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Evaluating Sustainable Approaches for Enhancing Building Resilience in Response to Climate Change (Case study: Tehran City)

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Abstract

As climate change poses significant challenges to our built environment, enhancing building resilience through sustainable approaches becomes crucial. This research evaluates sustainable strategies to fortify buildings against climate change impacts, specifically focusing on residential buildings in Tehran. Future climate data for Tehran are generated using Meteonorm 8 software. Comprehensive investigations identify predominant residential patterns, leading to the selection of a representative case study for detailed simulations. Energy simulations are conducted using DesignBuilder software to explore the impact of consumption reduction strategies on thermal performance under present and future conditions. Results indicate an increase in cooling energy consumption and a decrease in heating energy consumption from 2020 to 2090, with no significant change observed in total energy consumption. The implementation of insulation, double-glazed windows, and shading devices is shown to decrease overall energy consumption in the future. Notably, WI models with thermal insulation demonstrate the best performance in reducing heating energy, while WDG models with double-glazed windows significantly reduce cooling energy consumption. This study fills a gap in understanding the long-term impacts of climate change on building energy performance and provides practical design guidelines. The findings underscore the importance of sustainable building strategies in developing energy-efficient and resilient buildings capable of withstanding future climate conditions.

Keywords*:* climate resilient, sustainable approaches, Tehran, climate-related risks, energy simulations.

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1. Introduction

The issue of climate change has gained significant attention worldwide, with forecasts suggesting a potential increase in average global temperatures of 2.6 to 4.8 degrees Celsius by the close of the 21st century (Symon, 2013). Even if greenhouse gas emissions were halted hypothetically, the trend of rising global temperatures would continue. This trend is linked to a rise in extreme weather occurrences such as heatwaves and temperature fluctuations, which affect both natural and human-made environments, sometimes resulting in loss of life (Zuo et al., 2015).

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Buildings play a significant role in global energy usage, responsible for approximately 36% of the world's energy consumption and generating 40% of carbon dioxide emissions (Cabeza & Ürge-Vorsatz, 2020). Recent research indicates a notable uptick in this energy consumption due to various factors, including advancements in technology, shifts in lifestyles, and notably, the impacts of climate change (Baglivo et al., 2022, (Bardhan et al., 2020). According to reports from the International Energy Agency (IEA), there has been a 3% annual rise in energy usage within the building sector of developed nations, primarily spurred by the increasing demand for cooling systems to combat rising temperatures (Berardi & Jafarpur, 2020) (Cabeza & Ürge-Vorsatz, 2020), (Dickinson, 2016). Climate change has also altered winter temperatures in colder regions, resulting in decreased energy requirements for building heating (Baglivo et al., 2022).

In light of climate change, numerous areas are facing elevated temperatures and prolonged summers, leading to a notable increase in the cooling demands of buildings (Wang et al., 2021)(Saadatjoo, Alizadeh, Jahanbakhsh Asl, et al., 2024)(Saadatjoo, Alizadeh, jahanbakhsh, et al., 2024). With the anticipation of accelerated climate change in the forthcoming decades, there is an expectation of significant changes in energy consumption patterns across various sectors (Bardhan et al., 2020)(Saadatjoo et al., 2021), Saligheh & Saadatjoo, 2020). Against this backdrop, ensuring building resilience, particularly in terms of climate adaptation, has emerged as a critical consideration for enhancing building energy efficiency.

Tomrukcu & Ashrafian (2024) investigated how climate change affects residential buildings in Istanbul and Izmir. They developed future weather scenarios and performed dynamic simulations, discovering different levels of climate change's impact on the two areas. The study showed a reduction in heating degree days (HDDs) and a rise in cooling degree days (CDDs). Marco S. Fernandes and his team conducted a study on an office building in Portugal, revealing that the integration of PV panels could reduce future electricity purchases by around 23% to 59%. The research also highlighted that electrical energy consumption could be decreased by 16% to 25% through a mix of system upgrades, building envelope improvements, and operational adjustments (Fernandes et al., 2024). De Masi et al. studied a residential building in Benevento, Italy, using recent weather data and climate change projections. They found a 21% decrease in heating degree days and a 62% increase in cooling degree days, leading to a 56% reduction in heating energy use and a 62% increase in cooling demand. Implementing cool roofs and shading elements could potentially reduce cooling demand by up to 33% (De Masi et al., 2021). A study on residential buildings in six climate zones in New Zealand, using future climate data under scenarios RCP 8.5 and RCP 4.5, found that by 2090, cooling demand would rise by 40% to 79% and heating demand would fall by 15% to 71% under the RCP 8.5 scenario due to severe impacts on thermal performance (Jalali et al., 2023). A study in Italy examined residential buildings in Milan using future weather data obtained through the morphing method. The results showed a 30.9% decrease in heating demand and a significant 255.1% increase in cooling demand. Additionally, the risk of overheating increased by 155% (P. Tootkaboni et al., 2021). Andreu et al. (2018) conducted an analysis of a residential building in Valencia, foreseeing a decrease in heating demand and an increase in cooling energy requirements attributed to climate change. In a study encompassing 16 Mediterranean cities, Rodrigues and Fernandes (2020) observed variations in future cooling energy needs based on location. Similarly, Guarda et al. (2020) highlighted the necessity for efficient renewable energy technologies in zero-energy buildings due to a predicted surge in energy demand. Attia and Gobin (2020) projected a potential excess heat of about 43.5% in a Belgian zero-energy building by the century's end. In China, Zou et al. (2021) forecasted an escalation in cooling energy demand in hot climates and a reduction in heating demand in colder regions. Modeling residential buildings in Italy, Baglivo et al. (2022) highlighted the escalating challenge posed by excessive heat accumulation. In Argentina, Larsen et al. (2019) found a significant increase in the demand for cooling energy alongside a decrease in the demand for heating energy. Zhai and Helman (2019) revealed a projected rise in total energy consumption in the future primarily due to a substantial surge in cooling energy demand. Abbasizadeh et al. (2021) investigated factors influencing energy demand in various climates in Iran, foreseeing a decrease in heating demand and an increase in cooling demand by 2035. Golkar et al. (2022) observed that changes in cooling load surpassed those in heating load across 1000 locations in Iran.

There is a notable gap in research specifically focused on sustainable strategies to enhance building resilience against climate change impacts, particularly within the context of Tehran City. While several studies have investigated similar issues in different cities and climate zones, there is limited research on tailored approaches for Tehran's unique climatic, socio-economic, and infrastructural conditions. This study aims to fill this gap by evaluating sustainable methods to improve building resilience in Tehran, considering local climate projections and the specific challenges faced by the built environment.

