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Article

Evaluation of opaque and transparent facade component options for energy efficiency and carbon emissions in office buildings

Ebru ÜNVER KARAER*, Gül KOÇLAR ORAL

Department of Architecture, İstanbul Technical University Faculty of Architecture, İstanbul, Türkiye

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ABSTRACT

Energy-efficient buildings can be defined as buildings that use energy in the most efficient way throughout their life cycle. In this context, the building envelope is the most important component in separating the indoor and outdoor environments in terms of energy efficiency at the building scale. The properties of the building envelope can significantly improve the energy performance of buildings by reducing energy consumption and, therefore, operational carbon emissions. In addition, the building envelope has a significant impact on the embodied carbon emissions of a building. Consequently, the negative environmental impact of buildings can be reduced, and economic benefits can be achieved by reducing operating costs. The building envelope, especially in office buildings that are used for the entire day and contain spaces that require comfort due to the activities performed, should be carefully considered during the architectural design phase. It is obvious that designing building envelopes according to the space type, the activities to be carried out in the space, and the characteristics of the occupants will help to reduce artificial energy consumption, as well as operational and embodied carbon emissions. In this context, a study was carried out with Building Information Modelling (BIM) to determine the optimum building envelope options, combining both opaque and transparent components, that can provide thermal comfort to occupants while minimizing artificial energy consumption, as well as operational and embodied carbon emissions, in new office buildings. This study presents the results of calculations of energy consumption, operational and embodied carbon emissions for new office buildings in Erzurum, Türkiye, and provides recommendations to guide energy-efficient facade design at the architectural project phase.

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INTRODUCTION

Greenhouse gas emissions resulting from human activities such as energy use, land use, and increased resource consumption have become one of the most important environmental and social issues of our time, leading to global warming and climate change. Ensuring energy efficiency and reducing global greenhouse gas emissions play a critical role in preventing climate change and mitigating its consequences (IPCC, 2023). Decreasing greenhouse gas emissions has potential positive effects, such as improving human health, minimizing environmental impacts, and

***Corresponding author**
*E-mail adres: ebru@iltay.com.tr

mitigating the effects of climate change. The United Nations Paris Agreement, adopted in 2015 and entered into force in 2016, commits all countries worldwide to reduce their greenhouse gas emissions (United Nations, 2015; T.C. İklim Değişikliği Başkanlığı, 2021).

In 2019, European Union countries agreed to reduce net greenhouse gas emissions by 55% compared to 1990 levels by 2030 and to make the European continent carbon neutral by 2050, in accordance with the European Green Deal. In 2023, the Energy Efficiency Directive, which targets an 11.7% reduction in final energy consumption by 2030 compared to 2020 levels (European Commission, 2023; T.C. Dışişleri Bakanlığı, 2023), and in 2024 the revised Energy Performance of Buildings Directive were published. The 2024 Directive aims to ensure that all new buildings will be built to zero-emissions standards. This target has been set for January 2028 for public buildings and January 2030 for all other new buildings in Europe (European Commission, 2024).

In parallel with the above-mentioned global efforts, Türkiye prepared its Nationally Determined Contribution (NDC) in 2021, ratified the Paris Agreement, declared its net zero emission target as 2053, and published its Green Deal Action Plan (T.C. Resmi Gazete, 2021). In 2023, Türkiye announced the Updated First Nationally Determined Contribution. In the new NDC, a sectoral approach (energy, industry, buildings, transport, waste, agriculture, etc.) was developed to assess the emission reduction potential, and mitigation measures to be implemented by 2030 were outlined. With the Energy Efficiency Strategy 2030 and the National Energy Efficiency Action Plan II (2024–2030), Türkiye aims to reduce greenhouse gas emissions by 41% by 2030 compared to 2012 and to achieve net zero emissions by 2053 (T.C. İklim Değişikliği Başkanlığı, 2022; T.C. İklim Değişikliği Başkanlığı, 2023).

The above-mentioned national and international targets will provide significant benefits in terms of protecting the natural environment, ensuring the efficiency of resources such as energy, water, and materials, reducing carbon emissions, combating climate change, and promoting a sustainable circular economy. In order to achieve these goals, the work carried out in the construction sector and in the urban built environment is of great importance.

The built environment and buildings consume energy and natural resources throughout their life cycle, causing carbon emissions and contributing to global warming and climate change. According to the report published by the United Nations Environment Programme (UNEP) in 2024:

- Buildings are responsible for 34% of the world's total artificial energy consumption and about 37% of energy-related carbon emissions.
- Carbon emissions from the construction and operation of buildings reached nearly 10 gigatons, the highest level ever.
- • The operational energy consumption, such as heating, cooling, lighting, etc., accounts for about 30% of the final energy demand. When the energy used in the production of building materials is included, this ratio increases to 34% (UNEP, 2024).

The information in the report reveals once again that buildings should be designed to minimize artificial energy use and carbon emissions.

Buildings that use the energy required for their life cycle in the most efficient way and have low carbon emissions are defined by terms such as Energy Efficient, Nearly Zero Energy, and Zero Emission Building. Carbon emissions of buildings are expressed in two forms: Embodied Carbon and Operational Carbon. The term Embodied Energy/Embodied Carbon refers to the energy consumed and carbon emitted throughout the lifecycle of a building, starting from the extraction of raw materials to the transportation and production of building materials, delivery to the construction site, construction activities, maintenance and repair, demolition, and finally, the disposal of waste at the end of the building's lifetime. Operational Energy/Operational Carbon is defined as the energy consumption required for the operation of equipment and systems, including but not limited to heating, cooling, lighting, computers, etc., and the carbon generated by this consumption.

Building Information Modeling (BIM) has been defined in various ways, such as a numerical representation of the physical and functional characteristics of a building, a source of information where all of its characteristics are shared, and a collaborative environment where information about the building is brought together during the design, construction, occupancy, and maintenance phases (Türkyılmaz, 2016). In addition to its role in design and visualization, BIM has begun to take place in the building production process due to its features such as performance analysis, design, preparation of construction documents, and providing data on time and cost. In the building design phase, BIM plays an important role in sustainability decisions (İlhan & Yaman, 2015). In this context, it is possible to make preliminary design decisions, such as the building form, the building materials, and the window-to-wall ratio, before construction and evaluate them during the design phase. The assessment process and evaluations can be utilized to achieve optimum results in the context of energy usage and carbon emissions associated with the building.

It is a known fact that the building envelope is one of the most important elements separating the indoor and outdoor environments in terms of energy efficiency at the building scale. The main parameters that define the building envelope in terms of energy efficiency can be listed as the thermophysical and optical properties of the

Table 1. Building Envelope Component Properties.

