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A Multi-Variable Analysis for Heating Energy Performance and Thermal Comfort in Residential Buildings

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In this study, the energy performance of a gated community in a temperate-humid region of Turkey is evaluated while considering the thermal comfort of residential units. A total of twenty-three different options were analyzed, focusing on three design variables: the thermal insulation material for external walls (XPS, EPS, mineral wool) and its thickness (ranging from 3 cm to 10 cm), the infiltration rate of the building envelope (ranging from 0.8 ac/h to 0.4 ac/h), and the indoor set-point temperatures for both heating (ranging from 19°C to 23°C) and cooling periods (ranging from 24°C to 28°C). The impact of these variables on heating and cooling energy consumption, primary energy use, CO_2 emissions, and thermal insulation investment payback period was assessed through building energy simulation (BES)-based parametric analysis using the DesignBuilder software tool. Additionally, the indoor thermal conditions were computed for both the reference case and the combination of the most energy-efficient options. The thermal comfort performance of a model apartment, assessed using PMV–PPD criteria, was then compared against the standards of ASHRAE-55: 2023 and BS EN 16798-1: 2019.

Keywords: *residential buildings, energy efficiency, thermal comfort, building performance simulations*

Introduction

Following industry and transportation in Turkey, the residential sector emerges as the third-largest contributor to carbon emissions, accounting for 9% of emissions, 20% of total end-use energy, and 21% of electricity consumption. According to the current TurkStat Statistics (2022), there are more than 10 million buildings in Turkey as of October 2019, with over 100,000 new constructions annually while approximately 90% of the existing building stock consists of residential buildings, housing 24 million households. Given these figures, residential buildings hold significant potential in combating climate change and aligning with both national and EU carbon neutrality objectives.

According to the IEA (International Energy Agency) World Energy Statistics of 2021, space heating represents the largest portion of final energy consumption in dwellings, comprising 48% of total energy consumption in Turkish households in 2018. Emphasized within Turkey's Building Energy Performance regulations and TS 825 Standard (TSE 2013), external thermal insulation stands out as a prevalent strategy for enhancing the energy efficiency and thermal comfort of buildings by

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improving the thermal resistance (R-value) of the building envelope and reducing heat transfer through walls, roofs, and foundations. This approach prevents thermal bridging, moisture ingress, condensation, and indoor temperature fluctuations during both heating and cooling seasons, which can prolong the lifespan of building materials and structural components. Reduced energy consumption from heating also contributes to reduced HVAC (heating, ventilation, and air conditioning) equipment capacities, reduced energy bills for building owners and occupants as well as lower greenhouse gas emissions associated with energy consumption. Besides TS 825 (TSE 2013), Building Energy Performance Regulation (BEP 2008) building energy performance certification (EPC) program (BEP-TR 2010) mandate minimum insulation requirements for new and existing buildings in Turkey.

Research consistently shows that adequate insulation significantly reduces heating energy consumption in buildings, depending on factors such as climate, building size, thickness, and the efficiency of HVAC systems. For instance, the research by Aditya et al. (2017) investigates the performance of various insulation materials alongside life-cycle analysis and potential emissions. In Schiavoni et al.'s (2011) meta-analysis, findings from various studies on the impact of insulation materials on energy savings are consolidated. A comparative analysis is conducted with varied insulation types and installation methods including unconventional insulation materials. In Adamczyk and Dylewski's (2017) study, the significance of thermal insulation investments in buildings is examined across three dimensions: economic, environmental, and social. This study includes evaluations of economic and ecological benefits associated with the insulation of external walls, considering various types of thermal insulation materials, construction materials for walls, and climate zones. D'Agostino et al. (2018) also conducted a BES-based case study in Italy, examining passive strategies like thermal insulation and window properties using cost-optimal methodology and DesignBuilder simulations. The study evaluated eight retrofit options for reducing primary energy demand and discussed the practical challenges and benefits. It also compared the methodology with discounted payback analysis, finding consistent results in scenarios without HVAC or renewable energy interventions. Similarly, in the case study by Drissi-Lamrhari and Benhamou (2018), the impact of various construction parameters on the energy performance and thermal comfort of a flat is investigated using a TRNSYS-based numerical model across six climates. The study integrates field measurements and building monitoring with simulations to evaluate the effectiveness of different retrofit scenarios, focusing particularly on insulation levels and thermal conditions of the case study apartment.

The infiltration rate of a building envelope, typically quantified as air changes per hour (ACH), refers to the amount of outdoor air that infiltrates a building through cracks, gaps, and openings in the exterior walls, windows, doors, and other structural elements. It depends on factors such as building design, construction quality, weather conditions, and the presence of air sealing measures. Infiltration is a significant source of heat loss in buildings during cold weather and can contribute to cooling loads in the summer. It increases the demand on HVAC systems to maintain desired indoor temperatures, thereby increasing energy consumption.

The studies in the literature offer a range of perspectives on the relationship between air infiltration rate and building envelope components. For instance, Sadineni et al. (2011) assess how building envelope air tightness affects energy consumption and indoor air quality in buildings, emphasizing the importance of effective air sealing. Hu et al. (2023) investigate how variations in air infiltration rates at natural pressure differences impact energy consumption in southern China's hot summer and cold winter climate region, focusing on an office building and its subsequent cooling and heating energy consumption patterns. In Mathur and Damle's (2021) study, experimental and simulation techniques are employed to analyze the correlation between infiltration rates and window construction, elucidating their impact on India's residential envelope transmittance limit value and providing insights into heating energy gains and efficiency strategies across different climate zones. Recently, Arafah et al. (2022) conducted a study investigating the impact of building envelope parameters, including air leakage, on energy consumption in high-rise office buildings in urban Riyadh. Their research underscores both the challenges posed by air leakage and proposes potential solutions to mitigate its effects.

Indoor set-point temperatures, which refer to the desired temperature set by occupants or building management through thermostats, also play a crucial role in determining occupants' thermal comfort and influencing a building's energy consumption during both heating and cooling periods. Set-point temperatures can vary based on individual preferences, seasonal changes, building type, and local climate conditions. According to ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards, recommended indoor thermal comfort ranges vary slightly depending on the activity and clothing levels of occupants but generally fall within 20–23°C for heating and 23–26°C for cooling seasons. Occupants' perception of thermal comfort is influenced not only by indoor dry bulb temperature but also by factors such as radiant temperature, humidity levels, air movement, and personal preferences. On the other hand, maintaining higher set-point temperatures during heating periods, as well as lowering set-point temperatures during cooling periods, increases the energy demand for HVAC systems. Yet, educating occupants about energy-saving practices, such as adjusting clothing layers during moderate temperatures and utilizing programmable thermostats or smart controls that allow buildings to adjust set-point temperatures based on occupancy schedules and external weather conditions, can complement and reduce overall energy consumption.

