Journal of Engineering and Applied Research (JEAR)

National University of Skills

Winter & Spring 2025, Vol. 2, No. 1, p. 182-207

Journal Homepage: https://jear.tvu.ac.ir

:10.48301/jear.2025.516184.1109

Impact of Building Materials for the Exterior Envelope on Energy Consumption and Carbon Emissions (Case Study of Residential Buildings in Tehran)

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ARTICLE INFO

Article Type:
Original Research

Received: 04.22.2025
Revised: 05.30.2025
Accepted: 10.21.2025

Keyword:
Design Builder software
Carbon emissions
Embedded Carbon
Operational carbon
Building Materials
energy consumption
Exterior Envelope

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ABSTRACT

The façade of the building, as the main intermediary between the interior and exterior spaces, plays a significant role in adjusting the weather conditions and providing thermal comfort to the residents. In this research, 715 different scenarios were defined with the combination of different types of construction materials, and the effect of each of these scenarios on the process of energy loss from the surface of the external walls of the building during the operation period was determined. In the end, these scenarios were compared during a one-year operation period, and the amount of energy consumption in each of these scenarios was calculated. Also, by measuring the amount of carbon emissions in buildings during the operation period and before that, let's look at practical methods to reduce the effects of the construction industry on the environment. By comparing the research findings, it can be seen that the ranking of each scenario in the amount of total energy consumption is not necessarily the same as the ranking of energy consumption for gas consumption or electricity consumption for the same scenario. That is, choosing the optimal scenario depends on the type of energy consumed in the building. Finally, we determined the scenarios with the lowest and highest amounts of embodied carbon and operational carbon. At the end, we obtained the latent carbon compensation period for each scenario. This article can help designers and construction engineers optimize the energy consumption of buildings by deciding on the right materials.

E-ISSN: 3060-6357

Introduction

In the late 20th century, the environmental consequences of human intervention received more attention than ever before. Concepts of economic growth and development were questioned, and the notion of development became synonymous with environmental protection. Today, the global challenge of climate change affects everyone equally. Environmental issues have caused deep concerns both at the national and global levels. Currently, the reduction of greenhouse gas emissions is the ultimate goal of global energy and environmental policies. One critical issue related to air pollution is global warming caused by the greenhouse effect.

Greenhouse gases in the atmosphere prevent infrared radiation from returning to space from the Earth's surface. Since infrared radiation cannot directly pass through the air, it is carried away by air currents and transported from higher altitudes to space. Increasing temperatures are the easiest way to balance climate and energy, which will cause many changes in the climate (Nabi Bidhendi et al., 2007)[1].

The building envelope, as the primary interface between indoor and outdoor spaces, plays a crucial role in moderating climatic conditions and providing thermal comfort for occupants, thereby reducing heating and cooling loads. Designing and implementing building envelopes that efficiently provide the highest level of thermal comfort inside with minimal reliance on mechanical equipment can significantly contribute to energy savings.

By reviewing the literature and examining the background of the research done so far, none of the researchers carried out specifically comprehensive studies on the effect of the materials used to make the outer shell of the building, to define several layers for the wall (the main and middle layer of the wall, the inner layer of the wall, the layer exterior and exterior of the wall), consider different construction materials for each of these layers, and also put different insolations among these layers, and finally calculate the amount of carbon emissions resulting from the production to exploitation stage. The main gap and deficiency observed in the previous research is the neglect of the total carbon stored and emitted during the exploitation period.

Therefore, in this research, efforts have been made to measure carbon emissions in buildings during both the operational phase and before that. Practical methods have been employed to reduce the environmental impact of construction. Initially, the carbon emissions resulting from the production phase of various building materials were measured and determined. Subsequently, the impact of these materials on emissions throughout the operational period was assessed. Finally, the cumulative effect of these two aspects was investigated.

The Necessity of Conducting Research

Energy Consumption Status in Iran and the World

Energy consumption worldwide, although fluctuating in some years, has generally followed an upward trend and reached 167,788 trillion watt-hours in 2022. In Iran, this trend has consistently been upward, reaching 3,377 trillion watt-hours in 2022. This trend is illustrated in Figure 1. When we divide this energy consumption by the population, Iran's severe situation becomes clearer.

The average energy consumption per person globally is 21,039 kilowatt-hours, while in Asia, it decreases to 19,140 kilowatt-hours. However, the average energy consumption per person in Iran is 38,133 kilowatt-hours. Figure 2 depicts this trend.

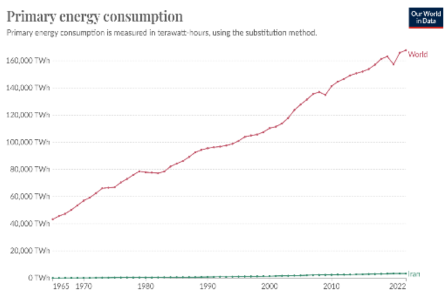

Figure 1. The energy consumption trends in Iran and the world

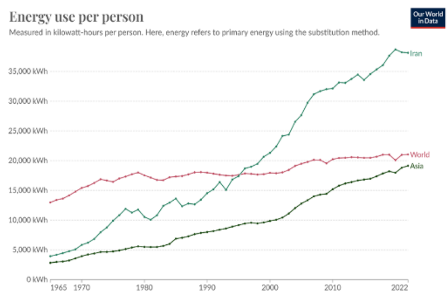

Figure 2. The energy consumption per capita in Iran, Asia, and the world

The Situation of Carbon Emissions in Iran and the World

The trend of greenhouse gas production worldwide has generally been upward, with occasional declines. In 2022, global production reached 53.85 billion tons. In Iran, the trend has consistently risen, reaching 935.35 million tons in the same year, according to Figure 3.

The rise in greenhouse gas and carbon dioxide emissions can be attributed to population growth. To investigate this, we can examine per capita emissions, which directly reflect the production per person.

Analyzing per capita greenhouse gas emissions in Iran reveals a consistent upward trend, except during specific periods (such as war and revolution). Meanwhile, global per capita emissions are decreasing. Unfortunately, Iran's trend has not only remained stable but has also increased. Refer to Figure 4.