Component	Materials	Density (kg/m³)	Thickness (m)	Thermal Conductivity (W/m.K)	Density (kg/m³)	Thickness (m)	Thermal Conductivity (W/m.K)
Soil Contact Floor (F-ext)	PVC floor covering	1500	0,005	0,230	1500	0,005	0,230
	Cement dosed screed	2000	0,020	1,400	2000	0,020	1,400
	Reinforced concrete slab	2400	0,400	2,500	2400	0,400	2,500
	Protective concrete	2000	0,050	1,400	2000	0,050	1,400
	Thermal insulation - (XPS)	30	0,082	0,035	30	0,115	0,035
	Light concrete		0,050	1,100		0,050	1,100
		Soil Contact Floor-1 (F-ext-1) U Value		**U F-ext-1: 0,36 W/m²K**	**Soil Contact Floor-2 (F-ext-2) U Value**		**U F-ext-2: 0,27 W/m²K**
Interior Floor (F-int)	PVC floor covering	1.500	0,005	0,230			
	Cement dosed screed	2.000	0,030	1,400			
	Reinforced concrete slab	2.400	0,250	2,500			
	Gypsum plaster	1.200	0,020	0,510			
		Interior Floor (F-int) U Value		**U F-int: 0,36 W/m²K**			
Roof (R)	Mosaic		0,010	3,500		0,010	3,500
	Protective concrete	2000	0,030	1,400	2000	0,030	1,400
	Thermal insulation - (XPS)	30	0,155	0,035	30	0,210	0,035
	Levelling concrete	2000	0,030	1,400	2000	0,030	1,400
	Reinforced concrete slab	2400	0,250	2,500	2400	0,250	2,500
	Gypsum plaster	1200	0,020	0,510	1200	0,020	0,510
		Roof 1 (R1) U Value		**U R1: 0,21 W/m²K**	**Roof 2 (R2) U Value**		**U R2: 0,16 W/m²K**
Exterior Wall (Wa-Ext-1) Type 1	Gypsum Plaster	1.200	0,020	0,510	1.200	0,020	0,510
	Brick	550	0,135	0,190	550	0,135	0,190
	Thermal insulation - Rock Wool	120	0,064	0,035	120	0,097	0,035
	Inorganic based external plaster	900	0,008	0,350	900	0,008	0,350
		Ext. Wall (Wa-Ext-1A) U Value		**U Wa-Ext-1A: 0,36 W/m²K**	**Ext. Wall (Wa-Ext-1B) U Value**		**U Wa-Ext-1B: 0,27 W/m²K**
Exterior Wall (Wa-Ext-2) Type 2	Gypsum Plaster	1.200	0,020	0,510	1.200	0,020	0,510
	Aerated Concrete	550	0,135	0,180	550	0,135	0,180
	Thermal insulation - Rock Wool	120	0,063	0,035	120	0,095	0,035
	Inorganic based external plaster	900	0,008	0,350	900	0,008	0,350
		Ext. Wall (Wa-Ext-2A) U Value		**U Wa-Ext-2A: 0,36 W/m²K**	**Ext. Wall (Wa-Ext-2B) U Value**		**U Wa-Ext-2B: 0,27 W/m²K**
Interior Wall (Wa-Int-1) Type 1	Gypsum Plaster	1200	0,010	0,510			
	Gypsum cardboard plate	800	0,013	0,250			
	Thermal insulation - Rock Wool	120	0,080	0,035			
	Gypsum cardboard plate	800	0,013	0,250			
	Gypsum plaster	1200	0,010	0,510			
		Int. Wall (Wa-Int-1) U Value		**Wa-Int-1: 0,37 W/m²K**			
Interior Wall (Wa-Int-2) Type 2	Gypsum plaster	1.200	0,020	0,510			
	Reinforced concrete slab	2.400	0,300	2,500			
	Gypsum plaster	1.200	0,020	0,510			
		Int. Wall (Wa-Int-2) U Value		**Wa-Int-2: 2,18 W/m²K**			

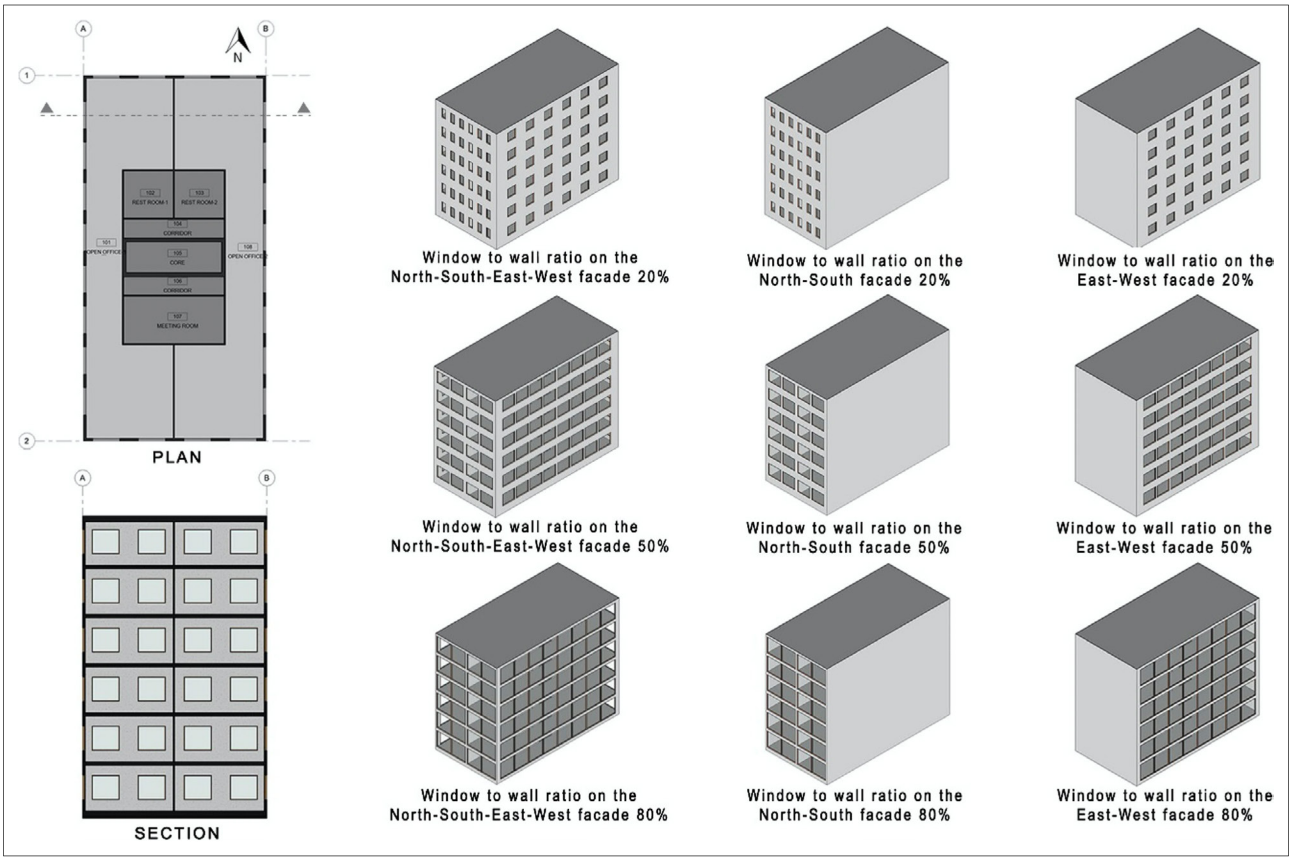

Figure 1. Plan, section and perspectives for different window-to-wall ratio of office buildings with building form factor 1/2 (Vertical Rectangle; 15mx30m).