The research in the literature shows that effective control of set-point temperatures and management strategies can enhance building energy efficiency and indoor thermal comfort. For instance, Bienvenido-Huertas (2021) discusses the implications of indoor set-point temperatures and thermostat accuracy in achieving energy savings across two residential buildings in three cities, showing that significant energy savings depend on energy consumption type, climate conditions, and thermal comfort model category. The study highlights the importance of adaptive thermal comfort models, particularly through adaptive set-point temperatures, for reducing building energy bills, especially in cooling but also in heating scenarios influenced by climate change. Luo et al. (2023) present an occupant-centric smart thermostat designed to improve energy efficiency and thermal comfort in single-family homes. The authors consider the indoor temperature preferences of occupants and adjust set-points dynamically to enhance both comfort and energy efficiency. Data analysis from 50 households reveals significant potential for reducing heating and cooling energy consumption while enhancing comfort across multiple rooms, providing valuable insights for future smart product development. Xu et al. (2014) propose an energy-saving strategy for multi-family buildings, emphasizing cost-effectiveness and sustainable energy reductions achieved by aligning residents' thermostat preferences with indoor temperatures in a public housing complex. They aim to optimize comfort and achieve substantial energy reductions simultaneously through simulations across various U.S. cities. Similarly, in the research by Kong et al. (2022), occupancy sensing technologies related to thermal comfort and energy efficiency in open-plan office buildings are discussed, including the role of smart building controls in achieving high occupant satisfaction with indoor conditions. This research synthesizes both simulation-based and experimental findings, highlighting opportunities for applying occupancy sensing systems in HVAC systems. Moon and Han (2011) also conducted a case study examining the impact of various set-point temperature strategies on heating and cooling energy consumption in residential buildings, underscoring the significance of data-driven decisions for achieving energy efficiency. Their research, which includes computer simulations across cold and hot-humid climates in the U.S., demonstrates that adjusting setback periods, set-point temperatures, and setback temperatures can notably decrease energy usage, especially in heating for cold climates and cooling for hot-humid climates.

In this study, the energy performance of a gated community in Turkey's temperate-humid region is evaluated, while the thermal comfort of a typical residential unit is considered. Twenty-three design options were analyzed, including variations in insulation materials and their thickness, building envelope infiltration rates, and indoor set-point temperatures during heating and cooling periods. Using BES-based parametric analysis, their impact on heating and cooling energy consumption, primary energy use, carbon emissions, and the payback period for thermal insulation investments is assessed. The baseline scenario is compared with the optimal configuration against ASHRAE-55 (2023) and BS EN 16798-1 (2019) standards, offering insights to enhance energy efficiency and thermal comfort in residential environments.

Materials and Methods

The impact of design variables on heating and cooling energy consumption, CO_2 emissions, thermal comfort, and the payback period of the initial investment cost are assessed for a case study residential complex using the DesignBuilder BES tool, the CBE thermal comfort tool, and Microsoft Excel. Figure 1 provides an overview of the study's methodology.

Figure 1. *The Methodology of the Study*

DesignBuilder v 7.0 & EnergyPlus v 9.4
- Building energy modelling
- Annual end-use heating, cooling energy simulation for the base case and improvement measures
- Parametric analysis
- Thermal comfort analysis based on operative temperature and the Fanger comfort indicators (PPD and PMV)

CBE Thermal Comfort Tool
- Thermal comfort calculations and visualizations according to standards (ASHRAE 55–2023, ISO 7730:2005 and EN 16798–1:2022).

Microsoft Excel
- Annual primary energy, operational carbon emissions and energy cost calculations based on the end-use energy simulation results and conversion factors
- Pay-back period and improvement rate calculations
- Creating charts and tables

Definition of the Case Study

The pilot study was conducted in Bursa, Turkey, which falls within the temperate-humid climate region. A multi-story residential building completed in 2014, primarily targeting high-income groups, was focused on. The residential site consists of ten apartment blocks, each with seven stories. There are a total of 132 apartments, with floor sizes ranging from 197 m² to 235 m². Each floor features two symmetrical 3+1 apartments, with the top floor of the building designed as a 5+1 duplex. The apartments' living spaces face inward, offering green areas and recreational facilities. Figure 2 shows the site plan (a) and outdoor image (b) of the residential complex.

Figure 2. *(a) Site Plan of the Apartment Blocks (b) Outdoor Image of the Case Study*

Source: Zırhlıoğlu Architecture Office Archive n.d.

The reinforced concrete frame buildings with asmolene flooring feature external infill walls made of autoclaved aerated concrete and 3 cm of EPS insulation. The facades are finished with plaster and acrylic-based exterior paint. Ceramic tile cladding is applied to anchor profiles on certain vertical surfaces. The pitched roof, covered with tiles at a 36% slope, includes 16 cm of mineral wool for thermal insulation. PVC windows with 4+12+4 mm clear double glazing are used in the apartment blocks. The Window-to-Wall Ratio (WWR) of the reference building is

29%. The windows have a Solar Heat Gain Coefficient (SHGC) of 0.75 and a Visible Light Transmittance (Tvis) of 0.8, according to the catalogue values provided by the selected glass manufacturer (Şişecam 2021). The total thermal transmittance coefficient of the building envelope meets the threshold values for thermal insulation requirements as specified by the building standard TS 825 (TSE 2013), with U-values of 0.23 W/m²K for the roof, 0.49 W/m²K for the walls, and 1.64 W/m²K for the window system. The apartments are equipped with combi boilers and radiators, providing heating to all dwelling units except for the entrance hall and corridor. For cooling, multi-split air conditioning systems are installed in all rooms except the entrance, corridor, dressing room, bathroom, and building's common areas.

