential sector is better understood by defining specific end-use functions and their driving forces [25]. The relative significance of each end-use component within the total energy consumption depends on a very intricate interaction among climatic conditions, physical characteristics of the dwelling, appliance and system specifications, ownership patterns, and occupant behavior [30]. For the purpose of assessing intervention impacts on particular consumption categories with a measure, energy consumption has been separated according to heating, cooling, and lighting by means of independent output variables in EnergyPlus [27].

2.2.2 Simulation conditions

Results have been entered into the database DesignBuilder using the database of integrated characteristics offered by it. Manual calibration has taken place afterward using three indices as per the regulations of ASHRAE Guideline 14. Comparisons have then been done using EnergyPlus building energy simulation software [31]. The operational detail and simulation inputs are as given in Table.3.Standard profiles for occupants were applied after field survey data was collected from 20 households in Bordj Bou Arreridj. Each apartment is thought to accommodate a family of 6 persons representing a generalized daily and weekly occupation scheme.

Heat gains internally from occupants were obtained, following ISO 7730 standard values, with metabolic rates changing with an activity. Lighting power density was set at 9 W/m², depending upon occupancy and daylight availability. Equipment load was assumed to be 6 W/m² in occupied hours [31,33].

2.2.3 Parametric analysis

Despite a lot of research devoted to building energy consumption, the gap in energy requirements analysis for maintaining internal thermal comfort is huge [11]. This study hence seeks to fill this gap by implementing a parametric study to investigate the effect of passive design strategies on the building energy performance so that a pathway for modeling optimal thermal renovation solutions may be identified and decisions informed during the design phase [20]. In particular, we analyze and assess variations in annual energy loads, which will allow predicting model performance, focusing on heating, cooling, and lighting demands. Using DesignBuilder, a renowned platform to calculate and simulate the behavior of multi-zone buildings and integrated active energy systems, this study aims to provide a rigorous and comprehensive analysis of the energy dynamics.

2.3 Calibration Method (Uncertainty analysis)

Uncertainty analysis is a technique for analyzing the variability in model outputs due to uncertainty in input parameters and provides information about the output confidence intervals [11,34]. The method has been validated by many comparative studies [34-37]. Specifically, this was used in assessing the effects of occupancy, internal gains, and climate on simulation results. This allows for a comprehensive evaluation of the reliability of the model, consistent with the general methods for uncertainty propagation in complex models [36], under different conditions.To make research findings objective and trustworthy [9, 25] and to develop a model well-coupled to reality, an intensive calibration effort was instituted. The baseline model representing an existing building in Bordj Bou Arreridj, exhibiting similar characteristics, was calibrated with five years (from 2018 to 2023) worth of measured monthly electricity consumption and natural gas consumption data. It was necessary for establishing reliable simulation models founded on actual energy use patterns [9,25]. According to ASHRAE Guideline 14 protocols [32], manual calibration of the models uses three critical indices: Mean Bias Error (MBE), Coefficient of Variation of the Root Mean Square Error [CV(RMSE)], and the coefficient of determination (R2). MBE indicates the average bias, while CV(RMSE) indicates the unsuitability of modeling the variability of the data. R2 represents the proportion of variance that can be predicted by the independent variables. The following are the computational methods:

$$MBE = \frac{\sum_{i=1}^{NP}(Mi - Si)}{\sum_{i=1}^{NP} Mi}\ (\%)$$

$$CV\ (RMSE) = \frac{1}{M}\sqrt{\frac{\sum_{i=1}^{NP}(Mi - Si)^2}{Np}}\ (\%)$$

$$R2 = \frac{SSres}{SStot}$$

- (**Mi**), (**Si**) ; the measured and simulated data at a time interval,
- (**I**), (**Np**) is the total number of data values used for the calculation.

Calibrated with respect to ASHRAE Guideline 14 [32], the simulation model is thus considered calibrated, if :

- Within hourly value of MBE: ±10% and hourly value of CV (RMSE): <30%.
- Within monthly value of MBE: ±5% and monthly value of CV (RMSE): <15%.

The simulation model was calibrated using the monthly consumption data of electricity and gas. This required iterative manual changes to the building-specific airtightness, operation schedules (occupancy, lighting, heating, cooling, and DHW), and setpoint temperatures. The evaluation of calibration efficacy through MBE and CV(RMSE), according to ASHRAE Guideline 14 thresholds, is presented in Table 4.

2.4 Improvement on reference case base don individual parameters

Energy conservation and occupant comfort must be kept in mind during the design of energy-efficient buildings (38). Successful architectural design is capable of reducing or even eliminating any dependence on any active HVAC systems [36]. The summers in Algeria are scorching, and Algerian winters are mild; therefore, for building design, the summer thermal comfort assumes the most significant value among the design parameters to be taken into account [39]. Cutting back on energy consumption will demand better insulation and a higher standard of ventilation so that thermal comfort can be achieved through reduced winter heating requirements and increased natural summer cooling while minimizing heat loss [12].

An effective architectural means creatively harnesses the positive predominant climatic elements for the purpose of thermal comfort [12,36]. In fact, low-energy building design sets an ideal relationship between building and climate, applying passive design actions to induce pleasant indoor environmental qualities from the benefits of climate (winter solar gain, summer ventilation) and keep away its disadvantages (summer solar heat gain, wind exposure), combining energy efficiency measures with occupant comfort [38,40].

The primary focus was thus identifying heat gain-contributing building components within the case base building with the most influence for implementing successful passive major reduction strategies of energy use in the very highland climate of Algeria, as concluded from results analyzed from dynamic simulation of internal heat gains and simulated external heat gains from the building envelope as shown in Figures.5 and 6, respectively.