building envelope. The selection of appropriate values for the parameters during the architectural design phase has a significant impact on the reduction of artificial energy consumption. As a consequence, there is an opportunity to achieve a decrease in heating and cooling costs, as well as a reduction in carbon emissions.

Nowadays, a wide range of users aged 25-65 spend a significant part of their day in office buildings. For this reason, the studies should be carried out during the architectural design phase of office buildings to properly determine the characteristics of the building envelope, with the aim of reducing artificial energy consumption and carbon emissions, while considering local climatic conditions.

In order to contribute to the aforementioned studies, a study was initiated to determine the optimum building envelope options that can provide climatic comfort for the indoor users, minimize building energy consumption, and reduce carbon emissions in office buildings. In the study, calculations were performed for different window-to-wall ratios, opaque and transparent building envelope components, and form factors for new office buildings to be constructed in Erzurum.

The calculations were performed using Building Information Modeling (BIM). The optimum building envelope combinations were determined from the options in the context of energy consumption, operational, and embodied carbon emissions of the building. The scope of the paper is to present and evaluate the results of the annual heating-cooling energy consumption, operational carbon, and embodied carbon values of new office buildings in Erzurum.

METHODOLOGY

The aim of this study is to contribute to the energy-efficient facade design of new office buildings in Erzurum, Türkiye. In this regard, a series of alternative building envelope options were developed, and the optimum alternatives were identified as those that can minimize their annual heating and cooling energy consumption, as well as operational and embodied carbon values. The steps regarding the methodology of the study are outlined below:

- Determining the main design decisions regarding design parameters such as building orientation, building form (form factor), and opaque and transparent components of the building envelope.
- Selecting the thermophysical and optical properties

Table 2. Window proprieties

Window (W)	Total Heat Transfer Coefficient (U Value; W/m²K)	W 1, UW: 1.8 (Double Glazing 1)
		W 2, UW: 1.4 (Double Glazing 2)
Glass (G)	Low-Emission (Low-E) Glass Combination	G 1: 6mm-12mm (Air)-6mm
		G 2: 6mm-16mm (Air)-6mm
	Total Heat Transfer Coefficient (U Value; W/m²K)	G 1, UG: 1.6
		G 2, UG: 1.3
	Solar Heat Gain Coefficient (SHGC; %)	G 1, SHGC: % 53
		G 2, SHGC: % 53

Table 3. Scenarios developed for form factors

Scenario No			Window-to-Wall ratio – WWR (%)	Window U Value (W/m²K)	Soil Contact Flooring U Value (W/m²K)	Roof U Value (W/m²K)	Ext. Wall (Wa-Ext) Type	Ext. Wall U Value (W/m²K)
NSEW-01	NS-01	EW-01	20%	1,80	0,36	0,21	Wa-Ext-1A	0,36
NSEW-02	NS-02	EW-02	50%	1,80	0,36	0,21	Wa-Ext-1A	0,36
NSEW-03	NS-03	EW-03	80%	1,80	0,36	0,21	Wa-Ext-1A	0,36
NSEW-04	NS-04	EW-04	20%	1,40	0,36	0,21	Wa-Ext-1A	0,36
NSEW-05	NS-05	EW-05	50%	1,40	0,36	0,21	Wa-Ext-1A	0,36
NSEW-06	NS-06	EW-06	80%	1,40	0,36	0,21	Wa-Ext-1A	0,36
NSEW-07	NS-07	EW-07	20%	1,40	0,27	0,16	Wa-Ext-1B	0,27
NSEW-08	NS-08	EW-08	50%	1,40	0,27	0,16	Wa-Ext-1B	0,27
NSEW-09	NS-09	EW-09	80%	1,40	0,27	0,16	Wa-Ext-1B	0,27
NSEW-10	NS-10	EW-10	20%	1,80	0,36	0,21	Wa-Ext-2A	0,36
NSEW-11	NS-11	EW-11	50%	1,80	0,36	0,21	Wa-Ext-2A	0,36
NSEW-12	NS-12	EW-12	80%	1,80	0,36	0,21	Wa-Ext-2A	0,36
NSEW-13	NS-13	EW-13	20%	1,40	0,36	0,21	Wa-Ext-2A	0,36
NSEW-14	NS-14	EW-14	50%	1,40	0,36	0,21	Wa-Ext-2A	0,36
NSEW-15	NS-15	EW-15	80%	1,40	0,36	0,21	Wa-Ext-2A	0,36
NSEW-16	NS-16	EW-16	20%	1,40	0,27	0,16	Wa-Ext-2B	0,27
NSEW-17	NS-17	EW-17	50%	1,40	0,27	0,16	Wa-Ext-2B	0,27
NSEW-18	NS-18	EW-18	80%	1,40	0,27	0,16	Wa-Ext-2B	0,27

of building envelope components determined in accordance with the main design decisions.

- Calculating the annual heating and cooling energy consumption, as well as, the annual operational and embodied carbon values of the office building based on the assumptions of the study in line with the determinations, limitations, and definitions made.
- Analyzing the calculations and determining the scenarios/options in which the opaque and transparent components of the building envelope have optimum performance according to the results.

According to TS EN 825, Erzurum city, which is located in the 5th degree-day region (cold climate zone), is considered in the study (Türk Standartları Enstitüsü (TSE), 2013). Based on data from the Turkish Statistical Institute (TÜİK), it is assumed that office buildings are 24 m high, have six floors (ground and five normal floors), are located in a detached layout, and have no external obstructions (Turkish Statistical Institute (TÜİK), 2024). For buildings with the same office floor area of 450 m² and total construction area (2700 m²), three building form factors were considered as form factors defining the building form: 1/2 Vertical Rectangle (15 m x 30 m), 2/1 Horizontal Rectangle (30 m x 15 m), and 1/1 Square (21.215 m x 21.215 m).