Building Energy Performance Analysis

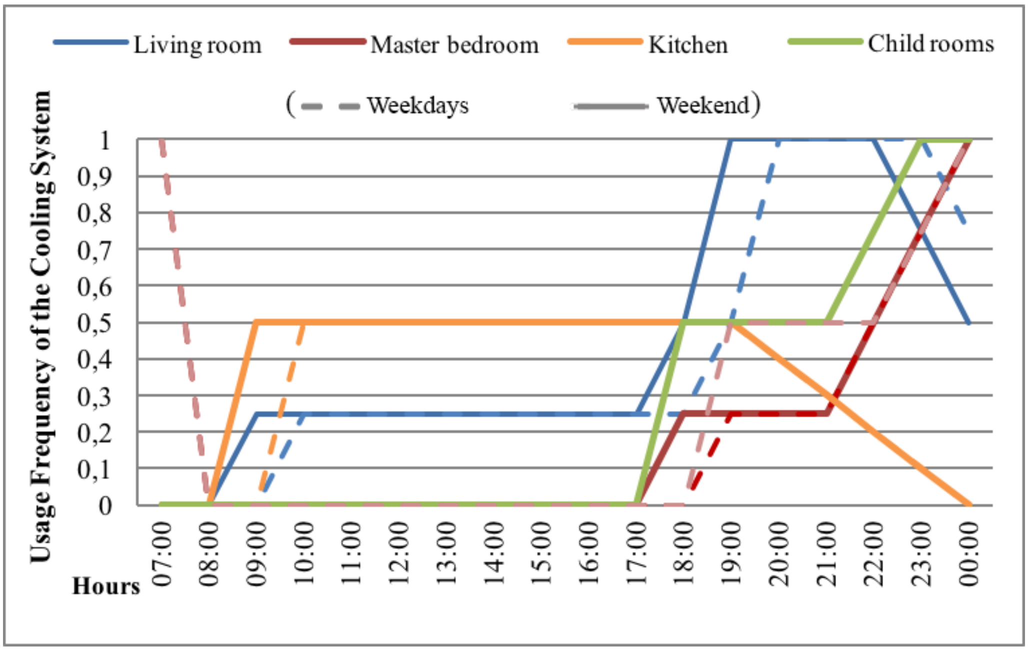
Utilizing a computer-aided detailed dynamic calculation method, the energy consumption of both the reference case and options for improvement was assessed. The geometric model of the buildings was configured using the DesignBuilder Architectural Edition v7.0 software application, and simulations were executed utilizing the EnergyPlus v9.4 engine. Weather data specific to Bursa was obtained in a typical meteorological year (TMY) format and EnergyPlus Weather (EPW) format from an online database (ClimateOneBuilding n.d.). The simulations were run for one year (8,760 hours) with four timesteps per hour.

Key parameters for building energy performance and thermal comfort, such as thermal mass and insulation levels, were aligned with the design project, which complies with the minimum requirements outlined in national BEP Regulations (2008) and the rating of energy performance in buildings according to BEP-TR (2010). Additionally, household energy expenditures and user preferences regarding indoor set point temperatures were analyzed through a previous in-person survey and integrated into the simulation model (Kaymaz 2023).

Based on post-occupancy evaluation (POE) results, where respondents favored an indoor temperature range of 23–25°C, the indoor set point temperatures for the reference case were set to 23°C during the heating season and 24°C during the cooling season in the energy model. The HVAC (heating, ventilation, and air conditioning) system activates when indoor temperatures fall below 16°C during the heating period and exceed 30°C during the cooling period. Natural ventilation is regulated by the duration and frequency of residential space usage. Windows are opened when the outdoor air temperature is at least 20°C, achieving an air exchange rate of 5 air changes per hour (ac/h), with a minimum indoor temperature of 23°C. The design infiltration rate of the building envelope—representing the maximum rate of unintentional air entry through cracks, holes, and the fabric's porosity—is included as 0.8 ac/h in the energy model. While this rate is typically assumed to be constant throughout the simulation, it varies over time based on a schedule that modifies the infiltration rate, as well as on temperature differences between the inside and outside and wind speed.

The heating and cooling system efficiencies were determined from equipment specifications identified in the field study. The Coefficient of Performance (COP) is 0.9 for heating and 3.0 for cooling systems. Data from the POE and residential complex administration were used to develop the operating schedules for the HVAC systems. During the heating period, individual combi boilers are assumed to operate daily from 06:00 to 24:00, depending on the indoor setpoint temperature. During the cooling period, operating schedules for multi-split air conditioners were tailored to the occupancy of each room. As seen in Figure 3, time-based operation is expressed as a percentage: "1" means the cooling system is active for the entire hour, "0.5" indicates 50% operation, and "0" means it is inactive.

Figure 3. *Cooling System Weekday and Weekend Operating Schedule for Residential Units*



Within the study's framework, natural gas and electricity consumption encompass the energy usage throughout an average year, both in terms of end use and primary energy for heating and cooling systems. The energy model incorporates the attributes of lighting, domestic hot water systems, electrical appliances, pumps, and fans to accurately depict the current scenario. The internal thermal gains from this equipment are factored into the heating and cooling loads. However, their individual share in the total energy consumption of the building is not stated here. The end-use energy consumption data from the simulation results are converted into primary energy using government-regulated conversion factors: 1 for natural gas and 1.788 for electricity. Carbon emission conversion factors are 0.234 and 0.484 for natural gas and electricity, respectively (Turkish Republic Ministry of Environment, Urbanization, and Climate Change 2022a).

Thermal Comfort Analysis

The thermal comfort conditions of the reference case and indoor setpoint temperature scenarios are evaluated according to PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) criteria based on the requirements in

ASHRAE-55 (2023), BS EN ISO 7730 (2005), and BS EN 16798-1 (2019) standards. Thermal comfort categories are classified in Table 1.

Table 1. *Categories of Thermal Environment*

Standard	PMV	PPD	Categories
BS EN ISO 7730 BS EN 16798-1	±0.2	<%6	A (I)
	±0.5	<%10	B (II)
	±0.7	<%15	C (III)
ASHRAE 55	±0.5	<%10	High standard (%90)
	±0.85	<%20	Typical Application (%80)

Source: BS EN ISO 7730 (2005), ASHRAE-55 (2023) and BS EN 16798-1 (2019).

According to all three standards, maintaining a PMV value within ±0.5 signifies thermal comfort, with the percentage of dissatisfied people (PPD) not exceeding 10%. BS EN 16798-1 (2019) further categorizes thermal comfort into four categories: Category I provides the highest satisfaction level and is recommended for spaces accommodating disabled individuals, the elderly, and children. Category II is suitable for new and renovated buildings, ensuring a high satisfaction level. Category III denotes an acceptable moderate thermal environment, while Category IV describes an uncomfortable thermal environment that is acceptable only for limited periods of the year. These standards provide a comprehensive framework for evaluating and categorizing thermal comfort conditions in indoor environments, ensuring occupant satisfaction and well-being.

The indoor set point temperatures during the heating and cooling seasons were input into the CBE thermal comfort calculation tool along with other comfort variables such as relative humidity, air velocity, metabolic rate, and clothing level. Using the PMV and associated PPD comfort indices defined by the 7-point Likert scale in BS EN ISO 7730 (2005), psychometric diagrams were generated for both heating and cooling periods. Static calculations are based on the operative temperature, which is the average of the mean radiant and dry bulb temperature.

Secondly, a climate-based dynamic simulation was performed using DesignBuilder software to assess the thermal conditions of a sample apartment. The PMV-PPD results are displayed in monthly tables using a color scale, where green indicates that thermal comfort is achieved and red signifies that it is not. Indoor conditions are considered thermally comfortable for the typical application category in ASHRAE 55 (2023) and for Category III in BS EN 16798-1 (2019).