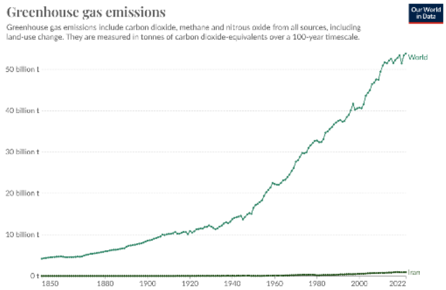

Figure 3. Greenhouse gas emissions in Iran and the world

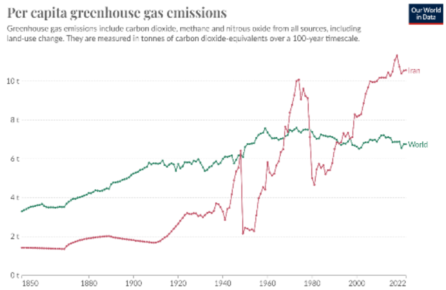

Figure 4. Per capita production of greenhouse gases in Iran and the world

The greenhouse gas emissions are being examined and categorized into various industrial, agricultural, transport, and other sectors. As you can see in Figure 5, 31.3% of the world's greenhouse gas emissions are attributed to heating and electricity production. Additionally, 15% is generated in the transportation sector. The construction sector ranks third with a share of 12.8%. Energy consumption in the building sector contributes 6.2% of global greenhouse gas emissions, placing it seventh. This breakdown and categorization in Iran is shown in Figure 6. As you can see, electricity production and heating contribute to 23.9% of Iran's total greenhouse gas emissions. Energy consumption in buildings ranks fourth with a share of 14.8%, while the construction sector ranks fifth with a share of 11.7%.

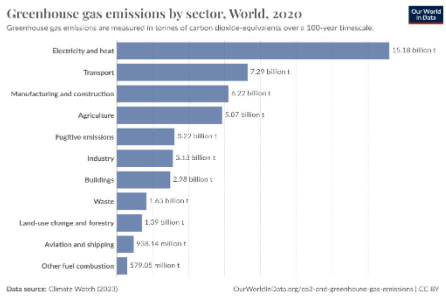

Figure 5. Separation of the source of greenhouse gas emissions in the world into different sectors

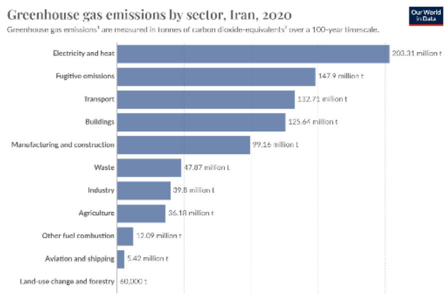

Figure 6. Separation of the source of greenhouse gas emissions in Iran into different sectors

The critical status of greenhouse gas emissions throughout the lifecycle of buildings in Iran becomes more evident when we consider the combined impact of the construction sector and energy consumption within buildings. Globally, this share amounts to 19%, but in Iran, this share reaches 26.5%. This highlights the importance of focusing on energy reduction and carbon mitigation in the construction industry. Notably, the share of greenhouse gas emissions from energy consumption in buildings even surpasses that of the construction sector. This underscores the significance of energy efficiency during the operational phase of buildings, leading to reduced greenhouse gas emissions over time.

The source of all the figure numbers 1 to 6 is Our World in Data[1] website.

Literature Review

In a study conducted by Gan and colleagues in 2024, titled "Measurement of Carbon Emissions from the Building Envelope of an Educational University Building in the City of Hefei," key findings emphasize that the type and thickness of external wall materials significantly impact the embedded carbon during the production phase. Conversely, the choice of window materials is crucial for reducing greenhouse gas emissions during the operational phase of construction. The study examined various insulation materials for external walls, including expanded polystyrene (EPS), extruded polystyrene (XPS), graphite-enhanced polystyrene (GEPS), vacuum insulation panels, polyurethane boards, and mineral wool. Heat transfer coefficients for the external wall were tested with different insulation materials at various thicknesses (ranging from 10 to 100 millimeters). The cost-benefit analysis in this study explores the optimal balance between retrofit costs and carbon emissions, proposing various optimization scenarios based on different budget levels. The renovation cost for the target building is divided into three categories: less than 1 million yuan, 1 to 2 million yuan, and more than 2 million yuan. Considering carbon emissions during the building's operational phase and emissions during the production of construction materials, an appropriate transformation plan can be selected for the specific building. Overall, seven retrofit designs were chosen, resulting in an annual reduction of 2.96-3.62 tons of carbon emissions during the operational phase compared to the studied building and a reduction of 30.36 to 165.97 tons of carbon emissions during the production of construction materials. When retrofit costs are less than 1 million yuan, it is recommended to use 50-millimeter extruded polystyrene for external walls, 70-millimeter GEPS for ceilings, and medium-transmittance glass for external windows. For retrofit costs between 1 and 2 million yuan, external walls made of expanded polystyrene (50 mm),

[1] www.ourworldindata.org

ceilings made of graphite-enhanced polystyrene (70 mm), and low-emissivity glass windows are advantageous. When retrofit costs exceed 2 million yuan, it is preferable to use 25-millimeter vacuum insulation panels for external walls, 60-millimeter polyurethane boards for ceilings, and insulated glass for external windows. This study highlights the critical role of improving thermal insulation performance in building envelopes to reduce overall carbon emissions. External walls significantly impact carbon emissions and control retrofit costs during the production of construction materials, emphasizing the importance of adjusting insulation type and thickness for external walls. External windows also have a notable impact on carbon emissions during the operational phase. Therefore, optimizing the material choice for external windows is highly significant in reducing carbon emissions during building operations [2].

Mosavi Navaee and colleagues conducted research in (2024) on the impact of air gaps in walls on reducing energy consumption in a residential building located in Ahvaz. They investigated three different air gap thicknesses (1 cm, 2.5 cm, and 5 cm) to assess their effect on overall energy consumption, heating, and cooling loads during different months of the year. Monthly cooling loads decreased by 10.3%, 12.8%, and 14% in the warmest month, and monthly heating loads decreased by 32.8%, 42.3%, and 48.2% in the coldest month, respectively. Annual heating energy consumption decreased by 25.7%, 30.9%, and 33.6%, while annual cooling energy consumption decreased by 8.3%, 10%, and 9.1%, respectively. Considering the high annual cooling energy consumption, these reductions are significant [3].