The calculations were made for cases where the windows are located on four (North, South, East, West) and two (North-South, East-West) facades of the building in a detached layout. In the study, three window-to-wall ratios (WWR; 20%, 50%, 80%) were determined, and 9 different typologies

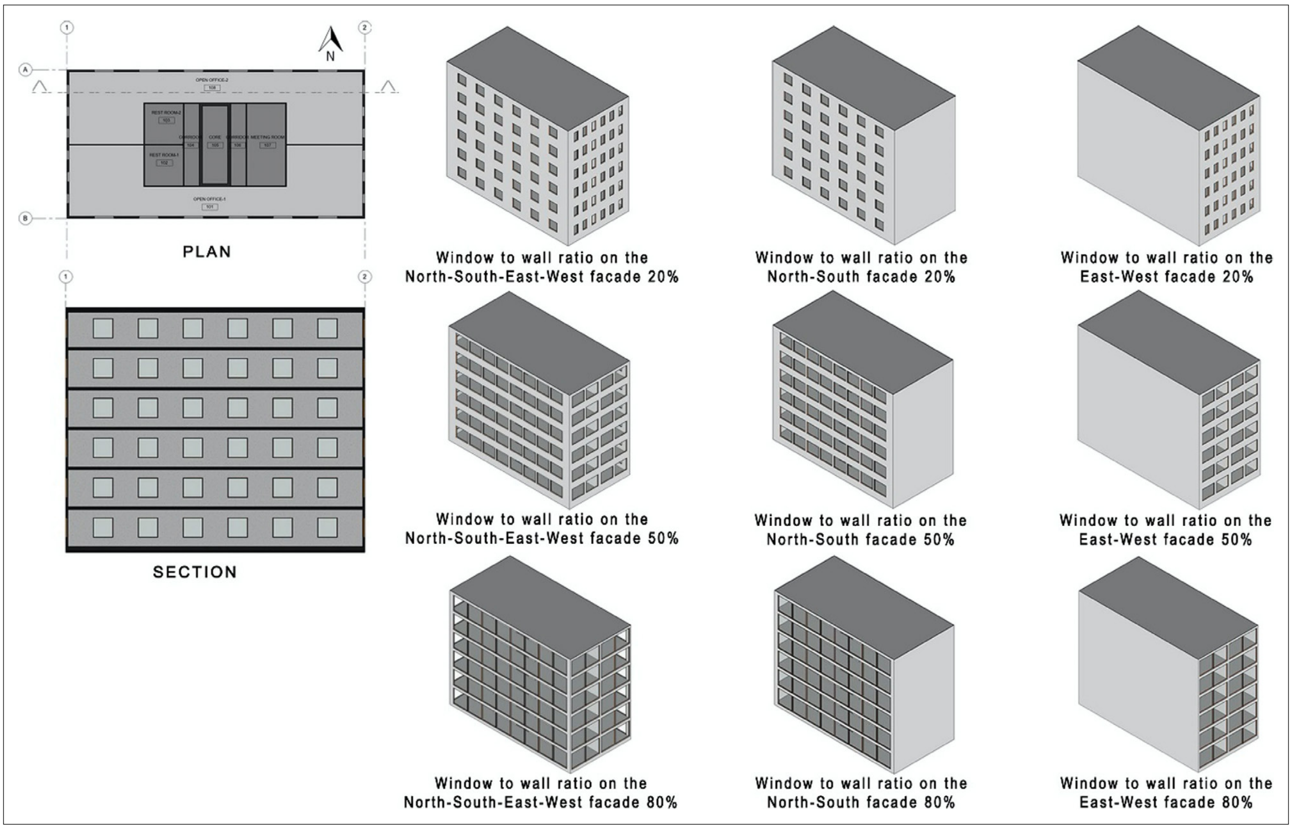

Figure 2. Plan, section and perspectives for different window-to-wall ratio of office buildings with building form factor 2/1 (Horizontal Rectangle; 30mx15m).

were created for each building form factor, considering the window directions. It is assumed that two opaque (brick, aerated concrete) and two transparent (double glazing with low emissivity coating, PVC joinery) materials are used for the vertical building envelope of the office building without solar control elements. The properties of the building envelope components and windows of these buildings are shown in Tables 1 and 2. Plans, sections, and perspectives of the office buildings in the study showing different window-to-wall ratios are given in Figures 1, 2, and 3.

The calculations were performed with Autodesk Revit 2025 v2 Building Information Modeling (BIM) and Autodesk Insight-Tech software. The general features of the calculations are listed below:

- The total heat transmission coefficients (U-Value) of the building envelope materials were selected in accordance with the TSE 825 Thermal Insulation Rules for Buildings standard.
- The annual building energy analysis was carried out with the simulation program EnergyPlus in line with the assumptions regarding the heating and cooling energy usage status and building characteristics. ASHRAE 90.1-2010 and ASHRAE 62.1 standards were used for the assumptions in the study.
- ASHRAE 90.1-2022 standard was used for the Lighting Power Density (LPD) values used by artificial lighting. For example, 6.02 W/m^2 was taken in the open office space.
- The amount of operational carbon emissions resulting from the building's energy consumption for heating, cooling, and artificial lighting during operation was calculated. This calculation was done by multiplying the CO_2 conversion coefficients (0.418 for electrical energy and 0.234 for natural gas) for fuel types in Türkiye by the data obtained from the analytical energy modeling (ETKB, 2019).
- The embodied carbon emission amounts of building construction materials were calculated using the "Autodesk Insight - Tech" program. In this program, the global warming potential of building materials during the production phase (raw material extraction-A1, transportation-A2, and production-A3 phases) was taken into account, and the database of the “Embodied Carbon in Construction Calculator (EC3)” program was used for carbon coefficients in the study.