Pay-back Period Analysis

According to the BS EN 15459-1 standard (2017), the payback period is defined as the time required for the investment cost to be offset by cost savings, serving as a means to compare the cost-effectiveness of different solutions. In this study, the payback period for the thermal insulation scenarios, compared to the reference case, is calculated using Equation 1 (BS EN 15459-1 2017), incorporating inflation data from 2018 to 2022 (Turkish Republic Central Bank 2022).

$$PB = \ln\left(\frac{1}{1-\frac{(CO_{INIT} - CO_{INIT,ref}).\ RAT_{disc}}{CF}}\right).\ln\left(\frac{1}{1+RAT_{disc}}\right)[t]$$

(1)

Where
PB: Payback period (year)
RAT_{disc}: Disount rate
CO_{INIT}: Initial investment cost
$CO_{\text{INIT, ref}}$: Initial investment costs for reference case
CF: Constant value of the difference of running costs between option and the reference case in all
years
RAT_{disc}: Discount rate

According to the Turkish Republic Central Bank statistics (2022), the following financial parameters are employed: an inflation rate (Ri) of 14.9%, a market interest rate (R) of 20.31%, a real interest rate (Rr) of 4.71%, and a corresponding discount rate (RATdisc) of 25.15%. Discount rates for energy are calculated separately (RATdisc_electricity: 16.06%, RATdisc_natural gas: 11.84%) because the price increases for natural gas and electricity, including taxes and fees, for residential subscribers from 2017 to 2021 differ from the average inflation rate based on annual consumer price inflation (Bursagaz 2022, Uludağ Elektrik 2022). The initial investment costs for thermal insulation products were obtained from the Construction and Installation Unit Prices book (Turkish Republic Ministry of Environment, Urbanization, and Climate Change 2022b) and local market research.

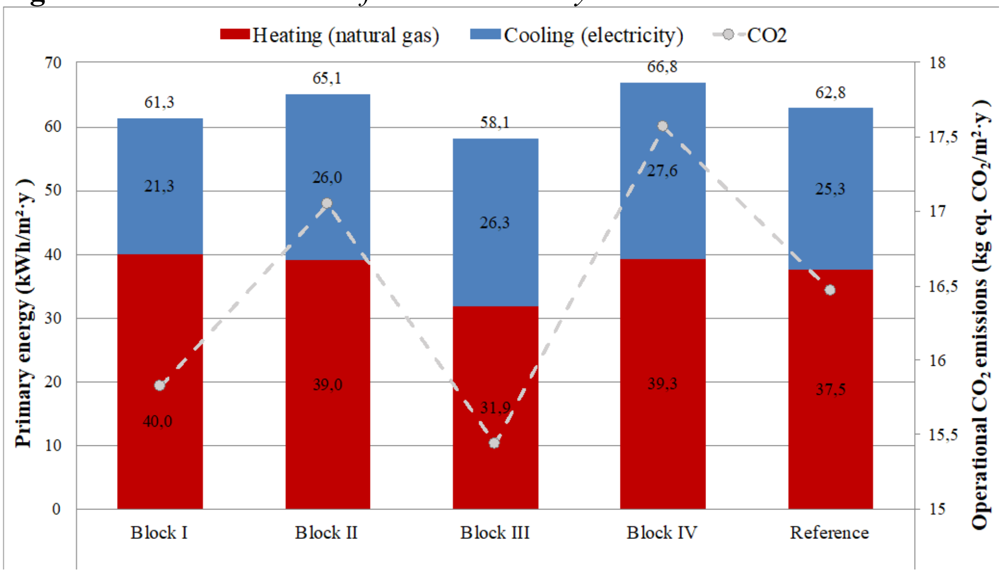
Results

In this study, the key building energy performance metrics analyzed include the percentage change in total annual heating and cooling end-use energy consumption, primary energy consumption, and carbon emissions. Using these metrics, the energy performance of four apartment blocks with identical floor plans but differing orientations was first evaluated. Figure 4 shows the DesignBuilder energy model utilized in the case study.

Heating, cooling, and lighting energy consumption varies based on the façade orientation and obstruction angle of each apartment block. The building with the highest annual total primary energy consumption and carbon emissions from heating and cooling loads was selected as the reference building. As seen in Figure 5, Block IV (living area facing NE) has the highest values, while Block III (living area facing S) has the lowest values, showing a difference of 13% (8.7 kWh/m²·y) and 12.1% (2.1 kg eq. CO_2/m²·y), respectively. It is also noted that the portion allocated to heating (55% - 65%) exceeds that allocated to cooling (35% - 45%) in terms of primary energy.

Figure 4. *Designbuilder Energy Model Used in the Case Study*

Figure 5. *Simulation Results for the Case Study*

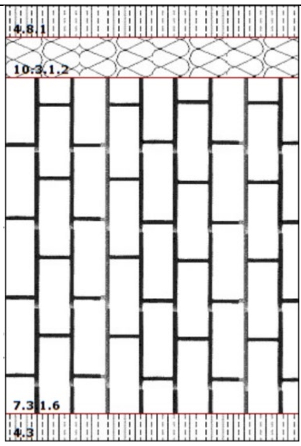


Next, building energy performance metrics are established for variables including thermal insulation level, building envelope infiltration rate, and indoor set-point temperatures. Each measure's effectiveness is evaluated through a series of parametric simulations. The results are visually represented using color coding: cells shaded in green indicate improvements, while cells shaded in red indicate values below the reference building (Block IV) threshold. The research encompasses the following scenarios, summarized as follows:

External Wall Thermal Insulation Material and Thickness

External thermal insulation is crucial for maintaining desired surface temperatures, average radiation levels, and indoor thermal comfort conditions in buildings. It effectively prevents thermal bridges within the building envelope and reduces heating energy consumption. In the case study, external walls are insulated with 3 cm thick EPS (Expanded Polystyrene), chosen for its thermal conductivity of λEPS: 0.04, as per the TS 825 thermal insulation requirements for buildings standard (TSE 2013). Table 2 displays the external wall section of the reference building along with the thermophysical properties of the materials.

Table 2. *External Wall Section of the Case Study and Thermophysical Properties of Materials*

Building Elements	**Code and definition**	**Material thickness**	**Thermal conductivity**	**Thermal resistance**	**Thermal transmittance**
	(TS 825)	d (m)	λ (W/m·K)	R (m^2K/W)	U (W/m^2K)
	$1/\alpha_i$: Surface heat transfer coefficient (interior)			0.13	
	4.3: Lime mortar	0.02	0.7	0.03	
	7.3.1.6: Autoclaved aerated concrete	0.25	0.25	1	
	10.3.1.2: EPS (density ≥ 20)	0.03	0.04	0.75	
	4.8.1: Plaster mortar with inorganic lightweight aggregates	0.025	0.30	0.08	
	$1/\alpha_e$: Surface heat transfer coefficient (exterior)			0.04	
TOTAL				**2.03**	**0.492**

Source: Created using TS 825 thermal insulation calculation tool by the author (IZODER n.d.).