In this research, after determining several climate-resilient strategies for buildings, the available scenarios to generate future weather data will be discussed. The data will then be generated using the Meteonorm tool. Focusing on routine residential buildings in Tehran across three boroughs and extracting their features will lead to the determination of one representative case study. Conducting land surveys and distributing

questionnaires among designers and building owners will help determine their preferences and prioritization of design solutions to be applied to the selected case study. The implementation of these strategies on the selected building, using simulation tools, will determine the amount of cooling, heating, and total energy consumption in 2020, 2050, 2070, and 2090 (Figure 1).
This study aims to fill the gap in the literature by providing a comprehensive analysis of climate-resilient strategies for residential buildings in Tehran. By focusing on a region that has been relatively underexplored in this context, the study contributes original insights into how climate change will impact energy consumption patterns and building performance in Tehran. Furthermore, the research will aid in the development of energy-efficient and resilient buildings capable of withstanding future climate conditions, offering practical solutions that can be applied in similar climates globally. This contribution is expected to enhance the understanding of climate adaptation strategies, thereby supporting policymakers, architects, and engineers in making informed decisions to mitigate the impacts of climate change on the built environment. The study's approach, utilizing future climate data and energy simulations for residential buildings in Tehran, provides valuable insights into sustainable building strategies under changing climate conditions. By focusing on widely applicable measures like insulation, double-glazed windows, and shading devices, the findings are relevant beyond Tehran, offering practical design guidelines for similar hot and arid climates globally. The research's methodology and results can be adapted to other regions, making it a useful reference for architects, urban planners, and policymakers aiming to enhance building resilience and energy efficiency in the face of climate change.

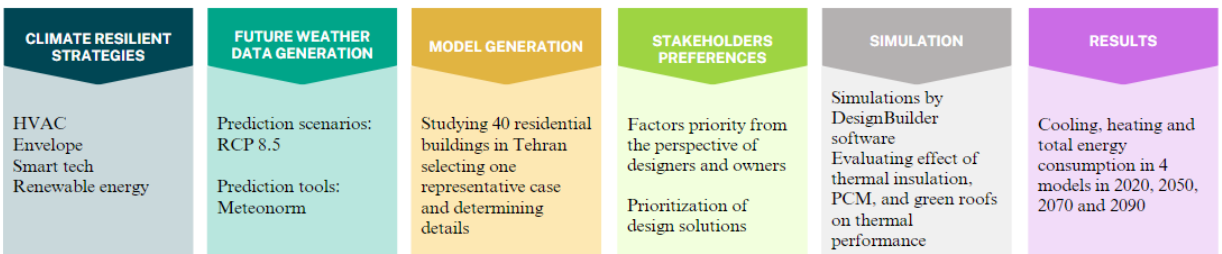

Figure 1 Structure of the research.

2. Material

2.1. Building Resilience

Building resilience is the ability of a building to withstand, adapt to, and recover from adverse conditions, particularly in response to climate change. With the increasing frequency of extreme weather events such as heatwaves, floods, and storms, enhancing the resilience of buildings has become essential for ensuring long-term sustainability and safety. Sustainable approaches to building resilience involve a range of strategies that consider environmental, social, and economic factors. Building resilience is essential for reducing the vulnerability of urban environments, ensuring that buildings remain safe, functional, and sustainable, even in the face of growing climate-related risks. This makes them critical to the long-term sustainability of cities.
In the context of Tehran City, where rapid urbanization and climate change pose significant challenges, evaluating the resilience of buildings is critical. Tehran faces risks such as rising temperatures, increased droughts, and potential seismic activity. Therefore, sustainable design strategies, including earthquake-resistant construction techniques and climate-responsive building designs, are necessary to enhance resilience. For example, implementing flexible design solutions that allow for future upgrades or retrofits can improve the lifespan and adaptability of structures in the city.
Moreover, urban planning that integrates green infrastructure, optimized building orientation, and natural ventilation can mitigate the effects of extreme weather while reducing energy consumption. These strategies contribute to a more resilient urban fabric, where buildings and communities can better absorb and recover from climate impacts (Sozer, 2010).

2.2. Climate-Related Risks

Climate-related risks encompass the challenges posed by climate change, affecting both natural and built environments. These risks include physical risks, such as extreme weather events like floods, storms, and heatwaves, which cause immediate damage, as well as chronic risks like rising sea levels, prolonged droughts, and increasing temperatures, leading to long-term impacts like water shortages and urban overheating. Additionally, transition risks emerge as economies and industries shift toward more sustainable, low-carbon practices. These include changes in regulations, policies, and market demands that may require significant adaptation, presenting challenges for businesses, industries, and governments as they adjust to new environmental standards and technologies aimed at mitigating climate change (Tootkaboni et al., 2021).

2.3. Sustainable Approaches

To enhance building resilience, architects, engineers, and developers are employing a multifaceted approach that integrates innovative strategies across various domains. Among these strategies are advancements in HVAC development, envelope enhancement, renewable energy utilization, and the integration of smart technologies. Each of these components plays a critical role in bolstering buildings against the intensifying effects of climate change, ensuring they remain efficient, comfortable, and adaptable in the face of shifting environmental conditions (Chen et al., 2023).
HVAC development enhances indoor climate control systems for energy efficiency and comfort. It incorporates technologies like variable refrigerant flow systems and heat recovery ventilation to minimize energy use while maintaining indoor air quality. Improvements in HVAC technology enable buildings to adapt to changing climate conditions, ensuring thermal comfort while reducing environmental impact (Mathews et al., 2001).
Enhancing building resilience through envelope design involves a multifaceted approach. Effective insulation materials minimize heat transfer, stabilizing indoor temperatures and reducing energy consumption. Sealing gaps and cracks ensure air tightness, enhancing energy efficiency and thermal comfort while preventing outdoor pollutants infiltration. Weatherproofing safeguards against moisture intrusion and extreme weather events. Solar shading devices control solar heat gain, reducing the need for mechanical cooling. Energy-efficient windows and doors minimize heat loss and improve daylighting. Green roofs and walls provide insulation, absorb rainwater, and improve air quality. Durable materials withstand environmental stressors, prolonging envelope lifespan. Adaptive design allows for flexibility and accommodation of future climate conditions and occupant needs, ensuring long-term resilience in the face of changing environmental challenges (Sozer, 2010).
Intelligent monitoring uses sensors for proactive maintenance. Automated controls optimize systems based on occupancy and weather. Predictive analytics forecast energy needs. Demand response eases grid strain. Remote monitoring offers flexibility. Energy management systems track and save. Grid integration manages storage and demand. Cybersecurity ensures reliability and privacy (Nawaz et al., 2022).
Enhancing building resilience through renewable energy exploitation involves various strategies. This includes installing solar PV systems and wind turbines to generate electricity, utilizing geothermal heat pumps for climate control, and implementing biomass heating systems for heat production. Hydropower and CHP systems further diversify energy sources, while energy storage technologies ensure continuous supply. Microgrid integration enhances reliability by creating self-sustaining energy systems. These measures reduce reliance on the grid, mitigate carbon emissions, and enhance overall energy resilience in buildings (Pagliaro, 2019) (Figure 2).