2.4.1 Internal heat gains

Figure.4, shows internal heat gains incorporated as lighting, equipment, occupancy, solar infiltration gains, and gains due to or losses because of HVAC systems. As the graph depicts a thermal balance, negative numbers below the zero line put heat loss by the building. Based on the daily data analyzed throughout a year against each one of the months, it turns out that the maximum heat gains come from solar radiation that enters through external glazing.
Following this, the windows are exposed to solar irradiation throughout the year as a result of the building's north-south orientation. Coming after that are the gains from transformer lighting and domestic appliances. These results directly point to areas and passive strategies which could be implemented for reducing these internal gains and by consequence energy consumption. This includes replacing the current window types with better thermal insulation performance, such as double-glazed PVC windows, which also offer the joint value of reduced heat gains and lower ends for artificial lighting as a result of improving the daylight factor. The application of external shading strategies on the southern facades would also protect the glazed surfaces from direct solar exposure during peak times and contribute to lesser heating and cooling loads.

2.4.2 External heat gains

Figure.5, shows the total external heat gains by the external components of the building envelope, including uncovered roofs, external walls, windows, and flooring, plus heat loss because of infiltration by external air. External heat gains and losses because of the annual analysis of air infiltration show that most values fell below the zero line, which shows significant heat losses from the building. Such dynamics are caused by an Algerian highland climate, characterized by extreme contrasts between hot, dry summers and cold, humid winters. Greatest heat loss through external walls, followed by roofs, next air infiltration and windows, respectively. Directly thus, it indicates the locations and hence the extent of passive design measures that could be adopted in such climates to lead to such heat losses under control, thereby leading to decreased energy consumption, specifically on that for heating demand. Most of which are probably composed of different strategies in the right materials for constructing the building structure, highly emphasizing the use of thermal mass subjected to thermal inertia [40]. Thermal mass is great in regulating seasonal weather temperature variations, thus considerably affecting the reduction of heating and cooling loads for each component of a building's external envelope [39].

2.4.3 Intervention specifications: Passive Design Strategies

Following the analysis and in conjunction with prior research, discussions, and the previously mentioned climatic analysis of the Algerian highlands, five passive design strategies were identified for parametric investigation. The analysis aims to review how each of these passive design strategies improves the energy efficiency impacts as compared to the baseline building model considered.

- ✓ **Improved thermal insulation:** This forms an important measure for improving any building's energy efficiency performance [1:40]. Research shows that nearly 40% of heating energy consumption (in northern areas) may be avoided by improving the energy effectiveness of the building envelope Figure.6.a.b [39, 40].
  Improvement of thermal insulation in the building envelope (walls and roof); extarnal walls 5cm expanded polystyrene, reduce U-value down to 0.38 W/m²K and roof (8cm extruded polystyrene reduce U-value further down to 0.33 W/m²K)
- ✓ **Glazing Optimization:** The windows by themselves cause major thermal vulnerability in the thermal transfer by glazing and frame, as well as volumetric infiltration. That is why the setting of PVC windows with insulated double glazing, which consists of two panes separated by an air or low-conductivity gas-filled cavity such as argon, is widely accepted as one of the best options to boast thermal insulation, Figure.5c [39].
  Replacement of single-glazed aluminum windows by double-glazed PVC windows, 24mm thick and filled with argon gas (U-value : 1.4 W/m²K, Solar Heat Gain Coefficient : 0.35).
- ✓ **Solar Control:** Horizontal projections on south facades (projection factor 0.5) and vertical fins on east/west exposures (projection factor 0.4).
- ✓ **Optimising natural ventilation:** Improved window design for better cross-ventilation with increased operable window area to 30% of window dimension (moisture-tightness expressed by infiltration rate (.air changes per hour 0.25 ac/h).
- ✓ **Thermal mass Adjustment:** Integration of 200mm high-density concrete in interior walls increasing thermal capacity of building from 165 to 243 kJ/m²K.

3. Results and Analysis

3.1 Baseline Energy Consumption Analysis

The simulation of the reference edifice established the baseline energy performance on the basis of high energy consumption resulting from heating and cooling needs. Figure.7,presents end-use monthly energy consumption of the reference case.

The total annual energy consumption in the reference building stood at 155.38 kWh/m²/year, with heating accounting for 55.7% (86.53 kWh/m²/year), cooling for 31.9% (49.62 kWh/m²/year), and lighting for 12.4% (19.23 kWh/m²/year) Figure 8. Such proportions support the substance of thermal conditioning on the collective energy profile of highland social housing levels, as they experience considerable heating needs from November to March and further cooling needs from June to September.

The bivariate regression analysis indicated that heating degree days (HDD) accounted for ($R2$ = 0.927) the variance in heating demand, whereas cooling degree days (CDD) accounted for ($R2$ = 0.894) the variance in cooling demand. The strong correlation confirms that energy consumption in this part of the region is driven by specific climatic factors.

The basic profile of consumption thus obviously shows to a double challenge in the highland climate of the city of Bordj Bou Arreridj : a longer season for winter heating, requiring large amounts of energy, and a shorter but intense summer cooling period, creating other demands. Hence, intervention strategies must be balanced to meet thermal requirements in both cases without being compromised by the performance of any season.

3.2 Individual Intervention Effects on End-Use Consumption

The effect of many design and operating measures on the total annual energy consumption can be calculated through a detailed parameterized analysis of the ideal model. Figure.9 shows the total percentage of energy savings through complete simulation associated with all individual parameters (mentioned in 2.4). It can be seen that the individual influence of passive design interventions exerted an extremely comprehensive difference over specific end-uses of energy in Figure.9. As is, figure.9 indicates that insulation offers the largest measure in reducing energy consumption in Algerian buildings; as evidenced in a study by Meftah.N, Mahri.Z.L [41], annual consumption decreased by 22.33%. The improvement majorly came from a 31.13% reduction in heating demand and 15.63% decline in cooling requirements. Lower U-values in the insulation composition usually yield better thermal performances and more energy savings. Most of this is due to the effect of the thermal insulation materials in reducing heat gain through building envelope components, thereby affecting positively the dominant heating and cooling loads. Implementing thermal insulation in walls and roofs combined is capable of producing total energy savings in usage ranging from 20% to 30%. This matches findings from literature which claim reductions in energy usage between 15% to 35% with thermal insulation for external wall and roofing applications [7,13,25,40]. This finding also reflects the theoretical principles concerning climates with high heating demands [42], thus, stressing the need for priority while adopting insulation methods in highland regions.