A total of 162 scenarios were developed for the three form factors, with 54 scenarios for each form factor. Subsequently, calculations were conducted. Table 3

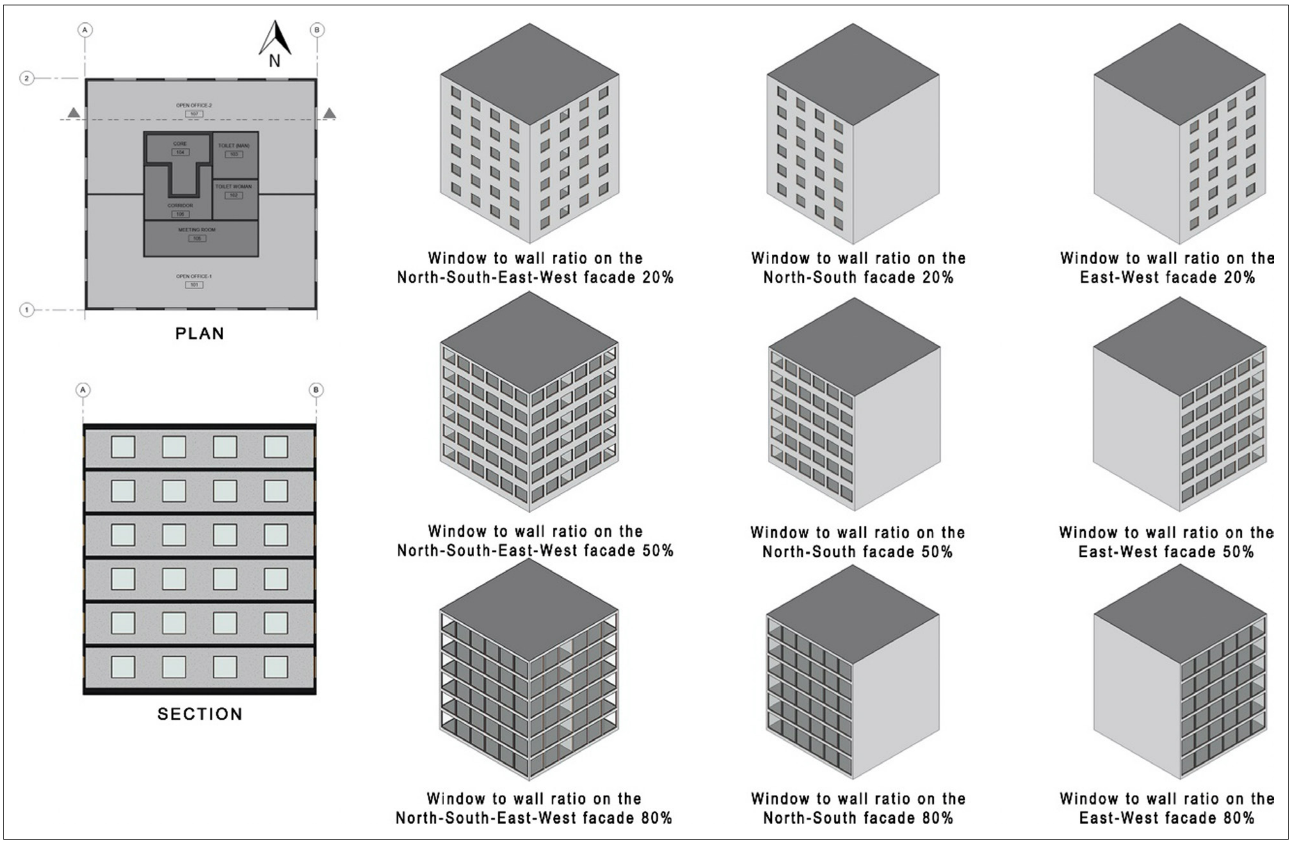

Figure 3. Plan, section and perspectives for different window-to-wall ratio of office buildings with building form factor 1/1 (Square; 21,215mx21,215m).

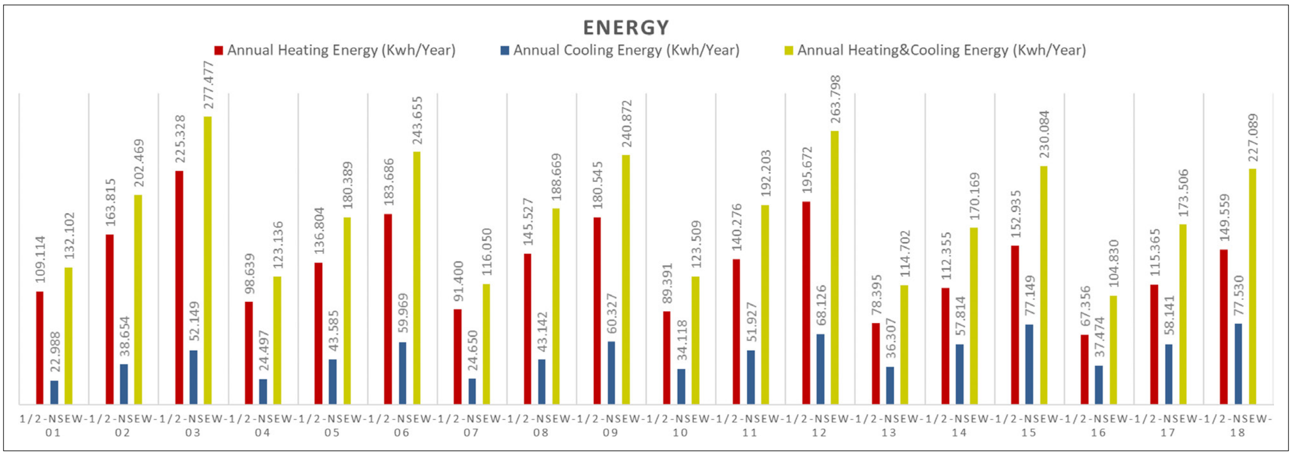

Figure 4. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 1/2 vertical rectangle and windows on four facades (North, South, East, West).

presents the codes of the scenarios considered for each form factor. The first three columns indicate the window orientation and scenario number. For example, NSEW-01 denotes a scenario encompassing four directions (North, South, East, and West), while NS-01 and EW-01 indicate scenarios with two directions (North, South and East, West), respectively. In total, 54 scenarios were obtained for each form factor.

FINDINGS

In line with the assumptions made in Chapter 2 and the scenarios created for the new office buildings to be built in Erzurum, Autodesk Revit 2025 v2 Building Information Modeling (BIM) and Autodesk Insight - Tech software were used to calculate the annual heating, cooling, interior lighting, and energy consumption of