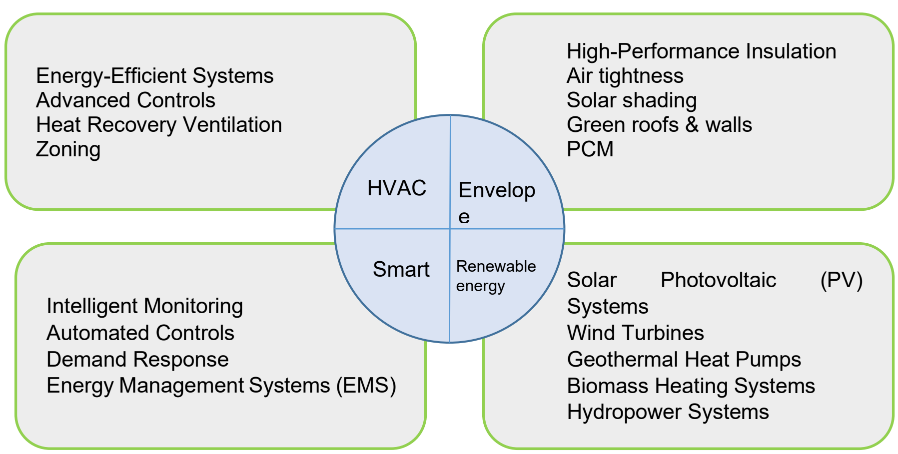

Figure 2 Several strategies to enhance building climate resiliency.

Despite global studies and concerns, there is limited similar research in Iran, particularly in Tehran. This article aims to fill this gap by examining projected climatic changes in Tehran over the next six decades and their impact on residential building energy consumption.
The primary research question of this study is: How would energy efficiency strategies fare in residential buildings in Tehran amidst impending climate change? Additionally, what are the stakeholders' preferences

for bolstering building energy efficiency and mitigating climate change? Another question pertains to identifying which strategy could optimize building energy performance and exhibit superior efficacy in the context of climate change.

The main objective of this research is to evaluate the current and future energy performance of residential buildings in Tehran. The study aims to implement various energy-efficient strategies targeting the building envelope and assess their effectiveness in future scenarios. To achieve this objective, the predominant types of residential buildings in Tehran will be identified, and several strategies related to building envelope development will be defined. Subsequently, the research will compare these strategies based on stakeholders' preferences, considering the perspectives of building designers, and residents. By examining and comparing multiple strategies, the research seeks to provide insights into the most effective approaches for enhancing building energy performance and resilience to climate change in Tehran's residential sector.

The article assesses sustainable strategies for strengthening buildings against climate change impacts in Tehran. It starts by generating future climate data for the city and determining predominant residential building patterns. Several solutions to enhance building climate resilience and energy efficiency are identified and compared based on stakeholder preferences. After selecting the most suitable solutions, they are implemented on the selected case, and energy simulations are conducted using DesignBuilder. Energy simulations evaluate the impact of consumption reduction strategies like thermal insulation, PCM, and green roofs on thermal performance under both present and future climate conditions.

Energy simulations will assess the effectiveness of consumption reduction strategies, providing practical guidance for urban planning and building design. Overall, the study seeks to contribute to the development of sustainable and climate-resilient building practices in Tehran.

This article begins by analyzing building plans to identify residential patterns and generate future climate data with Meteonorm 8 software. In the next step, various solutions for improving building resilience and energy efficiency are compared based on stakeholder input. Finally, selected strategies are then implemented and tested on a chosen case study using DesignBuilder software to assess their impact on thermal performance and CO2 emissions.

3. Methodology

This study applies energy-efficient techniques to residential buildings in Tehran city, to compare their effectiveness in light of anticipated climate changes.

The initial phase involves analyzing the typology of residential buildings in several districts of Tehran, considering factors such as size, orientation, finishing details, and construction materials. Based on this analysis, a representative building is selected for simulation using current climate data to evaluate energy consumption, thermal performance, and pollutant emissions. Future climate data, derived from current climate data, is used to project the building's energy usage and thermal performance for 2050 and 2080. In order to improve the performance of the base model, strategies (according to the stakeholder's preferences) are implemented to reduce energy consumption and environmental pollutants. These strategies are simulated using both current and future climate data, allowing for an assessment of changes in thermal performance, energy usage, and the efficacy of energy-efficient measures in response to climate change influences.

3.1. The City of Tehran

Tehran, the capital of Iran, is a bustling metropolis nestled in the foothills of the Alborz Mountain range. With a population exceeding eight million, it stands as the country's political, economic, and cultural hub (Asl & Abbassi, 2019). In Tehran, a sprawling metropolis, residential buildings exhibit diverse typologies across its twenty-two urban districts. The urban structure of residential areas in Tehran has evolved over time, transitioning from deep, irregular blocks to shallower, more organized grids.

In Tehran, the prevalent semi-arid climate brings significant temperature shifts between seasons, posing hurdles to maintaining comfortable indoor temperatures year-round. This results in heightened energy usage, particularly in residential structures, as occupants strive for thermal comfort. The necessity for increased energy consumption to sustain indoor coziness amplifies both environmental impacts and overall energy demand (Tabari & Hosseinzadehtalaei, 2011). Tackling these issues becomes imperative to advance sustainable building practices, minimize adverse climate repercussions, and curtail residential energy consumption. Historically, Tehran's residential architecture was characterized by traditional courtyard houses known as "hayats" or "kuches." These houses were typically single-story structures built around a central courtyard. However, residential units in Tehran have transformed from traditional courtyard houses to terraced houses with south-facing courts, and eventually to multi-story apartments (Figure 3).

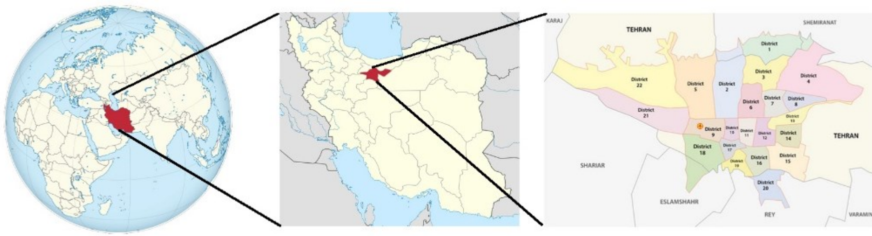

Figure 2. The location of Iran on the World map, The location of Tehran on Iran's map, and the twenty-two boroughs of Tehran.