Second in rank in terms of measure impact is the application of advanced window systems (glazing to double glazing) that leads to an estimated 9.85% reduction in annual energy consumption. Next on the ladder were optimized natural ventilation strategies yielding about 8.3% overall energy reduction achieved. Improvement was indeed largely a function of the cut in cooling energy demand (18.88%), rather slight ones for heating requirements.

Different interventions show different end-use effects. Solar control had an overall energy reduction of only 3.9% but delivered by far the most significant cooling savings (21.12%) and a negative influence on heating performance (-3.67%) due to reduced solar gains in cold months. On the other hand, thermal mass gave similar benefit to both heating (5.01%) and cooling (10.16%). This specificity indicates the need for different intervention packages dealing with specific seasonal challenges.

In the reading of the thermal interventions, lighting energy consumption was unaltered, with the exception of strategy measures really devoted to daylighting enhancement. This independence suggests that lighting strategies can be developed parallel with thermal interventions without significant interaction effects.

3.3 Synergistic Effects of Combined Interventions

The three combinations developed on the basis of effectiveness of the individual strategies include an optimal combination of energy efficiency measures:

- **Scenario 01 (BC):** Basic combination (Improved insulation + Enhanced glazing).
- **Scenario 02 (IC):** Intermediate combination (Improved insulation + Enhanced glazing + External shading).
- **Scenario 03 (OCP):** Optimized Combined Package (All five passive strategies working together)

Synergistic effects of passive design measures, when applied in optimized combinations, were proved to be greater than the simple arithmetic sums of individual contributions. In figure.10, the potential energy savings of the optimal intervention package is displayed for Bordj Bou Arreridj.

Some significant results arise from the statistical analysis of combined intervention outcomes.

A strong synergistic effect of combined interventions was exhibited, with the comprehensive combination of all five passive strategies achieving the highest energy efficiency with 47.9% annual energy savings with respect to the reference case. The Joined method resulted in a reduction of heating consumption of 45.95%, cooling demand of 53.28%, while lighting energy consumption increased slightly by 3.6% due to shading effects on daylighting. This synergy could be attributed to the complementary nature of insulation and thermal mass strategies in highland climates with significant diurnal temperature variation.Principal Component Analysis of the intervention combinations indicated that two principal components explained most of the performance variation; the first one associated with insulation and glazing parameters and the second one with thermal mass and ventilation parameters.

Cluster analysis identified an optimal package for interventions for the climate of the Algeria highlands, which consists of:

- ✓ Primary tier: Enhanced thermal insulation and glazing optimization.
- ✓ Secondary tier: Strategic placement of thermal mass.
- ✓ Tertiary tier: Passive solar strategies such as seasonal natural ventilation and selective solar control.

This hierarchical approach represents the dominance of winter heating regime while maintaining that summer comfort and peak cooling regime must be addressed.

3.4 Benefit Analysis of Passive Design Strategies for Social Housing Energy Performance

The present research effort used a computational effort devoted to modeling all the efficiency measures available to identify the optimal design strategies for a typical multi-family residential building. The effect of optimal passive design strategies on energy efficiency in social housing in the Algerian highland climate has been evaluated by DesignBuilder software. The simulation results for the enhanced building as compared to the baseline building indicated a significant difference based on varying parametric concerns examined. After investigating the effect of each parameter, as shown before in Figures.9,10, this section will analyze the overall effect of the combination of measures indicated in Scenario 03 in Section 3.3.

The integrated package of measures was able to carry down overall energy consumption by 47.9%, leveling at 80.93kWh/year/m2. Regression analyses showed highly significant correlations between reduction effectiveness and baseline consumption (r=0.81); this means that the greater the initial energy intensity, the more enhanced the improvement in the consumption reduction. Simulation results were in line with the trends of the baseline scenario, with peak consumption in December and January (the coldest months in the Algerian highlands climate). Thus, the synergistic effect of the interventions was clearly favored during the summer months (a reduction of 56.2%-56.4% in July and August) as opposed to winter (reduction of 45.4%-46.3% in December and January) as presented in Figure.11. This seasonal variation demonstrates both the potential of enhancing summer thermal performance and the hindrances with passive cooling in a climate that translates into a relatively low diurnal temperature variation during the summer peak. Cooling load accounted for 68% of the total energy consumption-the great significance accorded to it that perhaps contributed to 70% of the total energy savings from the integrated optimization package.The cost of electricity in Algeria is globally competitive, costing 10.54 DZD/kWh (1€=135 DZD), while the European average is 18.64 EUR/kWh [33]. A strategic shift in financial support toward funding building designs that conserve natural resources-such as sustainable architecture, particularly passive design strategies-is essential, despite the ongoing governmental subsidies. The savings in consumption due to the optimization done in this study amounted to about 53,360 DZD per dwelling per year, assuming Government subsidy of greater than 40% of the unit costs. Furthermore [10,33], low-energy consumption buildings improve the capacity for climate change adaptation and, in their way, mitigate CO2 emissions by 8.35 tons.

4. Discussion and Implications

4.1 Interpretation of Results

The simulation results indicated that passive design techniques notably increase the energy performance of social housing within Bordj Bou Arreridj, up to an estimated 47.9% energy savings on a yearly basis. These results correlate well with findings from previous studies conducted by Hadji et al, where savings of between 45% and 60% were reported as a result of passive optimization of envelope in one of the Algerian climatic zones [33]. While effectiveness was highly divergent for individual passive strategies, thermal insulation turned out to be the strategy with the highest impact as a single measure. This observation also concurs with evidence from studies in those climate zones emphasizing that envelope insulation is a major contributor to heating and cooling demand reduction [40, 41].The combined strategies therefore highlight the synergy of an integrated design approach. Medium improvements were achieved with single strategies alone but could generate major advantages in conjunction with each other, because of complementary interactions between different passive techniques. Such findings go hand in hand with Mana and, Siddig's conclusion; that optimizing multiple design variables can yield more significant energy savings than partial improvements toward individual parameters [25].