Allahyari and colleagues conducted a study in 2022 titled "Energy Optimization in the Construction Sector Using Neural Networks and Particle Swarm Optimization Algorithm: A Case Study in Bandar Abbas County." In this research, they explored various variables related to building materials, such as wall and ceiling materials, window area and type, and insulation thickness. Using the Design Builder software, they analyzed different scenarios. Ultimately, they developed a model that minimizes energy consumption and carbon dioxide production. The optimal model includes a brick wall with a 5 cm insulation thickness, a reinforced concrete ceiling with a 5 cm insulation layer, triple-glazed windows, and specific window-to-wall ratios. For instance, the north- and east-facing windows should cover 70% of the wall area, while the south-facing window-to-wall ratio should be between 41% and 43%. The west-facing window-to-wall ratio should range from 65% to 67% [4].

Ghodosi Far and Faramarzi Asli conducted research in (2022) on the analysis of a movable double-skin façade system's efficiency in energy consumption for sustainable residential buildings in Tabriz. Their results demonstrated that in cold seasons, blocking the upper and lower parts of the double-skin façade trapped air and acted as insulation, reducing energy loss. In warm seasons, allowing airflow between the two skins increases heat transfer from the building, resulting in reduced indoor temperatures [5].

Mahdinezhad Godarzi and colleagues conducted research in (2022) titled "Principles of Residential Building Façade Design in Warm and Humid Climates for Indoor Temperature Reduction Based on Vernacular Architecture." The study investigated the thermal performance and solar radiation absorption and transfer to the interior space by the façade of an apartment building in the warm and humid climate of Bushehr. The impact of vernacular architectural façade design strategies on reducing indoor temperatures was then assessed. Optimal façade performance included vertical roller blinds, latticed windows, and white cement façades, resulting in a cooling load reduction of up to 38% and an overall building load reduction of 33% [6].

Additionally, in a study by Ustaoglu and colleagues in 2021, titled "Investigation of Environmentally Compatible Building Materials with Enhanced Energy Performance in Different Climatic Regions: Cost-Effective, Low-Energy, and Low-Carbon Emissions," they explored the use of various additives such as lightweight aggregates, expanded vermiculite, fly ash, and sludge ash for producing fired clay bricks and lightweight concrete foams. For instance, instead of using conventional insulation materials available on the market, they employed lightweight concrete containing expanded vermiculite. They also replaced ordinary bricks with a new type of fired clay brick. Ultimately, annual energy savings and cost savings for different brick and lightweight concrete thicknesses were calculated, along with greenhouse gas emissions from various fuels (coal, electricity, furnace oil, liquefied gas, and natural gas). The results demonstrate that using these new building materials leads to energy savings of 11 kWh/m^2 in an insulated building and 31.2 kWh/m^2 in an uninsulated building. The annual energy savings rate reached 21.7%. The most significant energy savings occurred in buildings using electricity for heating. The highest carbon emissions were associated with coal. Natural gas was the cleanest heating option. Electricity contributed the highest carbon emissions after coal in the studied region. Additionally, carbon reduction for coal reached 18.7 kg/year. By utilizing these new materials, maximum carbon reduction reached 22% [7].

Aghakhani and colleagues conducted a study in 2021 titled "Environmental Effects of Using Concrete, Brick, and Wood in Construction on Energy Consumption and Carbon Emissions: A Case Study in Northwestern Iran." In this research, they investigated three types of building materials: brick, concrete, and wood. For each material, they examined three production factories and collected data related to electricity consumption, gas usage, human labor in the production line, and diesel fuel consumption for transportation (both rail and road). Using software tools like Revit for modeling and Energy Plus for energy analysis, they calculated average energy consumption and embodied energy (embodied energy) for each material. Additionally, they determined the amount of carbon dioxide emissions associated with each material. Their findings revealed that wooden beams are the most environmentally friendly, while concrete is the most polluting among these materials [8].

Fathalian and Kargar, in their research conducted in (2021) titled "Investigating the Impact of Various Energy Optimization Strategies on Building Energy Classification Using Design Builder Software: A Case Study of an Office Building". Explored the effects of different energy optimization strategies on building energy classification. They focused on an office building located in Semnan, Iran. The study involved simulating the total energy consumption of the building using Design Builder software and validating the results against actual energy consumption data from utility bills in (2016 - 2017). Subsequently, they compared various optimization approaches based on the building's energy consumption criteria. The findings revealed that replacing external sunshades with internal ones, along with upgrading standard windows to double-glazed windows, resulted in the least energy savings and had no significant impact on energy classification. However, a combination of double-glazed windows and thermal insulation in the external walls proved to be the most effective proposed solution for energy optimization [9].

Soler and colleagues conducted a study in 2020 titled ''Using Integer Linear Programming to Minimize the Embodied Carbon Dioxide Emissions in the Opaque Facade of a Building.'' In this research, they considered embodied carbon emissions in the building materials of the external shell and incorporated other facade construction parameters, such as maximum allowable heat transfer, wall thickness, and materials for different wall layers. By using linear programming, they aimed to minimize the amount of emitted carbon dioxide. They selected seven different layers for the walls and defined 70 different scenarios. Ultimately, they found that choosing appropriate materials could reduce embodied carbon emissions by up to 78.5% [10].

Dabaieh and colleagues conducted a comparative study in 2020 titled 'Comparative Study of Carbon Emissions and Embodied Energy Between Sun-Dried Bricks and Fired Bricks.' This study compared the life cycle carbon emissions and calculated the embodied energy between two types of bricks: sun-dried clay bricks and kiln-fired bricks. It served as a tool for evaluating energy and assessing the impact of weather conditions on both brick types and economic production factors. The focus was on the difference in the production chain between sun-dried clay bricks, which represent traditional norms, and kiln-fired bricks, which are the most commonly used wall materials in ordinary buildings. The results of this study indicate that using sun-dried bricks instead of fired bricks can lead to a reduction of up to 5907 kilograms of emitted carbon dioxide and 5305 megajoules of embodied energy per 1000 bricks produced. The article concludes by presenting alternative scenarios for brick production and suggesting improvements for sun-dried brick manufacturing. The method used in this study contributes to the development of a comparative research approach for evaluating material choices in construction. This research highlights the importance of sustainable practices in the construction industry, emphasizing the need to reduce carbon emissions and promote environmental balance while maintaining economic viability [11].

"Optimization of Two-Level Approach for Sustainable Development and Carbon Emission Reduction in the Building Materials Industry: A Case Study in China": In their 2020 research, Xu and colleagues explored an optimal two-level approach for sustainable development and carbon reduction in the building materials industry. They used a balanced Stackelberg equilibrium method to balance economic interests and carbon reduction. The main focus of their study was on material production quantities and transportation methods. The proposed model was applied to a case study in China, demonstrating its effectiveness in reducing carbon emissions associated with material transportation. It encourages building material suppliers to adopt environmentally friendly initiatives. By increasing the production and sale of sustainable products, significant strides can be made toward carbon reduction goals. The study also provides practical approaches based on the results to assist regional authorities in controlling carbon emissions in the construction industry [12].