3.2. Climate change in Tehran City

Currently, numerous tools are employed by researchers for forecasting and generating future climate data. Among these, a widely recognized and dependable tool in the field is the Meteonorm software, renowned for its performance grounded in statistical downscaling (Jalali et al., 2024). Historically, earlier iterations of this software relied on the HadCM3 model. However, in its latest iteration, the software incorporates scenarios such as RCP2.6, RCP4.5, and RCP8.5. Developed by Intersolar Europe, this software employs algorithmic processes facilitated by computational power to execute statistical downscaling. The data generators within the software rely on statistical analysis of weather data, enabling the generation and prediction of future weather series. Meteonorm offers advanced capabilities in forecasting hourly weather data, encompassing variables like temperature, humidity, precipitation, wind speed and direction, solar radiation, and more. These forecasts extend until 2090, encompassing various global scenarios delineated by the aforementioned RCP scenarios.

In this study, initially, the current hourly EPW (EnergyPlus Weather) file was extracted from reliable databases. Subsequently, employing the Meteonorm 8 software, climate data were generated for the years 2050, 2070, and 2090 based on the RCP8.5 scenario. These generated datasets facilitated a comparative analysis of the projected climate changes across a span of seven decades in Tehran city (Figure 4).

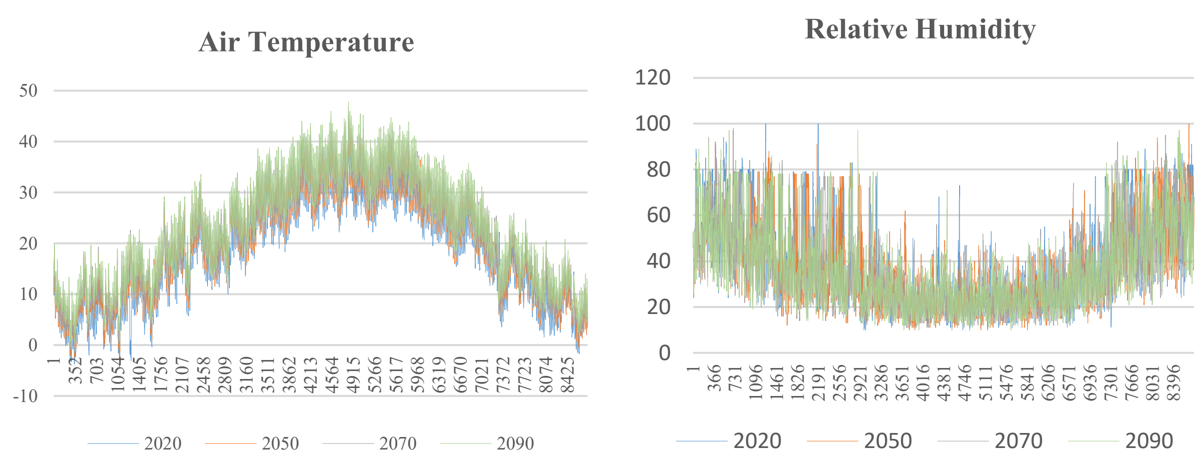

Figure 4. Hourly mean air temperature and relative humidity in Tehran for the years 2020, 2050, 2070, and 2090.

3.3. Simulation Models

To quantify these changes and select a representative case, GIS-based measurement techniques were applied to three sample areas in selected districts of Tehran. These areas, located in Boroughs 12, 11, and 2, were chosen to represent key stages of the city's development. The evolution of housing in Tehran has been driven by factors such as population growth, increasing land values, and advancements in construction techniques. As a result, traditional single-family houses have been replaced by multi-story apartments, leading to higher densities and a chaotic skyline. Modern construction techniques and the need for vehicle access have further influenced the city's morphology, resulting in significant demolition in historical areas. Each borough represents different phases of development, with Borough 12 retaining its traditional character, Borough 11 transitioning towards modernization, and Borough 2 consisting mainly of newer, planned developments (Shayesteh & Steadman, 2016).

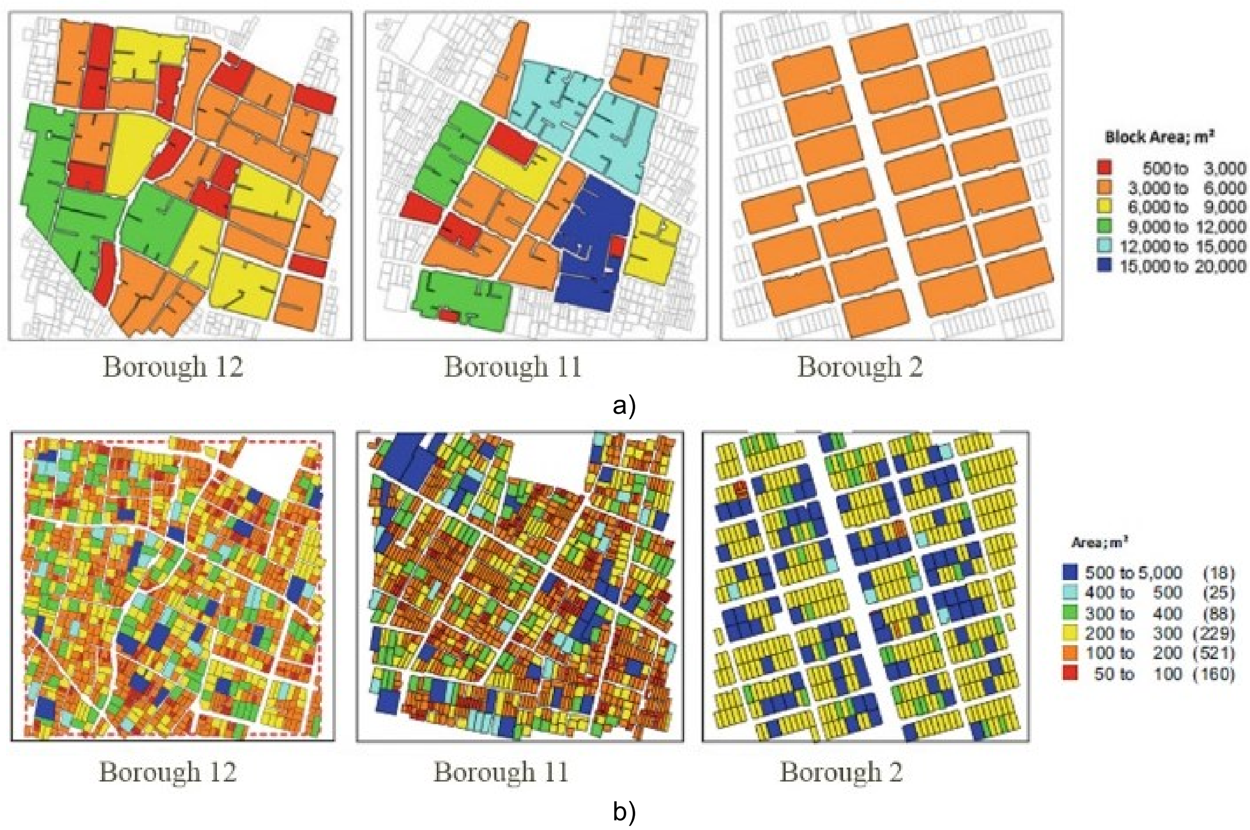

Figure 5. a) Thematic map of block area in sample areas. b) Parcel size of blocks in the sample area.