4.2 Comparison with Other Studies

This will place our findings within context compared to the same study done in Algeria and in regions of comparable climates. The study of Meftah and Mahri on office buildings in Algeria stated that optimizing only the glazing system can save approximately 10-15% of energy consumption [41], which is comparable to the reduction we found in energy consumption, 9.85%, through improving glazing alone.

There is another study relating to Benharkat and Telilani about residential buildings in the northeast of Algeria which also acknowledged the significance of thermal insulation methods for their saving potential of up to 40-45% by isolation des murs extérieurs et parois vitrées [40]. Our research indicates that energy savings for residential buildings in this climate are around 35%, which is considerably lower than what previous research documented. This difference is caused by earlier rather concentrating on single strategies and on energy consumption due only to heating and cooling, giving higher numbers. Conversely, results are presented to demonstrate strong methodology of which a breakdown end-use energy analysis and evaluation of synergistic effects would contribute.

It is further confirmed by researches carried out by the National Center APRUE in the "Guide pour une construction Eco-énergétique en Algérie", whereby insulation in the envelop of buildings is established to be the most important key to having residential buildings use energy highly efficiently. The study showed that an improvement in the envelop insulation would lead to an estimated 40% reduction in heating energy consumption in the northern conditions of the country [14]. Even more, this study showed a bigger potential for residential buildings at higher altitudes, where a 54 % reduction in heating energy demand was attained.

The research by Morini et al. [13] was developed in the framework of the Program "Technical Assistance to the EU Support Program for Renewable Energy and Energy Efficiency Sectors in Algeria". The need to surpass the Thermal Compliance Requirements (RTB), which mainly concern the building envelope, in order to undertake a general analysis of energy efficiency within the Algerian construction sector is stressed by this paper. Attaining sustainable and integrated energy efficiency entails a comprehensive and in-depth evaluation and assessment of energy consumption categories [13]. This has been observed in our study, where a protocol for climate-specific calibration for energy models was developed, addressing a major methodological gap concerning simulation accuracy within the Algerian climatic contexts, especially for buildings demonstrating season-dependent operational patterns as found in the highland climates typical in Algeria. Countless studies [11,12,16,19,20,36,38] have been carried out in different climatic contexts, including Algeria which clearly accentuated the importance of bioclimatic design principles in achieving thermal comfort and energy efficiency to residential places. But most of them assessed individual passive strategies in isolation without combining them to measure their joint implications through common annual performance metrics. Given that these studies such as performed simplistically model methods, it is likely that the overall performance of comprehensive passive design is understated in similar climates. The methodology used in the present research affords several advances in assessing passive design in similar contexts:

- ✓ A disaggregation of end uses combined with monthly analysis in time gives a more refined framework for evaluation compared to the predominant approaches, which are annual and whole building. This added granularity enables much more targeted interventions to specific consumption components.
- ✓ Arguably, the significant methodological deficiency in simulation accuracy within the Algerian climatic contexts, especially in buildings demonstrating seasonal operational modes typical in semi-arid climatic zones, is being handled by developing climate-specific calibration protocols for energy modeling.
- ✓ -It is a transferable methodology to conduct parametric optimization to find locally optimized implementation parameters rather than generalized recommendations based on different climates.
- ✓ synergistic effects induced in such combine interventions go beyond simple additive benefits-these involve more complex thermodynamic interactions that require further investigation from theoretical perspectives.

4.3 Implications on Social Housing Design in Algeria

These results become a very good base for respect to social housing design and policy as it were in Algeria. The observed potential energy savings would mean that if passive design strategies were implemented, social housing projects could be made such that operational energy costs would significantly decrease for residents while improving their thermal comfort.From an economic perspective, The reduction in consumption brought about by the optimization processes done in the study accounts to annual savings of nearly 53, 360.00 DZD (approx. €395); whereas few of these passive strategies need more initial investment, the investments are worthwhile on saving the energy from it long-term. The same is shown by the findings of these studies [10,33]: especially for measures regarding thermal insulation and improved glazing were given as they were and produced much profit. A life-cycle cost analysis, although outside the ambit of this study, would probably show very good economic returns for different passive design measures.From a policy perspective, these findings will strengthen the case for stricter standards for energy efficiency in building codes for social housing. The existing political machinery in Algeria now favors speedy construction and cheap costs to have low initial setting up costs for most social housing development-programs, but this also paved the way for the construction of houses that possess poor thermal such as [13]. and high operational energy consumption. Integrating passive design criteria into government housing interventions such as AADL would greatly improve the sustainability of Algeria's housing stock.

4.4 Limits and Future Research

Of course, this study had limitations. First, the study used typical meteorological year data to simulate whether all extreme events of weather can be captured or some futures with their possible effects of climate change would be accounted in the simulations. Secondly, the occupancy and usage criteria were all modeled mainly based on averaged behavior; actual energy consumption displays significant variability due to occupant behavior.
In addition, this has only been an energy analysis, not even an economic analysis or life-cycle assessment. Future research in this area should forever construct cost-benefit analysis to assess how viable the different passive design strategies are in doing so to determine the most cost-effective interventions in social housing in Algeria.Further work should also examine the possibility of hybrid strategies integrating passive design with renewable energy systems, especially using solar photovoltaics, given the exceptional solar resources in Algeria7. The combination of active and passive systems could be instrumental in achieving net-zero energy performance in social housing, therefore significantly contributing towards energy savings for Algeria.