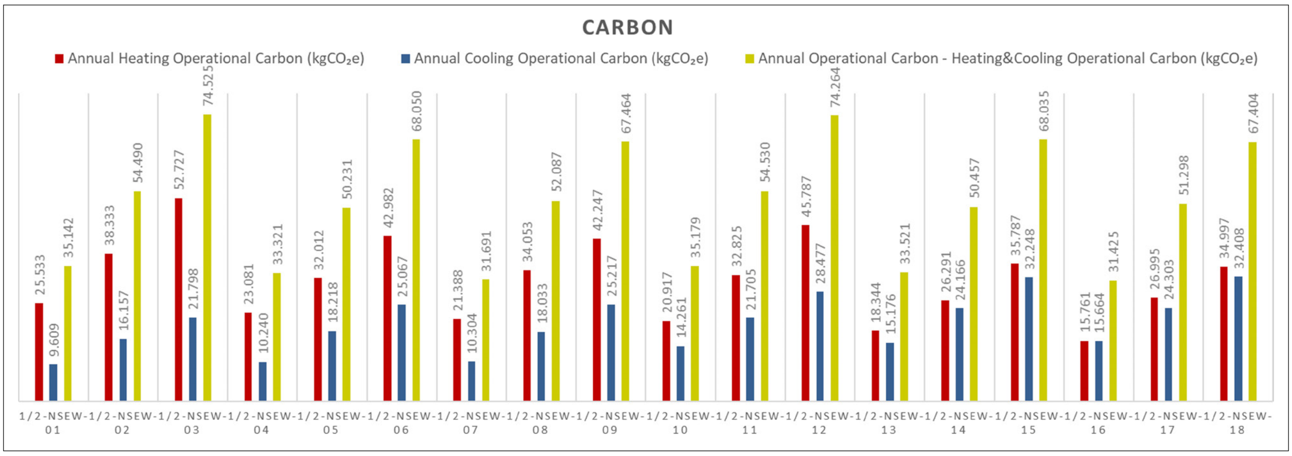

Figure 5. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 1/2 vertical rectangle and windows on four facades (North, South, East, West).

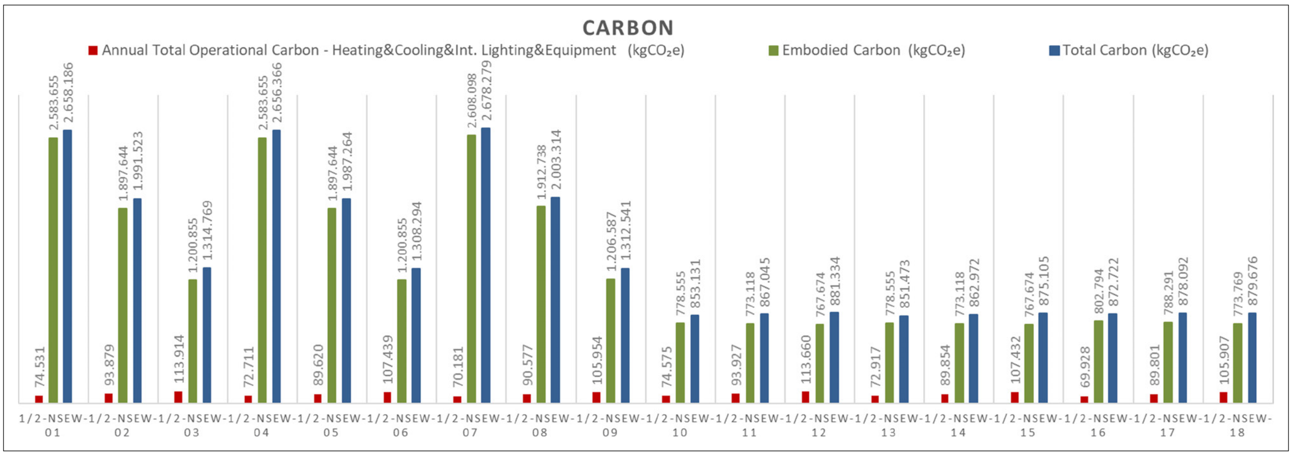

Figure 6. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 1/2 vertical rectangle and windows on four facades (North, South, East, West).

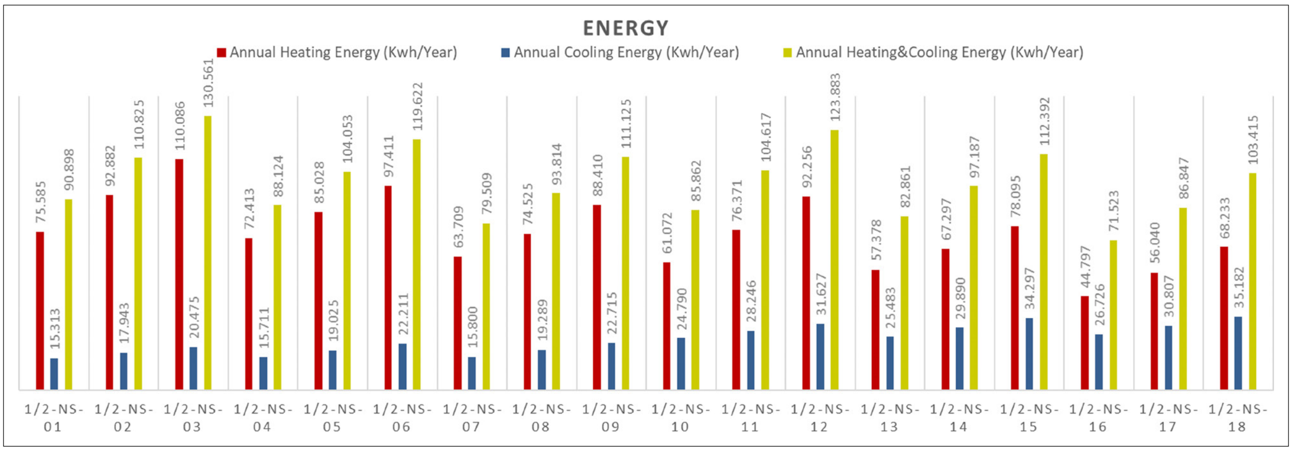

Figure 7. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 1/2 vertical rectangle and windows on two facades (North, South).

various equipment, as well as operational and embodied carbon calculations.

The calculation results obtained from the scenarios related to building form factor variables are given in Figures 4–30.

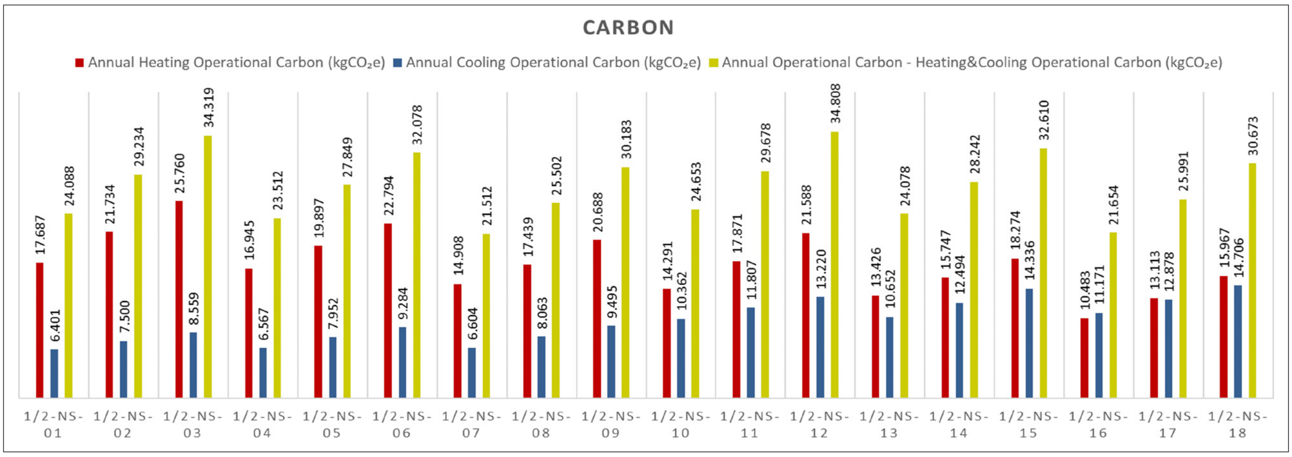

Figure 8. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 1/2 vertical rectangle and windows on two facades (North, South).