Within the scope of building energy performance improvement scenarios, the objective is to systematically lower the U-value of external walls from the regulatory limit of U_{wall}: 0.6 W/m²K (2nd heating degree day zone) stipulated in the current insulation regulation (TSE 2013) by increasing the thickness of the thermal insulation material. Table 3 presents the total thermal transmittance values for 15 different insulation options applied to the external walls, while Table 4 details the improvement rates and investment payback periods for these scenarios compared to the reference building.

Table 3. *Options of External Wall Thermal Insulation Material and Thickness*

Scenario	Definition	U_{wall} (W/m²K)
R (Reference)	3 cm EPS	0.492
INS1	4 cm EPS	0.442
INS2	4 cm mineral wool	0.432
INS3	4 cm XPS	0.410
INS4	5 cm EPS	0,398
INS5	5 cm mineral wool	0.388
INS6	5 cm XPS	0.366
INS7	6 cm EPS	0.362
INS8	6 cm mineral wool	0.352
INS9	6 cm XPS	0.330
INS10	8 cm EPS	0.307
INS11	8 cm mineral wool	0.297
INS12	8 cm XPS	0.277
INS13	10 cm EPS	0.266
INS14	10 cm mineral wool	0.257
INS15	10 cm XPS	0.238

Table 4. *Improvement Rates in Building Energy Performance and Pay-back Periods for Thermal Insulation Scenarios Compared to the Reference Building*

Scenario	Improvement rate (%)					Payback period (y)
	Heating Energy	Cooling Energy	CO_2 Emissions	Energy Cost	Primary Energy	
INS1	7.3	-2.8	2.4	1.5	3.1	3.0
INS2	8.2	-2.9	2.6	1.5	3.5	11.9
INS3	10.1	-3.4	3.0	1.7	4.4	9.3
INS4	11.3	-3.5	3.4	1.8	4.9	4.6
INS5	12.1	-3.7	3.6	1.9	5.3	12.1
INS6	14.0	-4.2	4.0	2.0	6.2	10.6
INS7	14.5	-4.1	4.2	2.1	6.4	5.8
INS8	15.4	-4.3	4.4	2.2	6.8	12.6
INS9	17.2	-4.9	4.8	2.3	7.6	11.8
INS10	20.8	-6.5	5.5	2.4	9.1	8.0
INS11	21.6	-6.7	5.6	2.5	9.5	14.2
INS12	23.4	-7.3	6.0	2.6	10.3	14.1
INS13	24.7	-7.3	6.4	2.8	10.9	9.3
INS14	25.5	-7.5	6.6	2.8	11.3	15.3
INS15	27.1	-8.0	6.9	2.9	12.0	15.5

By increasing the thickness of the thermal insulation layer, the thermal transmittance (U-value) of the building envelope decreases, resulting in reduced heat losses during the building's heating period. Analysis of simulation results shows that compared to the reference building, INS15 yields improvements of 12% (equivalent to 10.8 kWh/m²) in primary energy consumption, 2.9% (0.13 €/m²·y) in energy costs, and 6.9% (2 kg CO_2 eq. /m²·y) in carbon emissions.

Among insulation materials of the same thickness, 10 cm XPS achieves the highest improvement in primary energy consumption. Conversely, EPS insulation emerges as the superior option with a shorter payback period considering the initial investment cost. Increasing insulation thickness across all options reduces total annual heating energy, albeit slightly increasing cooling energy due to retained internal thermal gains of the building. This increase in cooling energy ranges from 2.8% to 8% compared to the reference building, corresponding to the increase in insulation material thickness. Additionally, the unit cost of electricity, which is 5.7 times higher than that of natural gas, reduces the rate of improvement in energy costs.

Infiltration Rate of the Building Envelope

Possible cracks, openings, and deformations in the building envelope, as well as leaks, joints, and expansions in window and door frames, contribute to energy losses through air leakage. The impact of the building envelope's infiltration rate on building energy efficiency is investigated considering the following options in Table 5. Energy performance improvements resulting from infiltration rate scenarios are compared to those of the reference building in Table 6.

Table 5. *Options of Infiltration Rate of the Building Envelope*

Scenario	**Infiltration rate (ac/h)**
R (Reference)	0.8
INF1	0.7
INF2	0.6
INF3	0.5
INF4	0.4

Table 6. *Energy Performance Improvements due to Building Envelope Infiltration Options Compared to the Reference Building*

Scenario	Improvement rate (%)				
	Heating Energy	Cooling Energy	CO_2 Emissions	Energy Cost	Primary Energy
INF1	12.9	-5.5	4.4	1.6	5.4
INF2	25.8	-12.5	8.5	2.7	10.4
INF3	38.1	-20.8	12.1	3.4	15.0
INF4	49.7	-30.8	15.1	3.5	19.0

The highest energy savings are achieved with option INF4, where the building envelope infiltration rate is reduced from 0.8 to 0.4 ac/h. This leads to a 19% improvement in primary energy consumption (22.85 kWh/ m²·y), a 3.5% decrease in total energy costs (0.27 €/ m²·y), and a 15.1% reduction in CO_2 emissions (4.91 kg CO_2 eq./m^2·y). Reducing the infiltration factor resulted in a notable improvement in heating energy compared to the reference case, while each 0.1 ac/h reduction led to a 5.5% to 10% increase in cooling energy (0.6 to 1.1 kWh/m²·y).

Indoor Set-point Temperatures

The set-point temperature in indoor environments significantly affects energy efficiency by influencing the operational duration of both heating and cooling systems. Depending on climate and building envelope configuration, minor adjustments in set-point temperatures can lead to substantial energy savings over time. For example, lowering the thermostat during colder months reduces heating energy consumption, while raising it in warmer months decreases cooling energy use. These adjustments not only enhance energy efficiency but also contribute to cost savings and environmental sustainability by optimizing HVAC system operations according to seasonal demands.