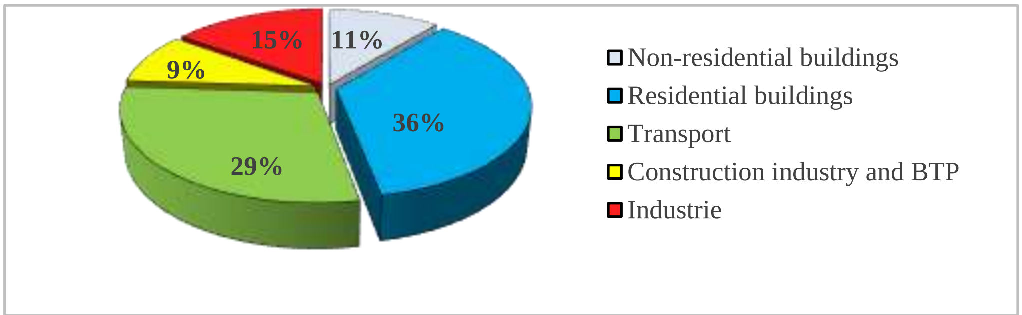

Figure 1; *Final Energy Consumption Structure by Sector of Activity, Reproduced from [15]*

Table 1. *Selected building characteristics*

Location	Bordj bou arreridj (algeria)
Façade and orientation	Front elevation of the north and south facades
Plan shape	Rectangular
Floor height	3,2 m
Total built area	68 m²
Gross wall area	124,8 m²
Total area of windows	10,14 m²
Surface area to volume s/v	0.31 (m^{-1})
Glazing area for each cardinal orientation	N (4.44 m^2), e (0.00 m2), s (5.7 m^2), w (0.00m^2)
Windows	Single pane windows (4 mm)

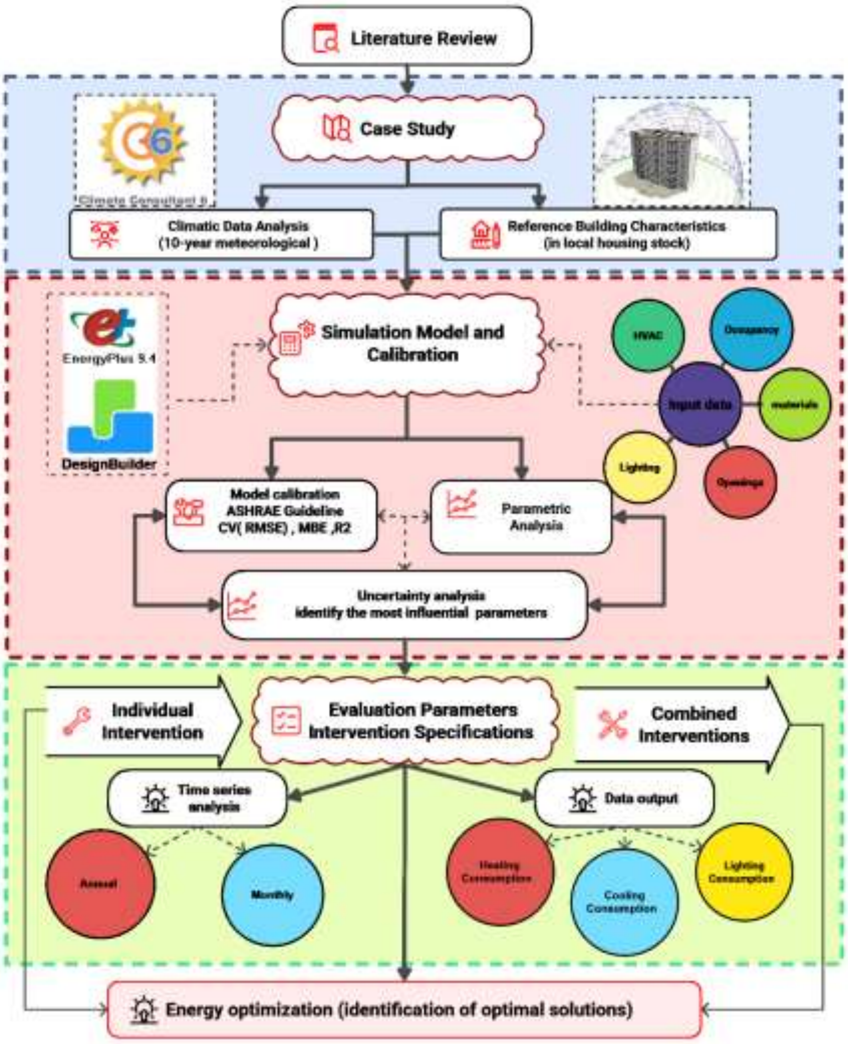

Figure. 2. *Study and simulation steps*

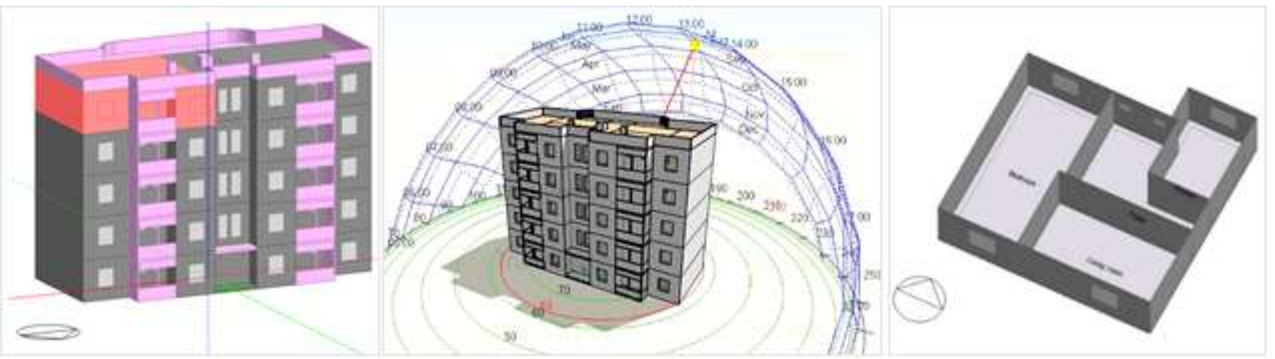

Figure. 3. *Case study: building model*

Table 2: *Specifications of building materials simulated in Design-Builder software are taken from the Energy Plus software library based on (DTR C3-2) [22,23].*

Envelope	Construction	Layer Thickness (m)	U-value (w/m²k)
External walls	Cement coating	0,02	1,51
	Hollow brick	0,10	
	Air blade coating	0,05	
	Hollow brick	0,15	
	Plaster coating	0,02	
InteriorWall	Plaster coating	0,02	2,3
	Hollow brick	0,10	
	Plaster coating	0,02	
Roof	Waterprooflayer	0,10	0,86