In the next step, 40 residential building plans with blocks ranging between 100 and 250 m2 (10 in Borough 12, 10 in Borough 11, and 20 in Borough 2) were selected and analyzed based on their layout, spatial arrangement, and number of rooms (Figures 5 and 6). These buildings are mid-rise apartment complexes, typically comprising 4-6 floors (based on frequency), with each floor housing one residential unit. Considering the mentioned factors, a case study was selected with a block area of 250 m2, featuring 5 floors, with each floor comprising one residential unit. Each unit contains two bedrooms, and the area of the residential units is 150 m2 (Figure 7).

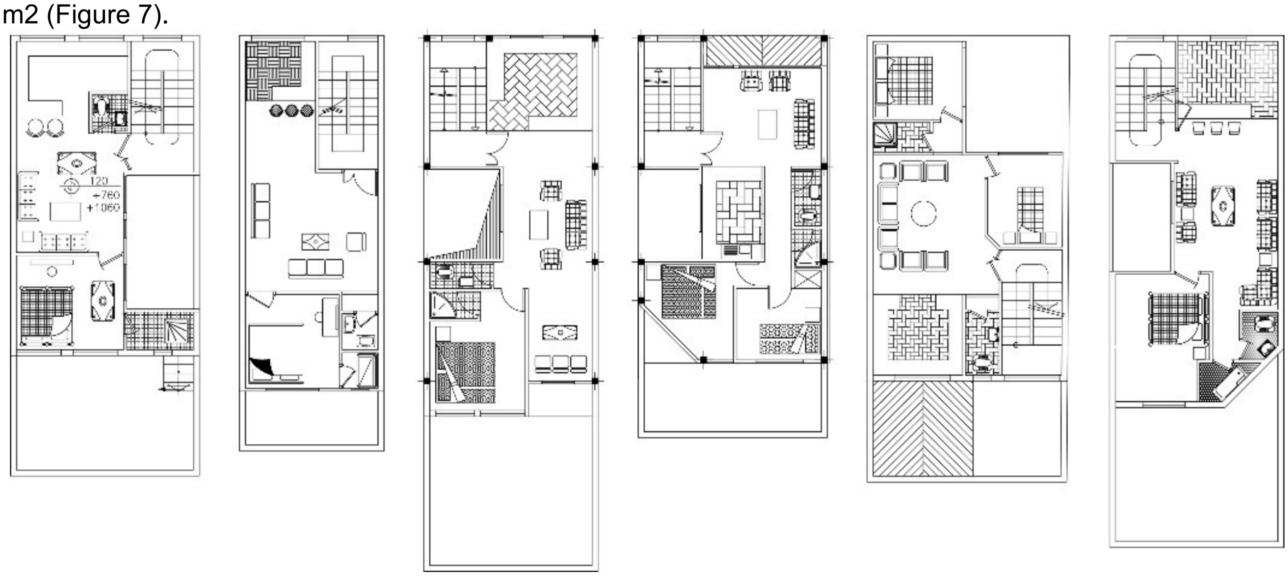

Figure 6. Some of the studied residential building plans in Tehran.

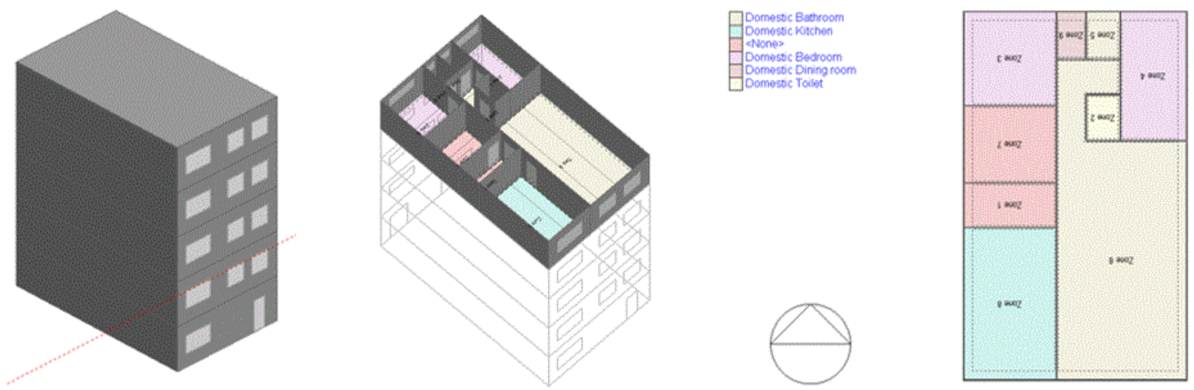

Figure 7. Perspective and plan of simulated building model consisting of nine controlled and uncontrolled zones.

Table 1. Details of the different building components in the simulated models.

	Layers	**Overall width (mm)**	**Heat transfer coefficient U (W/(m^2.°K))**	**Specific heat (J/(kg.°K))**	**Thermal conductivity coefficient λ (W/(m.°K))**	**Overall width (mm)**	**Heat transfer coefficient U (W/(m^2.°K))**
Ceiling-DET 1	Ceramic	20	1700	850	0.8	420	1.39
	Cement mortar	20	1860	840	0.72		
	Lightweight concrete	50	500	840	0.17		
	Concrete slab	300	2300	1000	2.3		
	Gypsum	30	1200	840	0.42		
Interior wall-DET2	Gypsum	30	1200	840	0.42	160	1.84
	Brick	100	1920	840	0.72		
	Gypsum	30	1200	840	0.42		
Exterior wall-Without insulation DET3	Brick facade	30	1700	800	0.84	300	1.67
	Cement mortar	30	1800	1000	1		
	Brick	210	1920	840	0.72		
	Gypsum	30	1200	840	0.42		
Exterior wall- With insulation-DET4	Brick facade	30	1700	800	0.84	240	0.37
	Cement mortar	30	1800	1000	1		
	Expanded polystyrene	50	35	1400	0.03		
	block AAC	100	2800	896	0.11		
	Gypsum	30	1200	840	0.42		
Exterior wall- With insulation – DET5	Brick facade	30	1700	800	0.84	240	0.37
	Cement mortar	30	1800	1000	1		