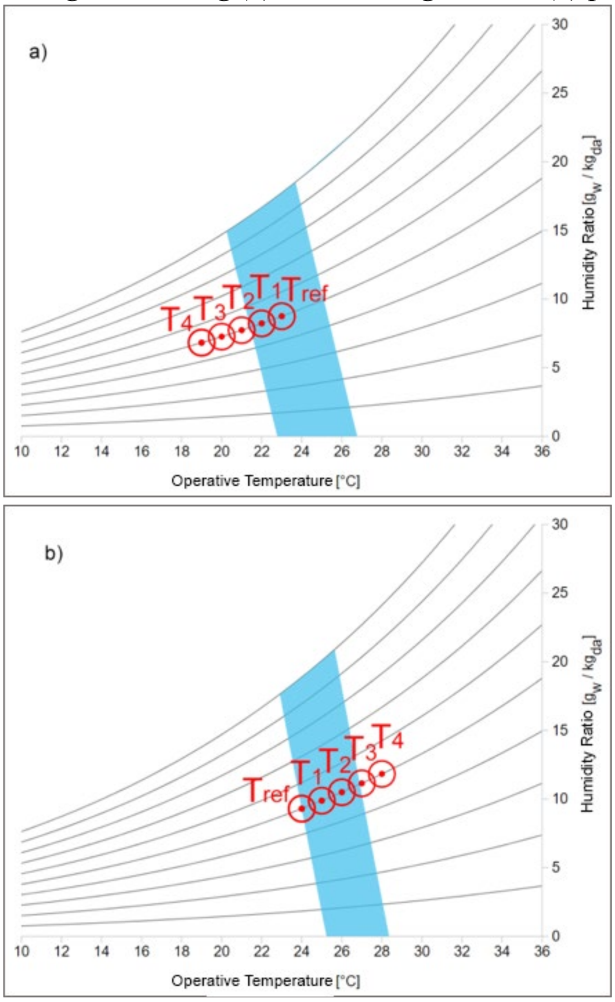
On the other hand, comfort considerations, influenced by varying preferences among individuals, along with occupants' behavioral factors, should be taken into account when balancing thermal comfort against energy efficiency. According to POE, the indoor setpoint temperatures for the reference case are assumed to be T_i: 23°C in winter and T_i: 24°C in summer. Table 7 outlines the indoor (thermostat) set-point temperature options being evaluated.

Table 7. *The Indoor Set-point Temperature Options for Heating and Cooling Periods*

Scenario	Heating period	Cooling period
$T_{i\ ref}$ (Reference)	23°C	24°C
T1	22°C	25°C
T2	21°C	26°C
T3	20°C	27°C
T4	19°C	28°C

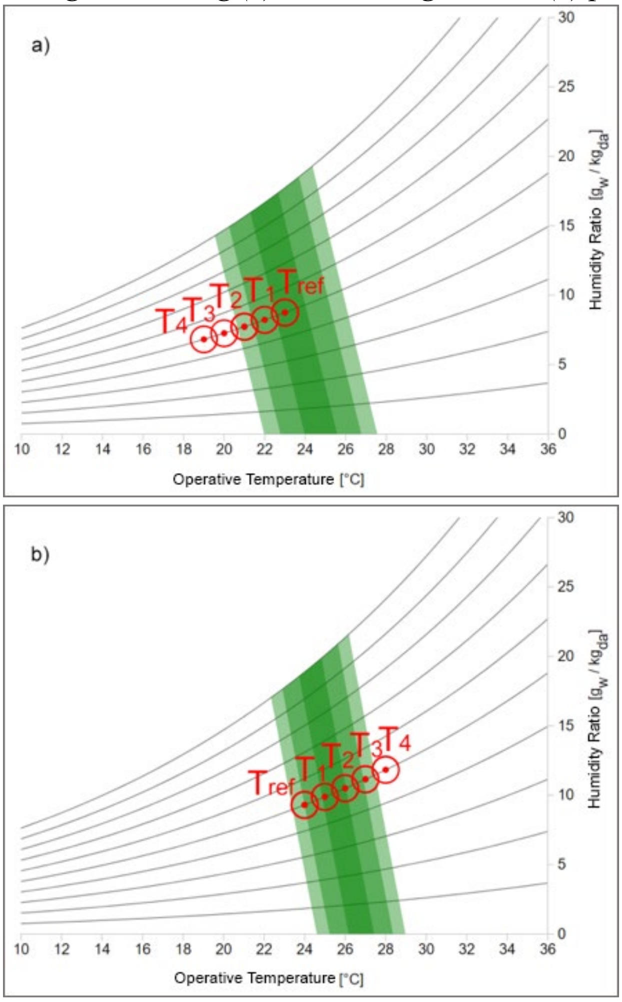
The thermal comfort conditions of indoor temperature options were evaluated using the CBE thermal comfort tool to assess compliance with ASHRAE Standard 55 (2023) and BS EN 16798-1 (2019). Psychometric diagrams illustrating operative temperature are presented in Figure 6 for ASHRAE 55 (2023) and Figure 7 for BS EN 16798-1 (2019). The red points represent scenarios for both heating and cooling periods, with a relative humidity (Rh) of 50%, air velocity (V_a) of 0.1 m/s, a metabolic rate (M) of 1 met (sitting position), winter clothing insulation (I_{cl}) of 1.0 clo, and summer clothing insulation (I_{cl}) of 0.61 clo.

Figure 6. *Psychometric Diagrams for Indoor Set-point Temperature Scenarios during the Heating (a) and Cooling Periods (b) per ASHRAE Standard 55:2023*



Source: Created with the CBE thermal comfort calculation tool by the author.

Figure 7. *Psychometric Diagrams for Indoor Set-point Temperature Scenarios during the Heating (a) and Cooling Periods (b) per BS EN 16798-1:2019*



Source: Created with the CBE thermal comfort calculation tool by the author.

The indoor thermal conditions for options T_{ref}, T1, and T2 meet comfort standards during both heating and cooling periods, with the PMV thermal sensation index remaining within ±0.5 and the PPD thermal dissatisfaction index not exceeding 10%. The PMV and PPD results are also presented in Table 8, categorized according to ASHRAE 55 and BS EN 16798-1 standards for the investigated thermostat strategies. For option T3*, adjusting the clothing thermal resistance from 1 clo to 1.25 clo during the heating period ensures compliance with thermal comfort criteria. However, T4* does not meet standards during both the heating and cooling periods.

Table 8. *PMV, PPD, ASHRAE-55: 2023 Thermal Sensation, and BS EN 16798-1: 2019 Category Values for Indoor Set-point Temperature Options during Heating and Cooling Periods*

Scenario		ISO 7730:2005		ASHRAE-55:2023	BS EN 16798-1:2019	Result
		PMV	**PDD (%)**	**Sensation**	**Category**	
Heating Period	$T_{i\ ref}$	-0.08	5	Neutral	I	✓
	T1	-0.35	7	Neutral	II	✓
	T2	-0.61	13	Slightly cool	III	✓
	T3	**-0.88**	21	Slightly cool	IV	✗
	T3*	-0.46	9	Neutral	III	✓
	T4	**-1.14**	33	Slightly cool	IV	✗
	T4*	-0.69	15	Slightly cool	III	✓
Cooling Period	$T_{i\ ref}$	-0.50	10	Neutral	II	✓
	T1	0.19	6	Neutral	I	✓
	T2	0.1	5	Neutral	I	✓
	T3	0.53	11	Slightly warm	III	✓
	T3*	0.34	7	Neutral	II	✓
	T4	**0.88**	**21**	Slightly warm	IV	✗
	T4*	**0.72**	**16**	Slightly warm	IV	✗
$I_{c\ winterl}$*:1.25 clo, $I_{cl\ summer}$*:0.5 clo						

Table 9 displays the improvement rates in building energy performance metrics for temperature combinations varying by 1°C during both heating and cooling periods. Each degree reduction saves approximately 14-20% on end-use heating energy, while each degree increase can save about 13-14% on cooling energy. Option T3*, which achieves the highest energy savings compared to the reference case, shows reductions of 27.5% (29.8 kWh/m²·y) in primary energy consumption, 20.6% (1.29 €/ m²·y) in total energy cost, and 25.6% (7.8 kg eq.CO_2 / m²·y) in CO_2 emissions. The performance results for options T4 and T4*, which does not meet the thermal comfort criteria, are not included in Table 9.