	Plancher avec entrevous en béton (Hourdis)	0,20	
	Plaster coating	0,02	
Intermediate floor	Floor tile	0,05	0,39
	Plancher avec entrevous en béton (Hourdis)	0.2	
	Plaster coating	0,02	
Windows	Single glazing	0,004	5.80

Table 3. *Summary of DesignBuilder model input data.*

	Parameter	Specification
Occupancy	Occupancy density Metabolic activity	0.088 people/m2 light manual work Metabolic factor = 0.9
Openings	Single glazing windows U value Position	4 mm 5.8 w/m²k inside
Lighting	Type of lighting Power density	LED 9 W/m^2 – 300 lux
HVAC	Split + Separate Mechanical Ventilation Heating set point temperature Cooling set-point temperature Fuel	CoP = 2.5 21°C 26°C Electricity from grid - Natural Gas
DHW	Instantaneous hot water with default CoP	0.85 Natural Gas

Table 4. *Calibration results of the building simulation model.*

Validation criteria	Monthly electricity use	Monthly gas use
MBE (%)	4.31	2.46
CV-RMSE (%)	10.7	6.73
R2	0.86	0.92

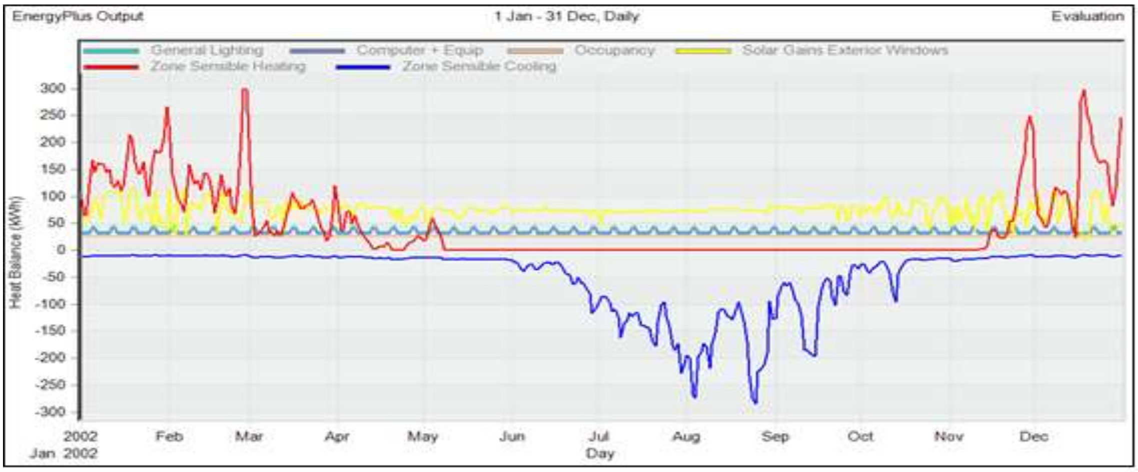

Figure 4. *Internal gains and solar infiltration, base case*

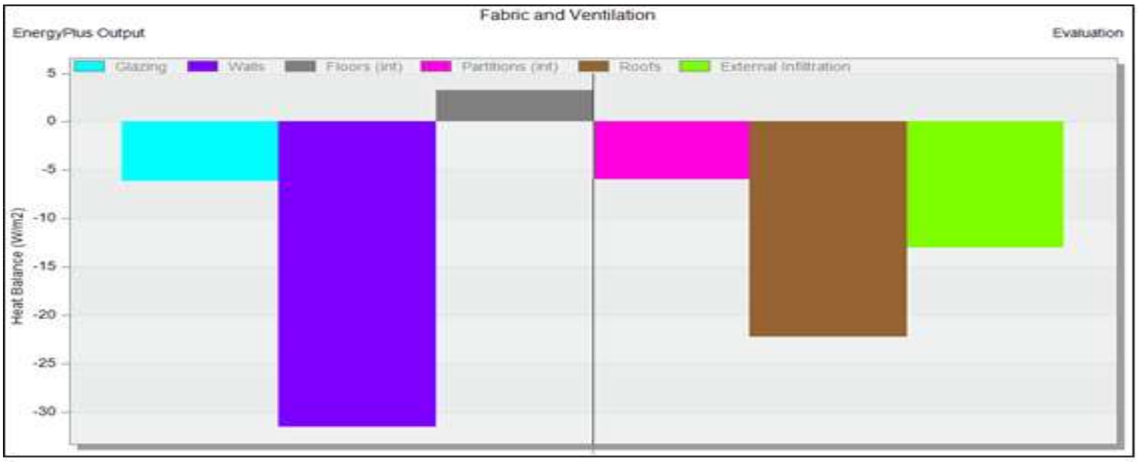

Figure .5. *External heat gains, base case*

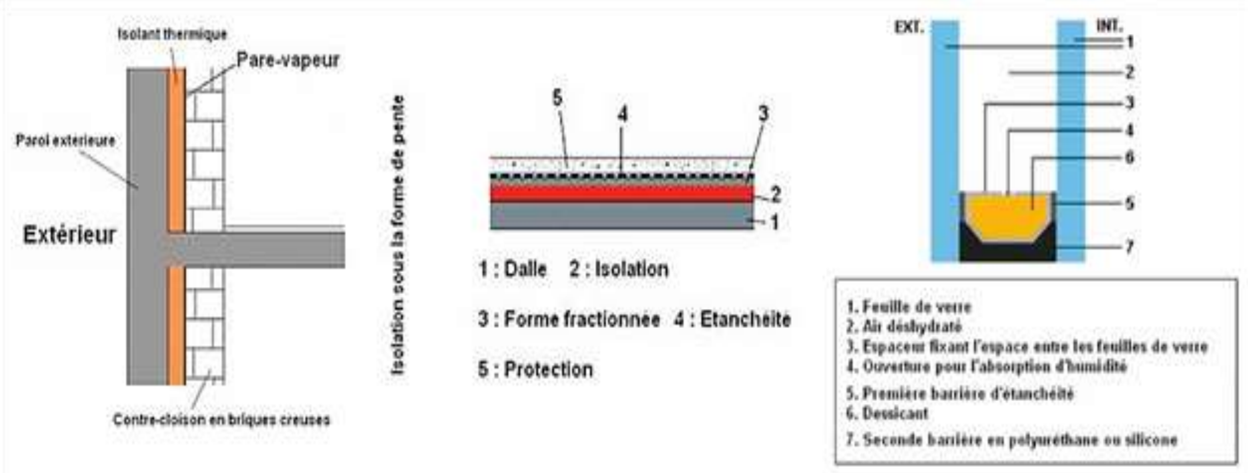

Figure.6.a. *Isolation des murs* *Figure.6.b.* *Isolation des murs* *Figure.6.c.* *Principe du double vitrage*