Karami and Anbarzadeh in 2020 conducted a study titled "Optimization of Building Insulation Thickness under Different Climatic Conditions with an Environmental Approach." The objective of this study was to investigate the impact of optimizing insulation thickness on carbon dioxide ($CO2$) emissions under various weather conditions. Initially, they modeled a sample building in different climatic regions of Iran using Design Builder software. Next, they employed a genetic algorithm (implemented in MATLAB) for optimization. Finally, based on the obtained results, they analyzed the environmental implications and compared the optimal insulation thickness for buildings over a ten-year period in various Iranian cities. The findings revealed that the overall $CO2$ emissions over the ten-year period were lowest in cold and dry climates (e.g., Tabriz) and highest in warm and humid climates (e.g., Bandar Abbas), with values of 350 and 770, respectively [13].

Mohaghar and colleagues in 2020 conducted research titled "Examining Policies for Reducing Carbon Dioxide Emissions from the Construction Industry Using a Dynamic Model." In this article, they developed a dynamic model that simulates CO2 emissions from the building supply chain. Simulation results using the Vensim software demonstrated that by implementing incentive policies, formulating restrictive laws and regulations, and promoting green supply chain practices, it is possible to reduce the growth of carbon dioxide emissions from the construction industry [14].

In another study, Saaebi Safa and colleagues conducted research in (2020) titled Auditing the amount of energy loss through the external walls of the building and the effect of thermal insulation by simulation in Design Builder software. They examined parameters such as reducing indoor design temperature from 24°C to 22°C, replacing triple-glazed windows with double-glazed ones, and adding 5 cm of rock wool insulation to the external walls. Their simulation results demonstrated the clear and substantial impact of thermal insulation on energy efficiency [15].

Pedrosu and colleagues conducted research in (2020) titled "Characterization of a multilayer external wall thermal insulation system. Application in a Mediterranean climate." This study compared the performance of a multilayer thermal insulation system with a super-insulating layer under Mediterranean climate conditions. Mechanical, physical, and microstructural tests were performed on the insulating layers. The protective layers in a multilayer system demonstrated improved mechanical performance and water resistance. When compared with other existing multilayer products on the market, this new solution provided competitive results, indicating improved performance under real operational conditions [16].

As noted, numerous studies have been conducted internationally and nationally on reducing the production and emission of carbon dioxide and greenhouse gases in the construction industry. Generally, these studies can be divided into three categories: Studies that address the pre-construction phase and focus on embodied carbon. Studies that address the construction phase and examine carbon emissions resulting from energy consumption for construction. The third category includes studies that target the post-construction phase and the operational period and examine carbon emissions resulting from energy consumption for heating, cooling, lighting, and so on.

The main gap and deficiency observed in previous research is the disregard for the total embodied and emitted carbon during the operational period. Few studies have addressed all three phases, or even two of the above phases. Also overlooked is the importance of comprehensive studies regarding the impact of building envelope materials in order to define the various layers for the wall (core and intermediate layers, inner layer), the facade (outer layer and exterior facade), considering different construction materials for each of these layers, as well as placing different insulation materials between these layers.

Therefore, this research endeavors to reduce the impact of the construction industry on the environment by measuring carbon emissions in buildings during the operational and pre-operational phases and examining various scenarios of external wall building materials using practical methods.

Research Methodology

Given the nature of the data, this research falls into the quantitative category. Since it measures the energy loss variables by varying the types of building envelope materials and thermal insulations used, it employs a correlational approach.

Considering that the goal of this study is to improve behaviors, methods, materials, and insulation used in construction, leading to the development of practical knowledge in the construction industry, it qualifies as applied research.

Software Used

For this research, Design Builder software version 6.1.0.006 was utilized.

Design Builder Software:

Design Builder software facilitates building modeling from various aspects, including building physics (construction materials), architectural design, heating and cooling systems, lighting systems, and more. Apart from modeling heating and cooling loads, it dynamically simulates various energy usages in buildings, such as heating, cooling, lighting, appliances, and domestic hot water. Additionally, it can model day lighting and even CFD (Computational Fluid Dynamics). Other capabilities include natural and mechanical ventilation modeling, thermal comfort assessment in indoor spaces, and energy gains/losses from different building components. The results of these simulations can be extracted for the entire year, specific months, daily, and even hourly. Furthermore, the results can be obtained for the entire building, different floors, and individual spaces. A special feature of this software is the ability to present modeling results in the form of diagrams or tables, which can be useful for subsequent analyses.

Case Study Sample

The case study in this research involves a five-story residential building located in Tehran. The ground floor serves as a parking area, while the other four floors are residential units. Each floor contains one apartment unit with an approximate area of 100 square meters. Each apartment includes two bedrooms, an open kitchen, a living room, a bathroom, a toilet, and a balcony. The floor plan zoning is depicted in Figure 1, with the building oriented to the south, where the living room and kitchen are on the north side and the bedrooms are on the south side. The land area is 250 square meters, with an occupancy area of 150 square meters. Exterior views of the building are shown in Figures 2A, 2B, and 2C.

Building Components

- Roof (Top Layer) Defined with 5 layers:

1. First layer: Bituminous waterproofing (a protective polymer layer based on bitumen and synthetic fibers) with a thickness of 3 mm.
2. Second layer: Cement plaster with a thickness of 2 cm.
3. Third layer: Concrete foam with a thickness of 20 cm.
4. Fourth layer: Reinforced concrete with a thickness of 20 cm.
5. Fifth layer: Gypsum and clay with a thickness of 2 cm.

- Interior Walls (3 layers):

1. First layer: Gypsum and clay with a thickness of 2 cm.
2. Second layer: Lightweight aerated concrete blocks with a thickness of 10 cm.
3. Third layer: Gypsum and clay with a thickness of 2 cm.

- Floor (Parking Level, 4 layers):

1. First layer: Granite stone with a thickness of 3 cm.
2. Second layer: Cement plaster with a thickness of 2 cm.
3. Third layer: Hand-compacted soil with a thickness of 20 cm.
4. Fourth layer: Reinforced concrete with a thickness of 1 meter.