	Expanded polystyrene	50	35	1400	0.03		
	block AAC	100	2800	896	0.11		
	BIO PCM	70	235	1970	0.2		
	Gypsum	30	1200	840	0.42		
Single glazed window-DET 6	Glass	3	-	-	-	3	5.8
Double glazed window-DET 7	Glass	3	-	-	0.9	19	2.7
	Air	13	-	-	-		
	Glass	3	-	-	0.9		

3.3. Stakeholder Preferences for Building Envelope Enhancements

The investigation into building envelope enhancements requires understanding the preferences of designers regarding various strategies to enhance building climate resiliency. This report presents the findings of this survey and highlights the strategies favored by designers. Questionnaires were distributed among designers and building owners, focusing on their preferences for different building envelope enhancement strategies. Respondents were asked to rank the strategies based on their perceived importance and effectiveness in improving building resilience to climate change impacts.

For this research on building envelope enhancement strategies, a survey targeting both designers and building owners to gather insights into their preferences was conducted. The decision to distribute questionnaires among these two groups was based on their significant roles in the design, construction, and ownership of buildings, making their perspectives invaluable for understanding preferences regarding resilience strategies.

The number of respondents chosen for each group was determined scientifically to ensure the statistical validity and reliability of the survey results. For this study, a sample size that provides a representative cross-section of the population while balancing practical considerations such as time and resources is defined. Therefore, a sample size of 30 designers and 30 building owners was determined. The aim of surveying a sufficient number of participants from both groups was to obtain robust data that accurately reflects the preferences and priorities of designers and building owners about building envelope enhancement strategies for climate resilience. Several evaluation features for comparing design strategies were determined. These factors include durability, cost effectiveness, indoor comfort, regulatory compliance, adaptibilities, aesthetics, and maintenance requirements, as seen in Table 2, 3, and Figure 8.

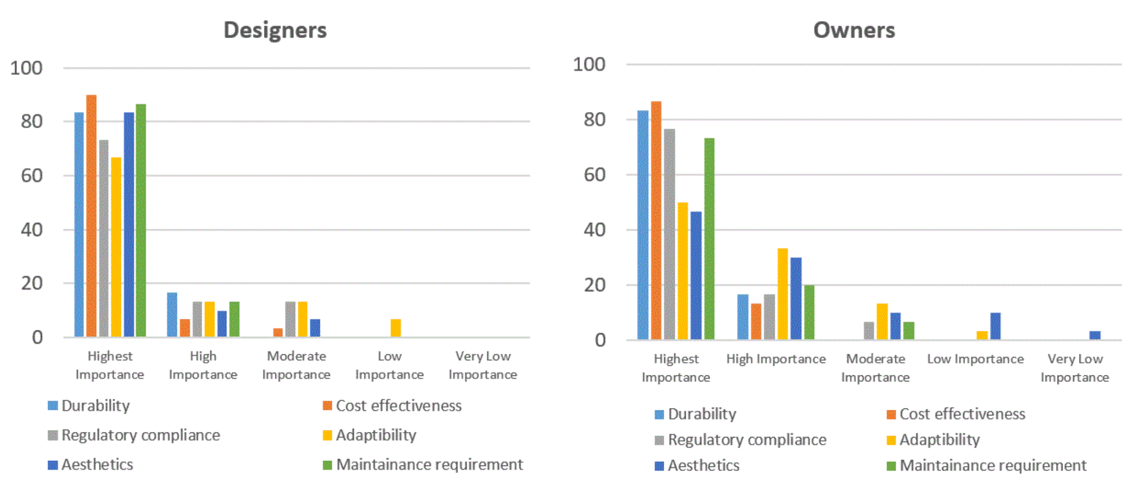

Figure 8. The importance of factors from the perspective of designers and owners.

Table 2. Overall scores were achieved by questionaries to determine stakeholders' preferences.

	Durability	Cost-effectiveness	Adaptability	Aesthetics	Regulatory compliance	Maintenance requirement
Owner scor	145	146	141	129	122	140
Designer scores	148	146	138	143	132	141

Table 3. Owners' and designers' preferences

	1	2	3	4	5	6
Owner	Cost-effectiveness	Durability	Adaptability	Maintenance requirement	Aesthetics	Regulatory compliance
Designer	Durability	Cost-effectiveness	Aesthetics	Maintenance requirement	Adaptability	Regulatory compliance

According to the owner's and designers' preferences durability, cost-effectiveness, and maintenance requirements are the most important factors that must be brought into consideration in selecting retrofit strategies. High-performance insulation, such as EPS and mineral wool, stands out for its exceptional durability, maintaining thermal resistance and stability against various environmental conditions. Advanced glazing systems offer energy savings but require proper installation and maintenance for longevity. Shading devices like overhangs provide solar control but may lack the durability of insulation or glazing. Green roofs offer durability benefits but require regular maintenance for vegetation health and water damage prevention. Green walls, involving living vegetation, have the highest maintenance needs and potential for degradation over time despite their aesthetic and environmental benefits. Consideration of these factors ensures the selection of retrofit strategies that optimize building performance and longevity.

From a cost-effectiveness perspective, high-performance insulation emerges as the most favorable solution due to its low initial investment and substantial long-term energy savings, offering a quick return on investment. Green roofs, while entailing higher upfront costs, yield significant environmental and economic benefits such as enhanced insulation, stormwater management, and prolonged roof lifespan, making them a viable cost-effective option. Advanced glazing systems, though delivering energy savings, may involve higher initial expenses relative to standard glazing, with their cost-effectiveness contingent on factors like energy efficiency and local incentives. Shading devices offer energy savings and comfort benefits but may incur elevated initial and maintenance costs compared to insulation or glazing. Conversely, green walls, necessitating specialized materials and ongoing maintenance like irrigation systems, rank as the least cost-effective option among those considered.

High-performance insulation stands out as the most maintenance-effective solution, requiring minimal upkeep beyond occasional inspections for damage due to its durable and stable nature. Advanced glazing systems follow suit with low maintenance requirements, primarily involving routine cleaning and occasional inspections for longevity assurance. Shading devices like overhangs and awnings necessitate moderate maintenance, including periodic inspections and surface cleaning for optimal functionality. Green roofs entail moderate maintenance tasks such as watering, weeding, and fertilizing to sustain vegetation and prevent water damage, crucial for plant health and system longevity. Green walls present the highest maintenance requirements, involving regular watering, pruning, fertilizing, and pest control to uphold plant health and prevent damage to the building envelope. Additionally, maintaining irrigation systems and substrate health is essential for supporting plant growth, rendering green walls the most maintenance-intensive option among those listed.