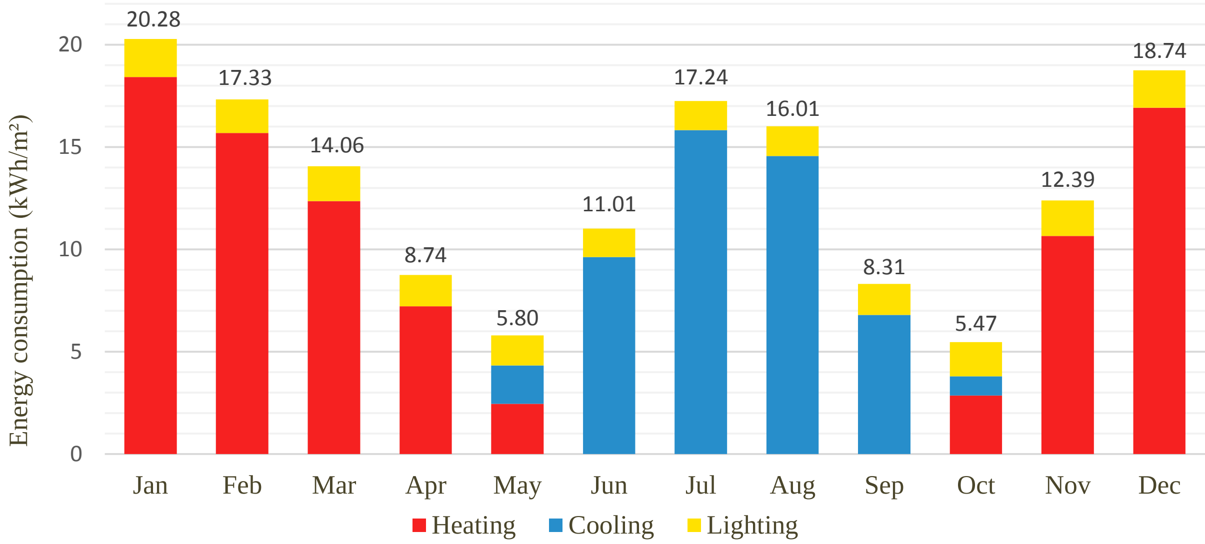

Figure.7. *Monthly Baseline Energy Consumption in Bordj Bou Arreridj by End-Use (kWh/m²)*

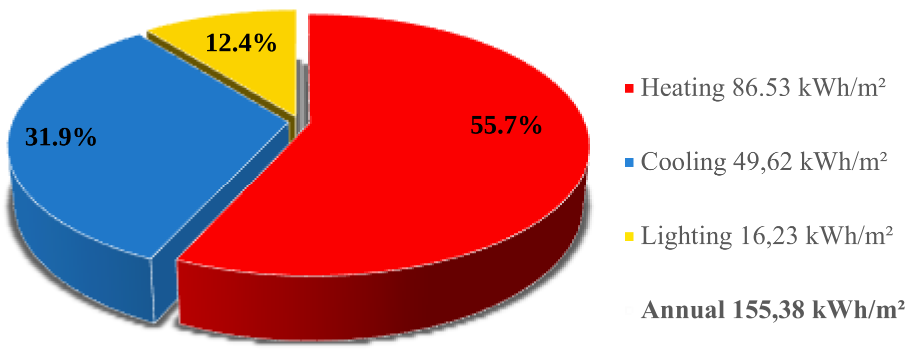

Figure.8. *Breakdown of the total annual energy consumption, base case*

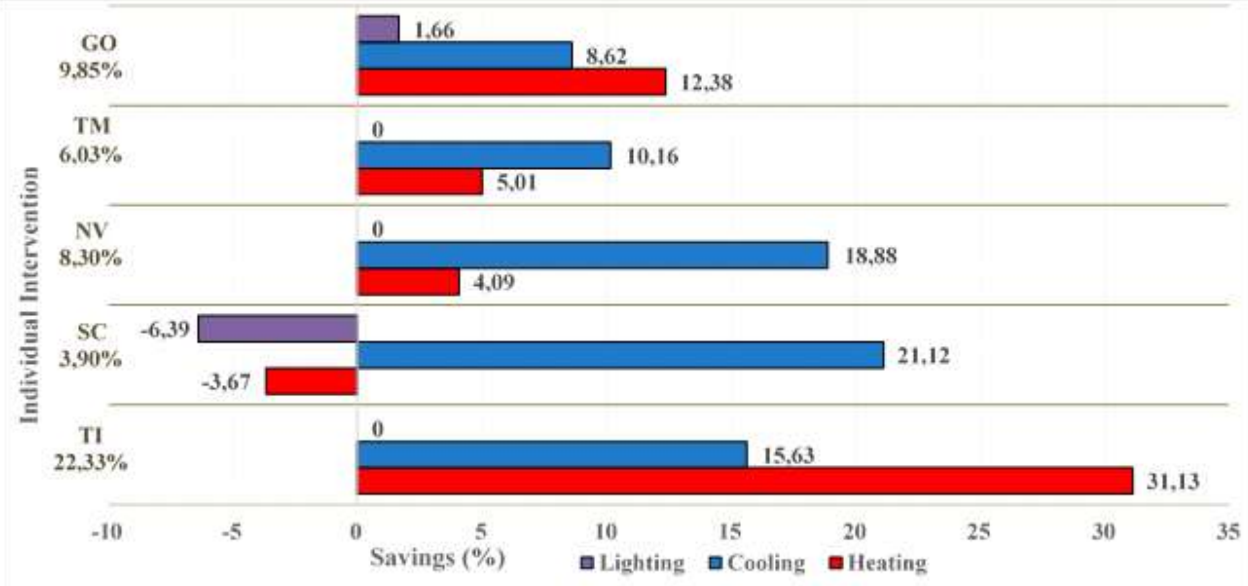

Figure.9. Impact of considered parameters on the energy saving.