- Intermediate Floors and Ceilings (5 layers):

1. First layer: Ceramic tiles with a thickness of 1 cm.
2. Second layer: Cement plaster with a thickness of 2 cm.
3. Third layer: Concrete foam with a thickness of 10 cm.
4. Fourth layer: Reinforced concrete with a thickness of 20 cm.
5. Fifth layer: Gypsum and clay with a thickness of 2 cm.

- Exterior Walls (5 layers):

1. First layer: Façade materials (variable).
2. Second layer: Insulation layer (if installed: 3 mm Bituminous waterproofing).
3. Third layer: wall construction materials (variable) with a thickness of 15 cm.
4. Fourth layer: Another insulation layer (variable) with a thickness of 1 cm.

5. Fifth layer: Gypsum and clay with a thickness of 2 cm.

- Windows (30% of wall area):
  - Double-glazed windows (2 layers of 3 mm clear glass with a 6 mm air gap).
  - UPVC frames without external shading, but with internal roller blinds made of aluminum.
- Natural Ventilation:
  - Each unit has two non-mechanical ventilation openings with roller blinds, circular in shape, and a diameter of 10 centimeters.
- Lighting:
  - All lighting is LED, and external façade lights have sensors, operating for 12 hours.
- Heating and Domestic Hot Water:
  - Gas-based heating and domestic hot water system (one unit per zone).
  - Cooling system: Water-cooled air conditioning with electricity consumption.
- Unit Zoning: Each unit is divided into the following zones:

1. Living room
2. Open kitchen
3. Two bedrooms
4. One toilet
5. One bathroom
6. One balcony connected to one of the bedrooms.

- Occupancy:
  - Each unit accommodates 4 people.
- Weather Data:
  - Weather data for the region was provided to the software via a file.

The building floor plan and zoning are shown in Figure No. 7, and the building façade is shown in Figure No. 8.

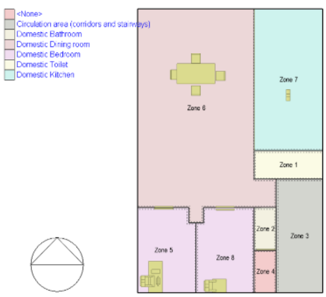

Figure 7. Building Plan and Zoning

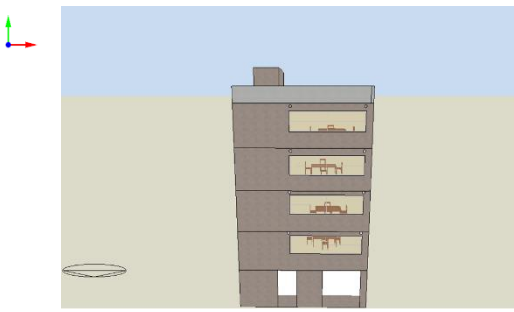

Figure 8. Northern Facade of the Building

The geographical location of this building is at 68.35° latitude and 32.51° longitude. The building's elevation above sea level is 1191 meters. The prevailing wind direction is from west to east, with an average speed of 11.9 meters per second. Weather simulation data from Tehran's Mehrabad Airport has been used for the analysis.

The heating system in each unit consists of wall-mounted gas heaters and radiators. Each unit has five radiators installed. The hot water supply for each unit also comes from the same system, while the cooling system relies on electricity.

Regarding the structural elements, they are categorized based on their controlled or uncontrolled exposure and various types, as shown in Figure 9.

In all cases, the interior wall finish is defined as a 2-centimeter-thick plaster layer. The thickness of all internal insulations is uniform and equal to 1 centimeter. A Bituminous waterproofing insulation layer with a thickness of 3 millimeters is considered. The cement facade has a thickness of 2 centimeters, the brick facade is 25 millimeters thick, and all stone facades have a thickness of 2 centimeters. The construction materials used for external walls have a thickness of 15 centimeters. For the execution of the brick facade and all stone facades, a 2-centimeter-thick mortar of cement and sand is applied. Prior to installing the Bituminous waterproofing insulation, a 2-centimeter-thick cement and sand mortar layer is also applied. An example of external wall layering is shown in Figure 10.

The source of all the figure numbers 7 to 10 is the output of the DesignBuilder software.

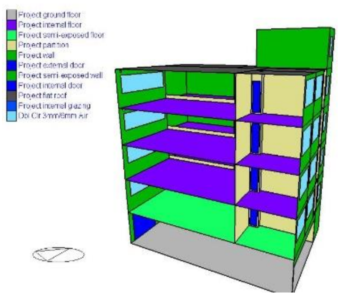

Figure 9. Building surfaces and Openings

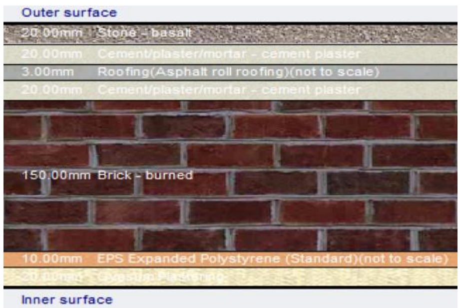

Figure 10. G-PS-B-I-BS Scenario

Findings

In each scenario, external walls are generally composed of three layers: the wall base, the interior facade, and the exterior facade. It's possible that an insulation layer has been applied before installing the facade on each side. Therefore, external walls can consist of a minimum of 3 layers and a maximum of 5 layers.

By combining these different layers, a total of 715 different configurations have been defined. These various states are specified with specific codes. The definitions of these codes are provided in Table No. 1.

Table 1. Encoding various scenarios for constructing external building walls

First inner layer		Internal insolation		Main wall material		External insolation		Building facade	
Gypsum	G	No Insulation	0	Cement Block	CB	No Insulation	0	Cement	C
		Cork	C	Brick	B	Bituminous waterproof	I	Brick Facade	B
		Coconut pith	CP	Calcium Silicate	CS			Basalt stone	BS
		Glass fiber	GF	Aerated Concrete	AC			Granite stone	GS
		Glass wool	GW	Autoclave d Aerated Concrete	AA C			limestone	LS
		plywood	PW					Marble stone	MS
		Polystyrene	PW					Tufa stone	TS
		Polyurethane foam	PU						
		Stone wool	SW						
		Rice husk	R						
		wool	W						

Outputs of the software used in this research are as follows:

- Embodied carbon is due to external walls per kilogram of carbon dioxide.
- The equivalent embodied carbon caused by external walls per kilogram of carbon dioxide in kilograms.
- Carbon emitted in kilograms for a one-year period.

You mentioned that examples of these software outputs are shown in Table 2. A and B.