According to Table 4, high-performance insulation, advanced glazing systems, and shading devices are considered the best options to address the challenges posed by climate change. These strategies are implemented on the selected building model to assess their performance under current and future climate conditions.

Table 4. Prioritization of design solutions based on the preferences of designers and owners.

	1	3	4	5	6
Durability	High-performance insulation	Advanced glazin systems	Shaders	Green roofs	Green walls
Cost-effectiveness	High-performance insulation	Green roofs	Advanced glazin systems	Shaders	Green walls
Maintenance requirement	High-performance insulation	Advanced glazin systems	Shaders	Green roofs	Green walls

4 Results and Discussion

4.1 Results

To investigate the building's energy performance over different years, the cooling, heating, and total annual energy consumption for the years 2020, 2050, 2070, and 2090 were analyzed. The results are illustrated in Figures 9 and 10, which include four models: the typical building, the building with double-glazed windows, thermal insulation, and shadings.

From these graphs, it is evident that in the base model, heating energy demand decreases while cooling energy demand increases over time. Specifically, the total energy consumption in this model shows a slight decrease from 2020 to 2050, followed by an increase in subsequent years. Detailed analysis of the base model reveals that annual heating energy consumption will decrease by 20.56%, 37.82%, and 58.85% in 2050, 2070, and 2090, respectively, compared to 2020. Conversely, cooling energy consumption increases by 20.97%, 41.27%, and 65.25% in the same years due to global warming. Overall, the total annual energy consumption remains relatively stable, with changes ranging from -1.1% to +3.06% over the study period.

By examining the behavior of the WDG group building model, which features double-glazed windows, it is observed that heating energy consumption decreases over time, similar to the basic model. Specifically, heating energy consumption in this model is projected to decrease by 30.65%, 49.82%, and 65.12% in the years 2050, 2070, and 2090, respectively, compared to the base year of 2020. Conversely, cooling energy consumption exhibits an upward trend, increasing by 15.68%, 37.31%, and 60.19% over the same years. As with the base model, the WDG group shows only slight changes in total annual energy consumption over time. Consequently, the maximum increase in total annual energy consumption is observed in 2090, with an increase of 1.5% compared to 2020.

By examining the WI group models, which feature thermal insulation, it was observed that the building's energy consumption behavior follows a pattern similar to the previous groups. In this category, the heating energy consumption of the building decreases significantly over time, with a reduction of up to 66.78%. This reduction is greater compared to the other groups. Specifically, the heating energy consumption decreased by 31.8%, 53.5%, and 66.78% in 2050, 2070, and 2090, respectively, compared to 2020. Conversely, the cooling energy consumption in this group shows slight changes of +20.59%, +42.66%, and +64.09% in 2050, 2070, and 2090, respectively. The total annual energy consumption in this group also exhibits higher changes compared to the previous models, with an increase of up to 3.78% in 2090.

By examining the WS group models, which feature shading devices, it was observed that the building's energy consumption behavior follows a pattern similar to the previous groups. In this category, the heating energy consumption of the building decreases significantly over time, with a reduction of up to 59.70%. Specifically, the heating energy consumption decreased by 21.37%, 38.08%, and 59.70% in 2050, 2070, and 2090, respectively, compared to 2020. Conversely, the cooling energy consumption increases by 15.94%, 37.94%, and 61.15% in 2050, 2070, and 2090, respectively. The total annual energy consumption in this group shows an increase of 1.21% in 2070 and 2.3% in 2090 compared to 2020 (Figure 9).

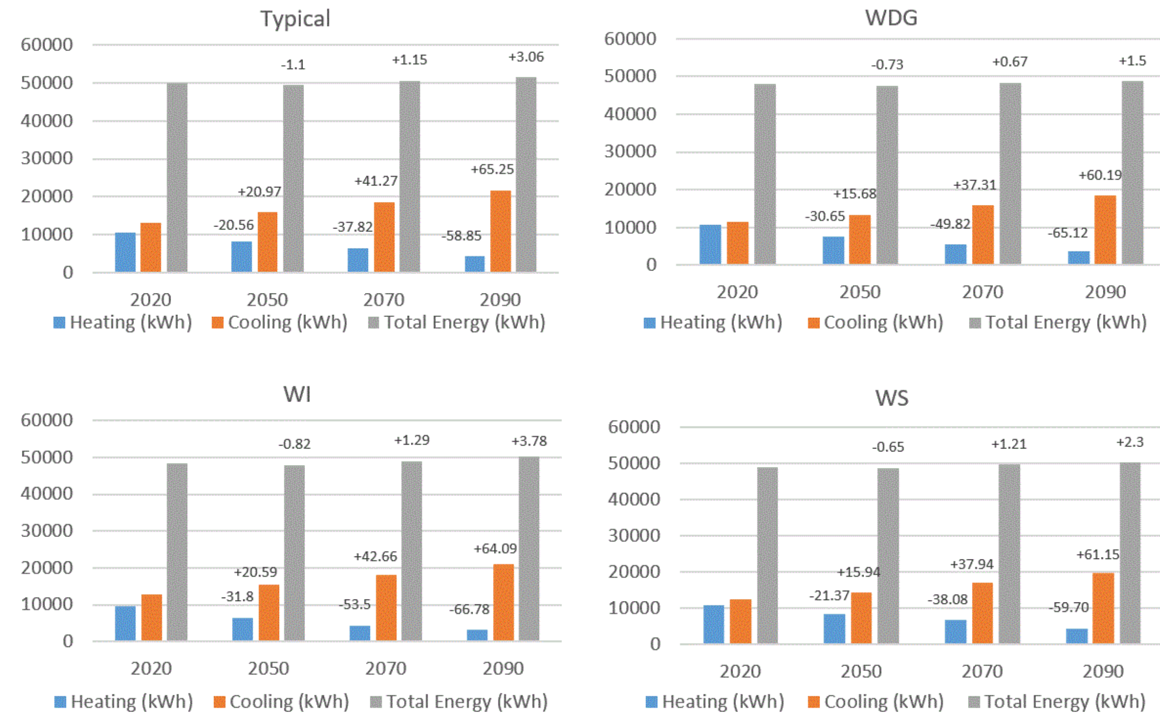

Figure 9. Heating, cooling, and total energy consumption in 4 models in the years 2020, 2050, 2070, and 2090.

The next step is to compare the thermal and energy performance of different models from 2020 to 2090. Figure 10 presents graphs that facilitate this comparison, displaying cooling, heating, and total annual energy consumption as separate charts.