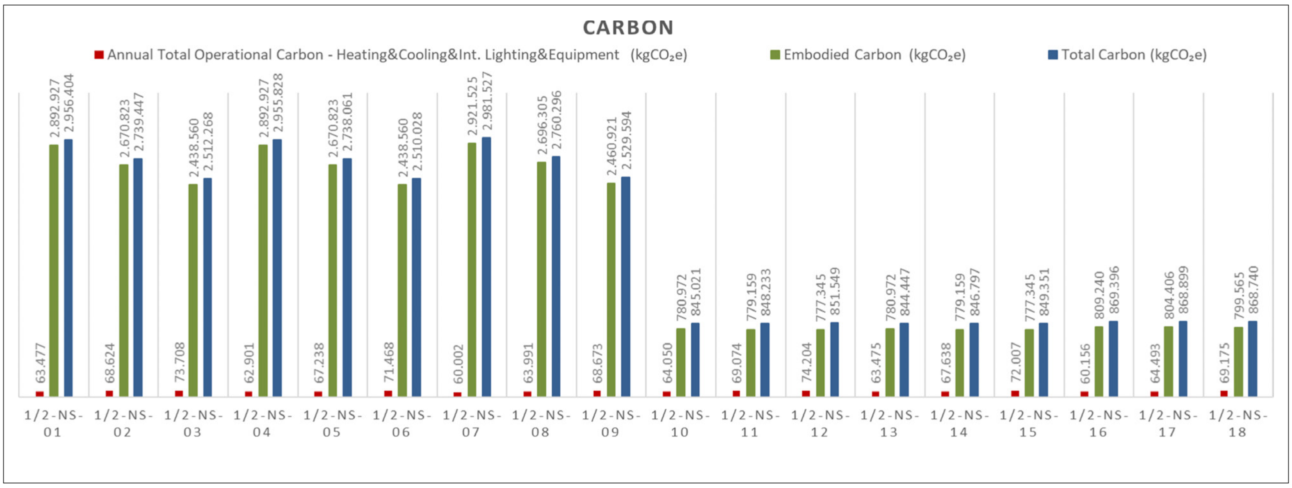

Figure 9. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 1/2 vertical rectangle and windows on two facades (North, South).

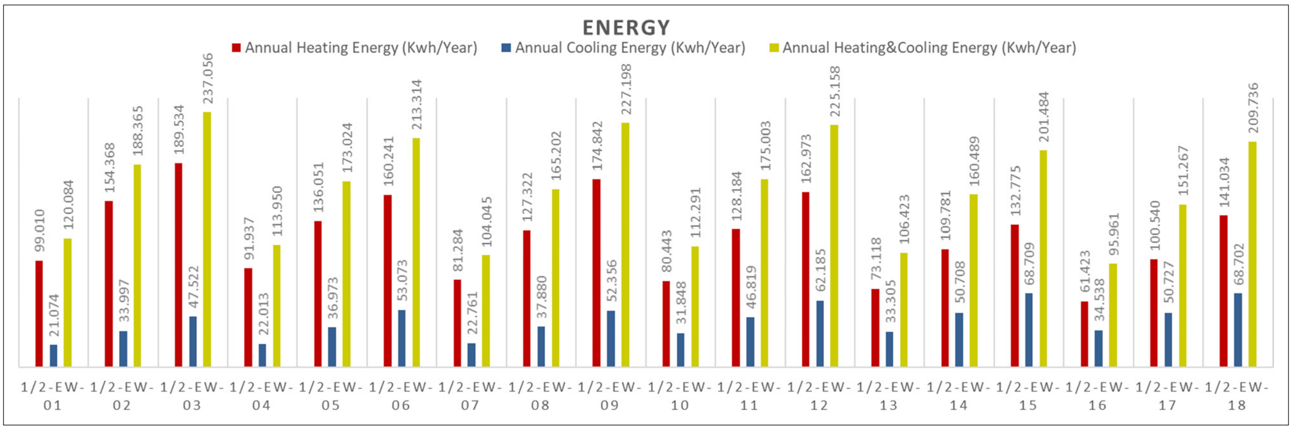

Figure 10. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 1/2 vertical rectangle and windows on two facades (East, West).

Figures 4–12 show the results obtained for buildings with a building form factor of 1/2 (Vertical Rectangle), Figures 13–21 show the results obtained for buildings with a building form factor of 2/1 (Horizontal Rectangle), and

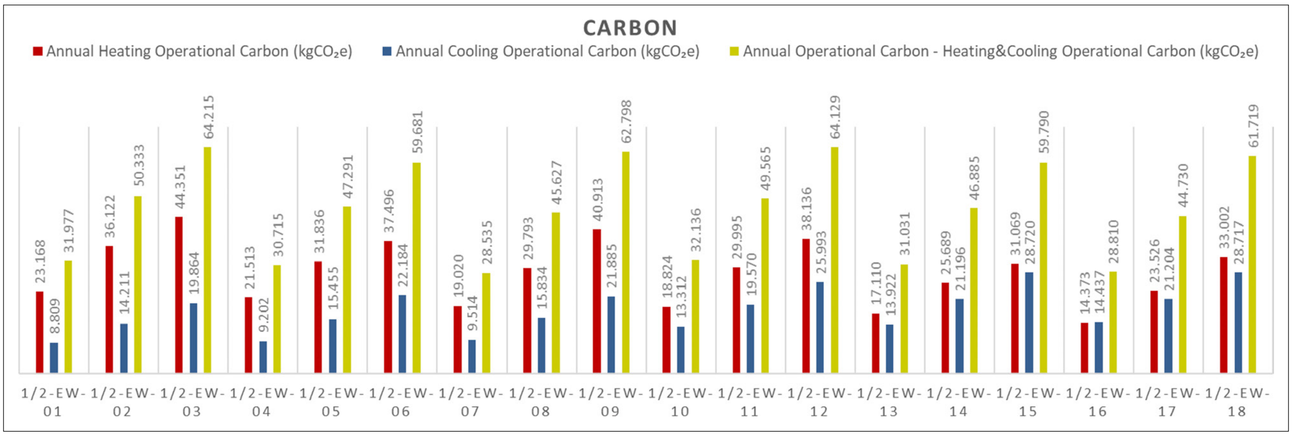

Figure 11. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 1/2 vertical rectangle and windows on two facades (East, West).