Table 2.A. Embodied Carbon by Structural elements

Materials Embodied Carbon and Inventory	Area (m2)	Embodied Carbon (kg CO2)	Equivalent CO2 (kg CO2)	Mass (kg)
foam beton	912.3	0.0	0.0	26557.5
Organic materials/derivatives coconut pith insulation board at 50 °C	700.5	1857.6	1930.5	3642.4
Stone - granite	150.0	5054.4	5443.2	12960.0
Stone - basalt	700.5	403.5	403.5	40346.3
Soil - earth common	150.0	876.0	876.0	43800.0
Cement/plaster/mortar-cement plaster	2463.2	16474.0	16474.0	86705.1
Ceramic glazed	762.3	12387.4	13149.7	19057.5
Painted Oak	42.1	0.0	0.0	1031.4
Gypsum Plastering	2423.1	18415.3	19384.5	48461.3
Concrete Reinforced (with 2% steel)	1062.3	247350.2	263308.3	797904.0
AAC Block	1105.6	134519.4	138595.8	407634.7
Sub Total		437337.8	459565.4	1488100.0

Table 2.B. Annual carbon dioxide emissions

CO2 Production – 1 Year Period	
CO2 Emissions	25027.63 (kg)

After receiving the software outputs, we collect the necessary data in a table. With this table, the data can be sorted according to any desired parameters. Due to the large volume of information, only the first 15 scenarios and the last 15 scenarios are displayed.

- Sorting by electricity consumption: Scenarios with the lowest and highest electricity consumption over a one-year period for building operations are identified. Due to the large volume of information, only the first 15 scenarios and the last 15 scenarios are displayed in Table 3.
- Sorting by gas consumption: Scenarios with the lowest and highest gas consumption over a one-year period for building operations are determined. The first 15 scenarios and the last 15 scenarios are shown in Table 4.
- Sorting by Total Energy Consumption: Scenarios with the lowest and highest total energy consumption over a one-year period for building operations are revealed. Table 5 displays the first 15 scenarios and the last 15 scenarios.

Table 3. Sorting based on Electricity consumption

No	Scenario	Electricity	No	Scenario	Electricity	No	Scenario	Electricity
1	G-PS-AAC-I-TS	34166.41	2	G-PU-AAC-I-TS	34218.05	3	G-PU-AAC-0-TS	34231.02
4	G-PU-AAC-0-C	34241.5	5	G-PU-AAC-I-BS	34246.93	6	G-PU-AAC-I-GS	34246.93
7	G-FG-AAC-I-TS	34252.85	8	G-PU-AAC-I-LS	34254.63	9	G-PU-AAC-I-MS	34254.63
10	G-W-AAC-I-TS	34257.18	11	G-PU-AAC-0-LS	34259.99	12	G-PU-AAC-0-MS	34259.99
13	G-PU-AAC-0-BS	34262.41	14	G-PU-AAC-0-GS	34262.41	15	G-GW-AAC-I-TS	34266.77
701	G-CP-CS-0-B	38787.38	702	G-PW-B-0-B	38956.95	703	G-0-B-I-B	39067.29
704	G-PW-CS-I-B	39159.06	705	G-0-CS-0-LS	39394.42	706	G-0-CS-0-MS	39394.42
707	G-0-CS-0-BS	39412.05	708	G-0-CS-0-GS	39412.05	709	G-0-CS-0-C	39429.79
710	G-0-B-0-B	39679.8	711	G-PW-CS-0-B	39870.53	712	G-0-CS-I-B	39969.71
713	G-0-CS-0-B	40834.08	714	G-FG-CB-I-BS	48839.49	715	G-CP-AC-0-C	49443.78

Table 4. Sorting based on Gas consumption

No	Scenario	Gas	No	Scenario	Gas	No	Scenario	Gas
1	G-PS-AAC-I-TS	20738.47	2	G-PU-AAC-I-B	20744.49	3	G-PU-AAC-0-B	20843.87
4	G-FG-AAC-I-B	20870.23	5	G-GW-AAC-I-B	20914.94	6	G-PS-AAC-I-B	20913.15
7	G-C-AAC-I-B	20913.4	8	G-GW-AAC-I-B	20914.94	9	G-SW-AAC-I-B	20916.78
10	G-PU-AAC-I-TS	20954.8	11	G-FG-AAC-0-B	20979.5	12	G-W-AAC-0-B	21004.41
13	G-R-AAC-I-B	21008.36	14	G-C-AAC-0-B	21028.23	15	G-GW-AAC-0-B	21029.6
701	G-PW-CS-0-BS	33321.3	702	G-PW-CS-0-GS	33321.3	703	G-0-B-0-C	33504.94
704	G-PW-CS-0-C	33552.53	705	G-0-CS-I-LS	33669.32	706	G-0-CS-I-MS	33669.32

707	G-0-CS-I-BS	33708.35	708	G-0-CS-I-GS	33708.35	709	G-0-CS-0-TS	33817.31
710	G-CP-AC-0-C	34595.76	711	G-0-CS-0-LS	35753.88	712	G-0-CS-0-MS	35753.88
713	G-0-CS-0-BS	35811.04	714	G-0-CS-0-GS	35811.04	715	G-0-CS-0-C	36147.22

Table 5. Sorting based on Total Energy consumption

No	Scenario	Total	No	Scenario	Total	No	Scenario	Total
1	G-PS-AAC-I-TS	54904.88	2	G-PU-AAC-I-TS	55172.85	3	G-PU-AAC-0-TS	55295.36
4	G-PU-AAC-I-BS	55299.81	5	G-PU-AAC-I-GS	55299.81	6	G-PU-AAC-I-LS	55303.61
7	G-PU-AAC-I-MS	55303.61	8	G-FG-AAC-I-TS	55342.66	9	G-W-AAC-I-TS	55372.73
10	G-GW-AAC-I-TS	55408.97	11	G-SW-AAC-I-TS	55415.64	12	G-C-AAC-I-TS	55416.68
13	G-PU-AAC-0-C	55424.03	14	G-PU-AAC-0-LS	55425.49	15	G-PU-AAC-0-MS	55425.49
701	G-PW-CS-0-GS	71861.76	702	G-PW-CS-0-C	72101.84	703	G-0-CS-I-LS	72264.42
704	G-0-CS-I-MS	72264.42	705	G-0-CS-I-BS	72325.94	706	G-0-CS-I-GS	72325.94
707	G-0-CS-0-TS	72406.46	708	G-0-CS-0-B	73935.93	709	G-0-CS-0-LS	75148.3
710	G-0-CS-0-MS	75148.3	711	G-0-CS-0-BS	75223.09	712	G-0-CS-0-GS	75223.09
713	G-0-CS-0-C	75577.01	714	G-FG-CB-I-BS	80974.07	715	G-CP-AC-0-C	84039.54

Depending on the project context and requirements, if electricity consumption is the focus, refer to Table 3. If gas consumption is of interest, consult Table 4. For total energy consumption, Table 5 provides relevant data.