Table 9. *The Rates of Change in Indoor Set-point Temperature Options compared to the Reference Building for Building Performance Measures*

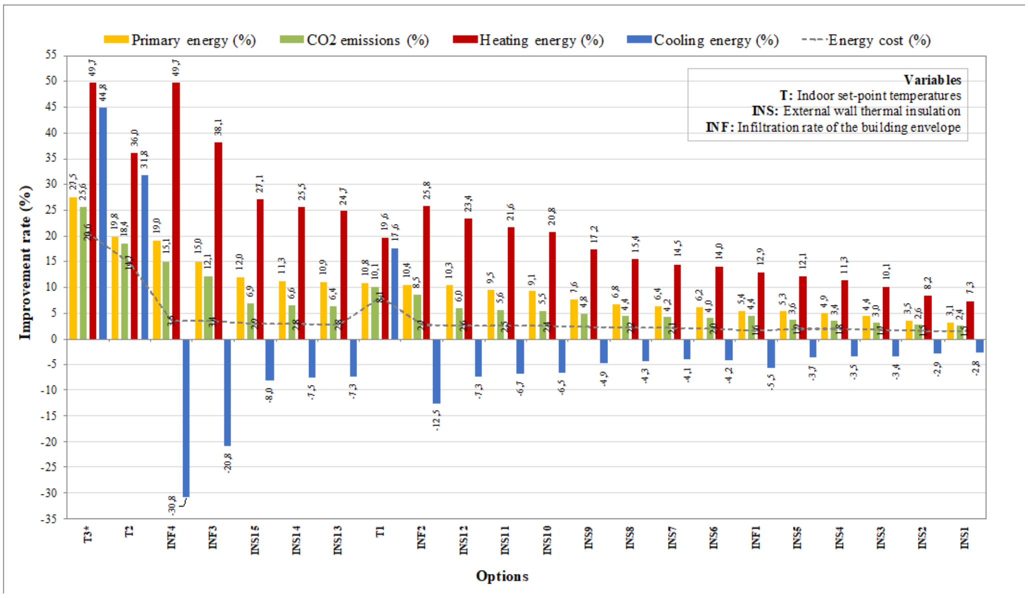
Scenario	Improvement rate (%)				
	Heating Energy	Cooling Energy	CO_2 Emissions	Energy Cost	Primary Energy
T1	19.6	17.6	10.1	8.1	10.8
T2	36.0	31.8	18.4	14.7	19.8
T3*	49.7	44.8	25.6	20.6	27.5

Discussion

Figure 8 summarizes the impact of three variables and a total of 23 options on building performance measures compared to the reference building, showing an increasing improvement rate in primary energy from right to left. The T3* option shows the highest improvement in terms of primary energy consumption compared to the reference case. Reducing the room set temperature from 23°C to 20°C during heating and increasing it from 24°C to 27°C during cooling yields the highest savings in annual total electricity and natural gas costs, as well as carbon emissions. Among the BES scenarios considered, tightening the building envelope from 0.8 ac/h to 0.4 ac/h (INF4) provides the greatest energy performance improvement for the apartment block.

The BES-based analysis for Bursa province shows that the combination of scenarios T3* (heating period T_i: 20°C I_{cl}: 1,25 clo, cooling period T_i: 27°C, I_{cl}: 0,5 clo), INF4 (0.4 ac/h) and INS15 (10 cm XPS) offer significant improvements compared to the reference building. According to the simulation results, this combination predicts a reduction in heating energy consumption by 88.6% (33.3 kWh/m^2·y), cooling energy by 22.6% (3.1 kWh/m^2·y), and overall primary energy use by 62.1% (39 kWh/m²·y). Additionally, savings in electricity and natural gas costs are expected to reach 43.8% (1.2 €/m²·y), accompanied by a decrease in carbon emissions by 57.8% (9.5 kg eq. CO_2/m²·y). These findings highlight the effectiveness of studied parameters in enhancing both energy and cost efficiency.

Figure 8. *The Improvement Rates of All Analyzed Scenarios compared to the Baseline Scenario*



In the final stage of the study, indoor thermal comfort conditions of the apartments were assessed using the DesignBuilder program. Monthly average values of indoor air (operative) temperature (T_o), relative humidity (*Rh*), and PMV–PPD indices for the reference building (Block IV) were computed under existing and energy-improved conditions. The comparative monthly thermal comfort results for a sample apartment located on the first floor are shown in Table 10.

In the reference case, the PMV values for residential spaces generally fall within the ±0.85 range specified by the ASHRAE 55 (2023) standard for typical applications, with the PPD not exceeding 20%. However, certain conditions are identified as thermally uncomfortable, particularly in July and August in the kitchen and children's room, where the PMV exceeds the ±0.70 range (Category III) and the PPD surpasses the recommended threshold of 15% according to BS EN 16798-1 (2019).

When analyzing the monthly simulation results for the combination of the best-performing options, it is observed that during the cooling period, the indoor operative temperature in all studied residential spaces is 1-2°C higher than the set point temperature. Additionally, the PMV falls outside the range of ±0.70, the PPD exceeds 15%, and the thermal sensation in these spaces is slightly warm (refer to Table 10).