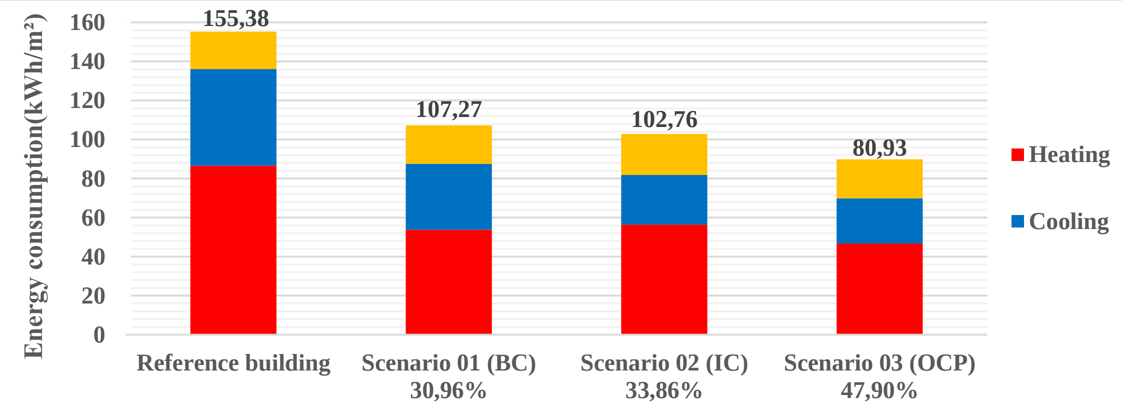

Figure.10. Annual energy consumption by end-use for combined passive strategies

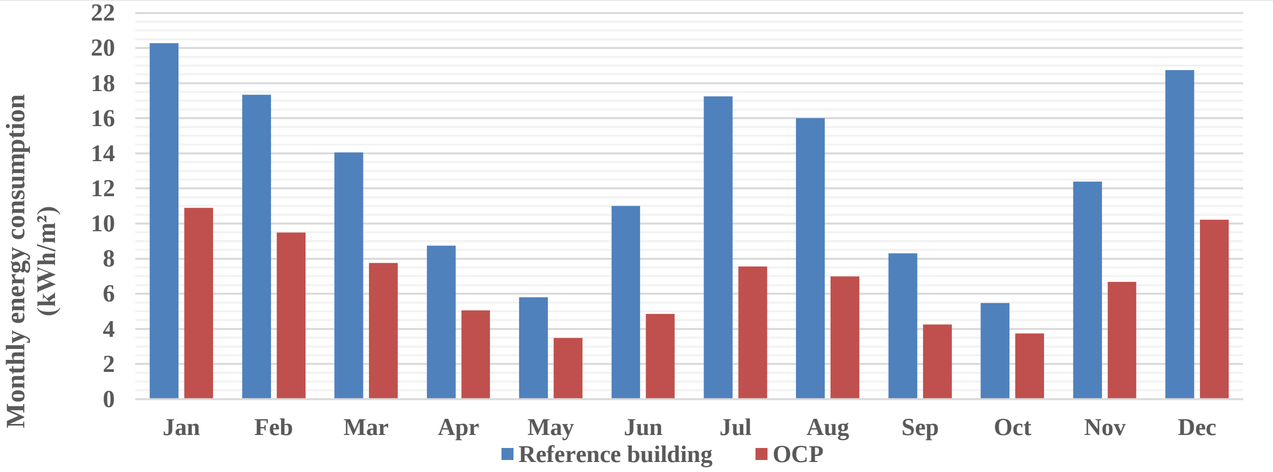

***Figure10.** Comparison of monthly energy consumption of base and improved case*

5. Conclusions

This study empirically demonstrated that appropriately selected passive design strategies are capable of maximizing energy efficiency enhancement in Algerian social housing. The influence of various passive interventions on consumption categories and periods of time in a typical social housing building was assessed using detailed building performance simulations with DesignBuilder software.

The crucial outcomes can be summarized as follows:

- Implementation of passive design strategies (thermal insulation, enhanced glazing, external shading, thermal mass, and optimized natural ventilation) could reduce annual energy consumption by 47.9%.
- Thermal insulation was the most potent individual strategy in achieving energy savings of 22.33%, followed by enhanced glazing (9.85%) and natural ventilation optimization (8.3%).
- The synergistic effect is observed in combining some strategies, with the highest energy reductions during peak cooling months (42.1%) and still significant improvements in the heating season (36.5%).
- Two-season climate conditions of Bordj Bou Arreridj necessitate the use of balanced passive design strategies for both heating and cooling needs so that horticultural performance in either season is not sacrificed.

These conclusions have very pertinent implications for social housing design and construction in Algeria. A significant impact on energy saving could be made by applying passive design strategies in new housing projects and renovation programs, thereby alleviating environmental impacts and reducing operating costs for residents.

We recommend that housing authorities and policymakers incorporate a minimum requirement for passive design into social housing specifications, especially for those aspects that showed most influence: thermal insulation, window performance, and shading systems. Architects and engineers must also adopt an integrated design approach that considers interplay between several passive strategies for maximizing energy efficiency.

Future works must extend this analysis to other climatic zones in Algeria, incorporating economic analysis to identify cost-optimal solutions while bringing in renewable energy systems to achieve near-zero energy buildings. Since energy efficiency through passive design represents a historic opening towards sustainable built environments, time-wise, it must be promoted in the face of Algeria's ambitious housing development programs.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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