By sorting based on the amount of embedded carbon (measured in terms of carbon dioxide), scenarios for all exterior walls are determined. The 15 scenarios with the lowest and highest embedded carbon are shown in Table No. 6. Similarly, by sorting based on equivalent embedded carbon for all exterior walls, the 15 scenarios with the lowest and highest equivalent embedded carbon are displayed in Table No. 7.

Table 6. Sorting based on Embodied Carbon

rank	scenario	Embodied Carbon
1	G-0-CB-0-C	15051.40
2	G-GW-CB-0-C	15180.00
3	G-FG-CB-0-C	15251.40
4	G-C-CB-0-C	15264.30
5	G-SW-CB-0-C	15272.00
6	G-PS-CB-0-C	15314.10
7	G-R-CB-0-C	15345.60
8	G-0-CB-0-TS	15415.60
9	G-0-CB-0-BS	15454.90
10	G-GW-CB-0-TS	15544.20
11	G-GW-CB-0-BS	15583.50
12	G-FG-CB-0-TS	15615.60
13	G-C-CB-0-TS	15628.60
14	G-SW-CB-0-TS	15636.30
15	G-FG-CB-0-BS	15654.90
701	G-PU-AAC-0-GS	123456.80
702	G-W-AAC-0-GS	123856.00
703	G-CP-AAC-0-GS	124684.00
704	G-PW-AAC-0-GS	126003.60
705	G-0-AAC-I-GS	127511.00
706	G-GW-AAC-I-GS	127639.60
707	G-FG-AAC-I-GS	127711.00
708	G-C-AAC-I-GS	127724.00
709	G-SW-AAC-I-GS	127731.70
710	G-PS-AAC-I-GS	127773.70
711	G-R-AAC-I-GS	127805.20
712	G-PU-AAC-I-GS	128141.40
713	G-W-AAC-I-GS	128540.70
714	G-CP-AAC-I-GS	129368.60
715	G-PW-AAC-I-GS	130688.30

Table 7. Sorting based on Equivalent Embodied Carbon

rank	scenario	Equivalent Embodied Carbon
1	G-0-CB-0-C	15331.60
2	G-GW-CB-0-C	15472.80
3	G-FG-CB-0-C	15531.60
4	G-C-CB-0-C	15544.50
5	G-SW-CB-0-C	15566.90
6	G-R-CB-0-C	15642.60
7	G-PS-CB-0-C	15674.10
8	G-0-CB-0-TS	15695.80
9	G-FG-CB-0-TS	15895.80
10	G-0-CB-0-BS	15735.00
11	G-GW-CB-0-TS	15837.00
12	G-GW-CB-0-BS	15876.30
13	G-C-CB-0-TS	15908.80
14	G-SW-CB-0-TS	15931.20
15	G-FG-CB-0-BS	15935.00
701	G-PU-AAC-0-GS	127889.30
702	G-W-AAC-0-GS	128357.20
703	G-CP-AAC-0-GS	129189.30
704	G-PW-AAC-0-GS	130553.80
705	G-0-AAC-I-GS	131943.50
706	G-GW-AAC-I-GS	132084.70
707	G-FG-AAC-I-GS	132143.50
708	G-C-AAC-I-GS	132156.40
709	G-SW-AAC-I-GS	132178.90
710	G-R-AAC-I-GS	132254.50
711	G-PS-AAC-I-GS	132286.00
712	G-PU-AAC-I-GS	132573.90
713	G-W-AAC-I-GS	133041.80
714	G-CP-AAC-I-GS	133874.00
715	G-PW-AAC-I-GS	135238.40

By sorting based on carbon emissions during the operational phase, scenarios with the least and greatest carbon emissions are identified. The 15 scenarios with the lowest and the 15 scenarios with the highest carbon emissions are shown in Table 8.

Table 8. Sorting based on one-year Carbon emissions

Rank	scenario	Carbon Emissions
1	G-R-AAC-I-MS	21358.76
2	G-PU-CB-I-BS	22570.42
3	G-PS-AAC-I-TS	24594.53
4	G-PU-AAC-I-TS	24666.40
5	G-PU-AAC-0-TS	24694.80
6	G-PU-AAC-I-BS	24702.30
7	G-PU-AAC-I-GS	24702.30
8	G-PU-AAC-I-LS	24706.23
9	G-PU-AAC-I-MS	24706.23
10	G-FG-AAC-I-TS	24712.81
11	G-W-AAC-I-TS	24720.27
12	G-PU-AAC-0-C	24723.33
13	G-GW-AAC-I-TS	24731.07
14	G-PU-AAC-0-LS	24731.33
15	G-PU-AAC-0-MS	24731.33
701	G-0-CS-I-MS	29703.63
702	G-0-CS-I-BS	29724.58
703	G-0-CS-I-GS	29724.58
704	G-0-CS-0-TS	29727.78
705	G-0-B-0-B	29870.13
706	G-PW-CS-0-B	29990.20
707	G-0-CS-I-B	30111.95
708	G-0-CS-0-LS	30578.99
709	G-0-CS-0-MS	30578.99
710	G-0-CS-0-BS	30600.39
711	G-0-CS-0-GS	30600.39
712	G-0-CS-0-C	30674.20
713	G-0-CS-0-B	30954.01
714	G-FG-CB-I-BS	35623.86
715	G-CP-AC-0-C	36451.68

To obtain the optimal scenario, we first need to calculate the payback period for each scenario. The payback period represents the time each scenario requires to offset the additional embodied carbon compared to the scenario with the least embodied carbon.

To calculate the payback period, follow these steps:

1. Determine the increase in embodied carbon for each scenario relative to the reference scenario (G-0-CB-0-C, as shown in Table No. 6).
2. Next, identify the reduction in carbon emissions compared to the G-0-CB-0-C scenario.
3. Divide these two values to find the time needed to offset the additional embodied carbon per year for each scenario.