Table 10. *Monthly Thermal Comfort Averages for Residential Spaces in the Reference Case and with the Best-Performing Options*

Scenario	Residential Space	Evaluation index	January	February	March	April	May	June	July	August	September	October	November	December
REFERENCE	Kitchen (NE)	Ti (°C)	23,0	23,4	23,8	25,3	26,4	27,4	27,9	28,0	27,2	25,7	24,1	23,2
		Rh (%)	26,3	27,3	28,2	33,2	41,8	45,4	47,1	45,1	46,0	43,6	39,1	28,8
		PMV	-0,25	-0,14	-0,03	0,41	0,25	-0,63	0,82	0,83	0,57	0,03	0,14	-0,18
		PPD (%)	6,0	5,0	5,0	9,0	6,0	13,0	19,0	20,0	12,0	5,0	5,0	6,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	I	I	II	II	III	IV	IV	III	I	I	I
	Living room (NE)	Ti (°C)	22,3	22,6	22,8	23,6	24,7	26,0	26,9	27,0	25,8	24,0	22,9	22,5
		Rh (%)	25,7	26,7	28,0	34,6	45,2	49,0	50,5	47,9	49,5	46,6	39,8	28,2
		PMV	-0,44	-0,35	-0,29	-0,03	-0,30	0,18	0,50	0,51	0,11	0,17	-0,18	-0,37
		PPD (%)	9,0	8,0	7,0	5,0	7,0	6,0	10,0	11,0	5,0	6,0	6,0	8,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	II	II	I	II	I	III	III	I	I	I	II
	Master bedroom (SW)	Ti (°C)	22	23	23	24	25	26	27	27	26	25	23	23
		Rh (%)	26	27	28	34	44	49	51	48	48	46	40	29
		PMV	-0,38	-0,30	-0,21	0,15	-0,14	0,21	0,48	0,52	0,27	-0,26	-0,09	-0,34
		PPD (%)	8,0	7,0	6,0	5,0	5,0	6,0	10,0	11,0	7,0	6,0	5,0	7,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Neutral	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	II	II	I	I	II	II	III	II	II	I	II
	Childroom (SW)	Ti (°C)	23	23	24	25	26	27	27	28	27	25	24	23
		Rh (%)	26	27	28	33	42	46	49	47	47	44	39	29
		PMV	-0,28	-0,11	0,02	0,46	0,22	0,53	0,70	0,82	0,40	-0,07	0,06	-0,23
		PPD (%)	7,0	5,0	5,0	9,0	6,0	11,0	15,0	19,0	8,0	5,0	5,0	6,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	II	I	II	II	III	III	IV	II	I	I	II
IMPROVED ENERGY PERFORMANCE	Kitchen (NE)	Ti (°C)	20,9	22,5	23,3	26,5	27,1	27,9	28,2	28,4	27,7	26,6	23,6	21,9
		Rh (%)	29,6	30,5	31,1	33,7	40,6	44,0	45,3	43,5	44,5	42,1	40,4	32,3
		PMV	-0,38	0,00	0,19	0,01	0,29	0,62	0,75	0,80	0,55	0,12	0,33	-0,13
		PPD (%)	8,0	5,0	6,0	5,0	7,0	13,0	17,0	18,0	11,0	5,0	7,0	5,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	I	I	I	II	III	IV	IV	III	I	II	I
	Living room (NE)	Ti (°C)	19,6	20,7	21,5	25,2	26,2	27,4	27,9	28,1	27,2	25,7	22,7	20,1
		Rh (%)	29,7	30,1	30,7	33,0	41,9	45,5	47,0	44,5	45,8	43,5	41,4	32,5
		PMV	-0,67	-0,42	-0,23	-0,47	-0,03	0,45	0,65	0,70	0,38	-0,20	0,13	-0,54
		PPD (%)	15,0	9,0	6,0	10,0	5,0	9,0	14,0	15,0	8,0	6,0	5,0	11,0
		ASHRAE-55 Sensation	Slightly Cool	Neutral	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral	Slightly Cool
		EN 16798-1 Category	III	II	II	II	I	II	III	IV	II	I	I	III
	Master bedroom (SW)	Ti (°C)	21,1	23,3	24,4	27,4	27,7	28,2	28,5	28,7	28,3	27,5	25,4	22,2
		Rh (%)	28,9	28,4	28,9	32,5	40,2	43,7	47,0	44,9	43,1	41,3	38,4	30,8
		PMV	-0,34	0,17	0,43	0,32	0,51	0,73	0,88	0,93	0,76	0,45	-0,35	-0,07
		PPD (%)	7,0	6,0	9,0	7,0	10,0	16,0	21,0	23,0	17,0	9,0	8,0	5,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	I	II	II	III	IV	IV	IV	IV	II	II	I
	Childroom (SW)	Ti (°C)	20,5	22,5	23,8	27,3	27,9	28,6	28,9	29,0	28,3	27,2	23,7	21,4
		Rh (%)	29,2	28,9	29,6	32,8	39,6	42,7	46,0	44,2	43,4	41,6	39,7	31,4
		PMV	-0,47	-0,01	0,30	0,29	0,58	0,87	1,02	1,04	0,76	0,34	0,35	-0,25
		PPD (%)	10,0	5,0	7,0	7,0	12,0	21,0	27,0	28,0	17,0	7,0	8,0	6,0
		ASHRAE-55 Sensation	Neutral	Neutral	Neutral	Neutral	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Slightly Warm	Neutral	Neutral	Neutral
		EN 16798-1 Category	II	I	II	II	III	IV	IV	IV	IV	II	II	II

Conclusions

The research investigated the impact of three design variables—external wall thermal insulation materials and thicknesses, building envelope infiltration rates, and indoor set-point temperatures—on heating and cooling energy loads, annual energy costs, and carbon emissions using advanced simulation tools. According to BES-based calculations, increasing thermal insulation thickness from 3 cm EPS to 10 cm XPS in external walls led to up to a 27% reduction in heating energy consumption, along with notable improvements in primary energy use by 12% and 15.5-year payback period. This enhancement, however, also resulted in an 8% increase in cooling loads, balancing energy efficiency targets with economic feasibility. Adjusting the building envelope's infiltration rate from 0.8 to 0.4 ac/h produced substantial savings with 19% reduction in primary energy, underscoring the critical role of minimizing air leakage in sustainable building performance. Similarly, optimizing indoor set-point temperatures within recommended thermal comfort ranges effectively reduced heating (by approximately 50%) and cooling energy loads (by about 45%) as well as HVAC system operation time. Moreover, combining the best-performing options yielded significant opportunities for enhancing energy efficiency, achieving approximately a 62% reduction in primary energy consumption.

The study primarily focused on total annual heating and cooling energy consumption in a sample apartment block, exploring the synergistic effects of optimal combinations across three variables and 23 options using standard simulation methods. To ensure that PMV values and PPD percentages align with the thermal comfort criteria set by ASHRAE 55 and BS EN 16798-1 standards, the parametric analysis can be reframed as a multi-objective optimization problem. Future research should incorporate more advanced calculations for airtightness and natural ventilation rates, as well as explore the integration of dynamic environmental factors and real-time data into detailed HVAC sizing through an interdisciplinary approach to enhance the accuracy of energy performance predictions. This approach facilitates the concurrent objectives of minimizing energy consumption and maximizing thermal comfort through BES-based parametric analysis.

In conclusion, this study contributes valuable insights to residential building practices in Turkey, offering actionable recommendations for sustainable design and operation. The findings underscore the significance of BES-based parametric analysis and the careful consideration of building physics in residential construction to achieve energy efficiency goals while ensuring occupant comfort. As residential buildings play an increasingly pivotal role in global climate initiatives, this research aims to inform designers, contractors, and occupants on advancing energy-efficient and comfortable living environments.

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