Examining the results shows that the WI group models, which feature thermal insulation, have the best performance in terms of heating energy consumption, exhibiting the lowest energy usage. The building models with double-glazed windows follow in terms of performance. Notably, the Typical and WS group buildings (with shading devices) demonstrate relatively similar heating energy consumption. In some instances, the basic model consumes less thermal energy than the model with a canopy. This observation is expected because the use of shading canopies can limit the entry of radiant heat, potentially increasing the need for heating. A general review of the graphs from 2020 to 2090 indicates that, over time, and with the rise in global temperatures, heating energy consumption gradually decreases.

The graphs in Figure 10 indicate that, in terms of cooling energy consumption, the WDG (double-glazed windows), WS (shading devices), and WI (thermal insulation) models perform the best. Comparing the four groups of models reveals that the basic model has the highest cooling energy consumption. Additionally, the trend in the graphs shows that cooling load increases over time across all models. Furthermore, the cooling energy diagram indicates that the differences in cooling load between the various models are relatively small in 2020. However, these differences become more pronounced over time.

Finally, the comparison of total annual energy consumption shows that the WDG model, featuring double-glazed windows, has the best performance with the lowest energy consumption. The WI (thermal insulation) and WS (shading devices) models follow in the subsequent categories. The basic model, with the highest energy consumption, demonstrates the weakest performance. The graph also reveals that the difference in energy consumption between the WDG and WI models is minimal in 2020 and 2050, but this difference increases over time. Additionally, by 2090, the energy consumption of the WI and WS models is nearly the same, indicating similar performance at that time.

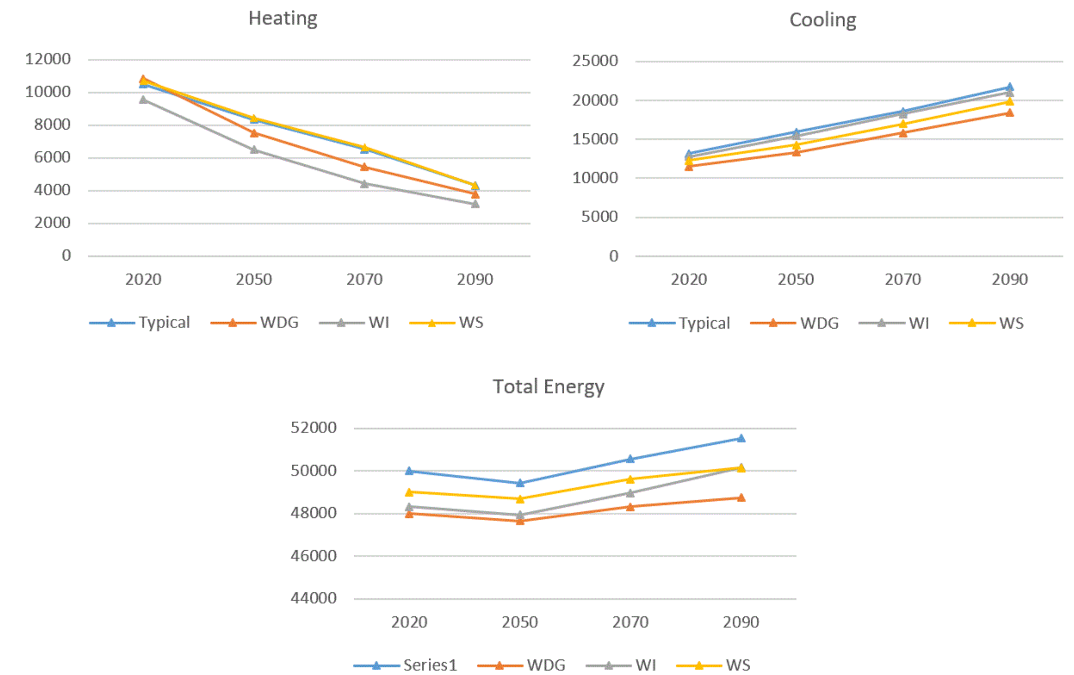

Figure 10. Heating, cooling, and total energy consumption in 4 models in the years 2020, 2050, 2070, and 2090.

4.2 Discussions

The analysis of the energy performance of different building models from 2020 to 2090 reveals significant insights into the impact of various energy-saving measures. The base model demonstrates a clear trend of decreasing heating energy demand and increasing cooling energy demand over time, driven by global warming. Although the total annual energy consumption remains relatively stable, the shift towards higher cooling energy highlights the growing importance of implementing effective cooling strategies.

The WDG model, featuring double-glazed windows, shows a substantial reduction in heating energy consumption, outperforming the base model. However, it also experiences an increase in cooling energy consumption over time. The WI model, which incorporates thermal insulation, exhibits the greatest reduction in heating energy consumption, making it the most efficient in terms of heating. Despite a slight increase in cooling energy consumption, the WI model's overall energy performance remains strong.

The WS model, with shading devices, also demonstrates a significant reduction in heating energy consumption, albeit to a lesser extent than the WI model. The cooling energy consumption in the WS model increases over time but at a slower rate compared to the base model. This indicates that shading devices effectively mitigate some of the cooling load increases due to global warming.

The comparison of total annual energy consumption highlights the superior performance of the WDG model, followed by the WI and WS models. The base model consistently shows the highest energy consumption, underscoring the need for energy-efficient upgrades in building design.

5. Conclusions

This study aimed to evaluate the impact of various energy-saving measures on the energy performance of buildings under future climate conditions from 2020 to 2090. The key findings indicate that thermal insulation (WI model) is the most effective in reducing heating energy consumption, while double-glazed windows (WDG model) exhibit the best overall energy performance. However, all models showed an increase in cooling energy demand over time due to global warming.

These results imply that while energy-efficient upgrades can substantially reduce heating energy consumption, they are insufficient on their own to address the rising cooling demands. This highlights the need for a holistic approach that combines multiple energy-saving technologies to optimize building energy performance in the face of climate change.

The study is limited by the scope of the climate scenarios and building models analyzed, suggesting that future research should explore a wider range of climate projections and additional energy-saving strategies. Future research should examine diverse climate scenarios, combine various energy-saving technologies, and assess their long-term performance in real-world settings. Evaluating emerging materials, their economic and environmental impacts, and considering occupant behavior will provide a more comprehensive understanding of energy efficiency. Additionally, integrating these measures with renewable energy sources could further improve sustainability.

Overall, this research contributes to the scientific understanding of building energy performance under changing climate conditions by highlighting the effectiveness of different energy-saving measures and their limitations. It provides a foundation for developing more effective and comprehensive energy efficiency strategies and emphasizes the importance of combining various technologies to achieve sustainable and resilient buildings.

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Conflicts of interest

The Authors declare that there is no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding authors/s.

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