Negative values indicate that the scenario, despite adding embodied carbon, still has lower operational carbon emissions than the reference scenario. Positive values indicate that the scenario has higher operational carbon emissions, even after accounting for the added embodied carbon. After this analysis, eliminate scenarios with positive payback periods. You'll be left with 372 scenarios. Given that the average lifespan of buildings in Tehran is 30 years, remove scenarios with payback periods exceeding 30 years.

Not necessarily will the scenario with the shortest payback period will be the better scenario. This is because a scenario with a shorter payback period may have a higher carbon emissions rate over a specific time period. Therefore, we now sort the remaining scenarios based on their carbon emissions. The scenario with the fewest carbon emissions is the optimal scenario. You can find the top 15 scenarios in Table 9.

Table 9. Sorting Scenarios with a Payback period of less than 30 years

Rank	Scenario	Embodied Carbon	Carbon Emissions	Payback Period
1	G-R-AAC-I-MS	116307.90	21358.76	-6.04
2	G-PU-CB-I-BS	20769.90	22570.42	-1.70
3	G-PS-CB-I-TS	20625.60	25004.53	-6.04
4	G-PU-CB-I-TS	20730.70	25156.32	-7.36
5	G-PU-CB-0-TS	16046.00	25209.09	-1.38
6	G-PU-CB-I-MS	24604.20	25227.42	-13.64
7	G-PU-CB-I-LS	21137.00	25227.42	-8.69
8	G-FG-CB-I-TS	20300.30	25260.67	-7.87
9	G-PU-CB-0-C	15681.80	25261.83	-0.95
10	G-W-CB-I-TS	21130.00	25273.76	-9.30
11	G-PU-CB-0-MS	19919.60	25280.22	-7.52
12	G-PU-CB-0-LS	16452.30	25280.22	-2.16
13	G-PU-CB-0-GS	31416.90	25285.14	-25.47
14	G-PU-CB-0-BS	16085.30	25285.14	-1.61
15	G-C-CB-I-TS	20313.20	25294.55	-8.31

Discussion

By comparing these three tables (Tables No. 3, 4, and 5), it can be seen that although the G-PS-AAC-I-TS scenario has the lowest consumption and the highest energy savings in all three scenarios, but necessarily the energy consumption rating for gas and electricity consumption, or the total in different scenarios, is not the same.

For example, the G-PU-AAC-I-TS scenario ranks second in terms of electricity consumption and overall energy usage, but it ranks tenth in terms of gas consumption.

The most energy-efficient scenario across electricity, gas, and total energy consumption is G-CP-AC-0-C. However, in terms of gas consumption, the highest-consuming scenario is G-0-CS-0-C.

By comparing tables 6 and 7, it can be seen that, in carbon sequestration, the order and position of certain scenarios change compared to non-sequestered carbon sorting. For example, in carbon sequestration, scenario G-PS-CB-0-C has a lower rank than scenario G-R-CB-0-C. However, in the equivalent non-sequestered carbon sorting, this relationship is reversed. This indicates that the carbon dioxide emissions during the production of materials in scenario G-PS-CB-0-C are lower than in scenario G-R-CB-0-C, but the emissions of other greenhouse gases (such as methane, sulfur dioxide, nitrous oxide, hydrofluorocarbons, sulfur hexafluoride, and perfluorocarbons) apart from carbon dioxide are higher in scenario G-PS-CB-0-C compared to scenario G-R-CB-0-C. Mineral sequestration is another method where carbon dioxide is removed from the atmosphere and can be stored in the Earth's crust by injecting it underground or in the form of insoluble carbonate salts, ensuring long-term sequestration. To enhance carbon sequestration in oceans, various technologies have been proposed, including seaweed farming, ocean fertilization, artificial upwelling, basalt storage, mineralization, deep-sea sediments, and adding bases to neutralize acids. However, large-scale application of these methods has not been achieved yet.

Conclusion

By comparing tables No. 3, 4, and 5, it can be seen that:

1. In all 15 scenarios, using AAC (Autoclaved Aerated Concrete) blocks for the basic wall materials results in the lowest energy consumption for both electricity and gas.

2. Among the scenarios with the highest energy consumption, calcium silicate bricks play the most significant role as the basic wall material. This suggests that calcium silicate bricks are not an optimal choice for energy reduction.

3. The foam polyurethane insulation layer has the greatest impact on reducing electricity, gas, and overall energy consumption in the top 15 scenarios.

4. For gas consumption reduction, brick veneer (brick cladding) shows the most influence.

5. Walls without internal insulation have the highest impact on electricity, gas, and overall energy consumption in the top 15 scenarios, emphasizing the importance of using internal insulation layers.

6. After uninsulated walls, Plywood insulation has the most negative effect on reducing electricity, gas, and overall energy consumption in the highest-consuming scenarios, indicating that plywood insulation plays a minor role in energy reduction.

By comparing tables No. 6 and 7, it can be seen that:

7. In all 15 scenarios with the lowest amount of embodied carbon and equivalent embodied carbon, the basic materials of the wall are cement blocks, and the wall has no insulation layer on the outside.

8. Also, the top 7 scenarios with the lowest amount of embodied carbon and equivalent Embodied carbon have a cement facade, and the other 8 scenarios have a facade with tufa stone or basalt stone.

9. In all 15 scenarios with the highest amount of embodied carbon and equivalent embodied carbon from Granite stone has been used in facades.

10. In all 15 scenarios with the highest amount of Embodied carbon and embodied carbon equivalent, the basic wall materials are AAC blocks.

By checking table number 8, it can be seen that:

11. In the top 15 scenarios with the lowest amount of carbon emission, except for one case, in 14 scenarios, the basic wall material is AAC block.

12. In the top 15 scenarios with the lowest amount of carbon emission, the internal insulation layer of polyurethane foam has had the greatest effect.

13. In 15 scenarios with the highest amount of carbon emission, the most basic material of the wall was calcium silicate brick.

By checking table number 9, it can be seen that:

14. In all the top 15 scenarios with the lowest number of emissions among the scenarios with a return period of less than 30 years, except for one case, the basic material of the wall is cement block.

15. The polyurethane insulation layer had the most impact among the top 15 scenarios.

Suggestions for future research

Based on the new insights and questions that emerged during and after this research, the following topics are recommended for esteemed researchers in their future studies:

1. Investigating the impact of the thickness of various layers in the building's external shell on energy consumption and carbon emissions.
2. Examining the influence of different regional climates on the studied sample and the optimal scenario.
3. Assessing the effect of facade colors on energy consumption and carbon emissions.
4. Analyzing the economic feasibility of implementing the top scenarios and the payback period.

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