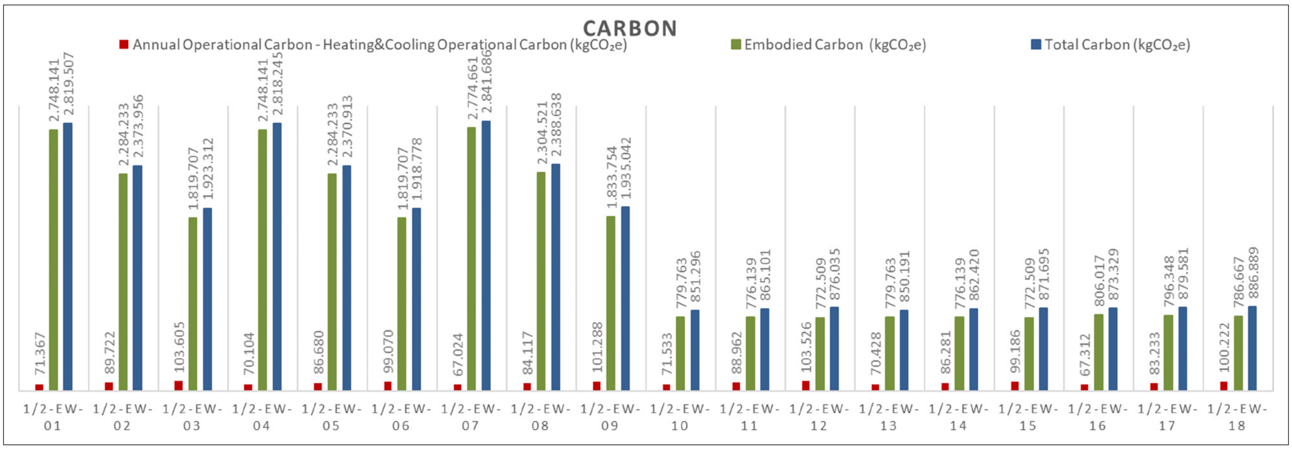

Figure 12. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 1/2 vertical rectangle and windows on two facades (East, West).

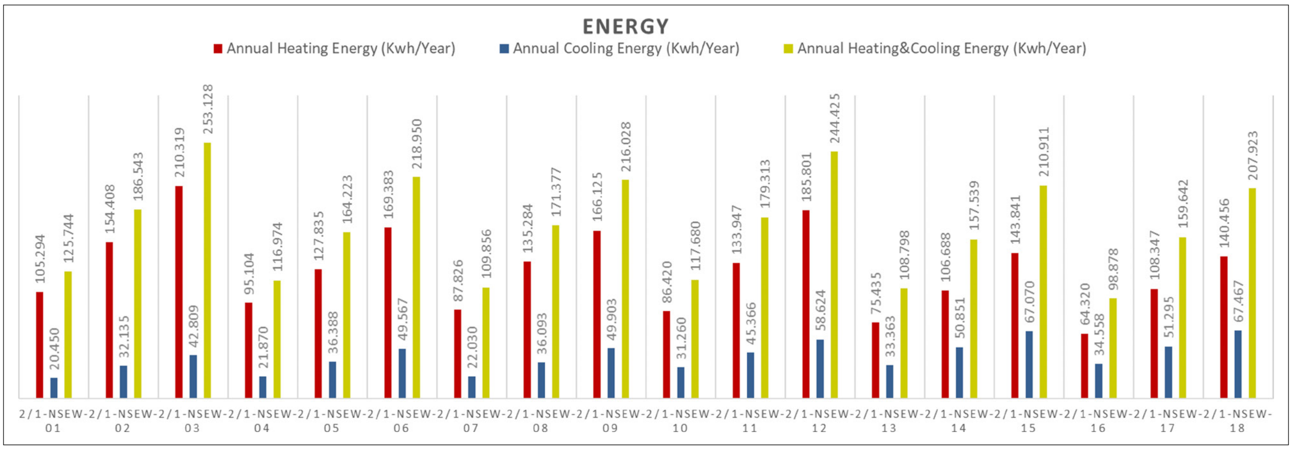

Figure 13. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 2/1 horizontal rectangle and windows on four facades (North, South, East, West).

Figures 22–30 show the results obtained for buildings with a building form factor of 1/1 (Square). The figures can be explained as follows:

- Figures 4, 13, 22 show the calculation results of Annual Heating, Cooling, and Total Heating and Cooling Energy consumption of building scenarios with North,

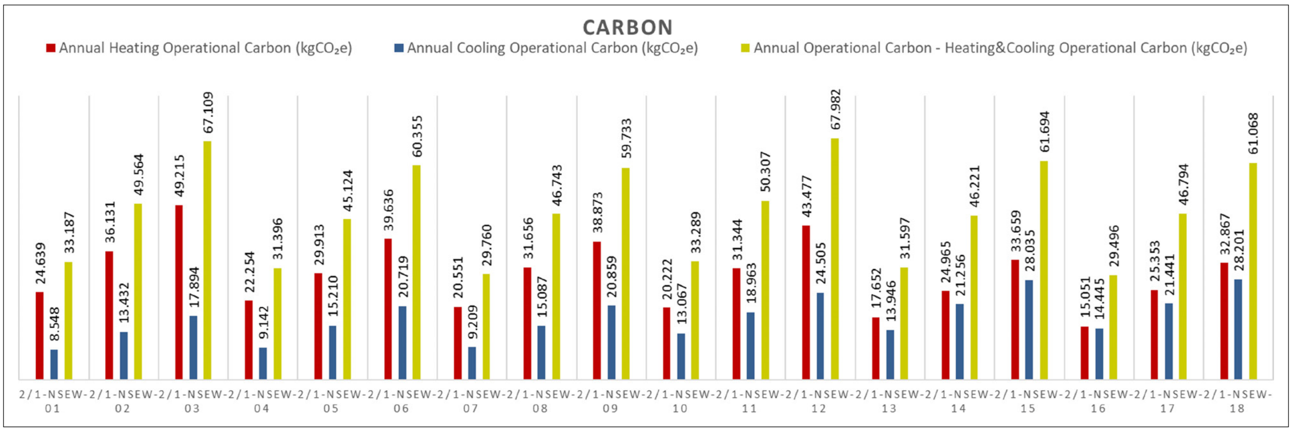

Figure 14. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 2/1 horizontal rectangle and windows on four facades (North, South, East, West).

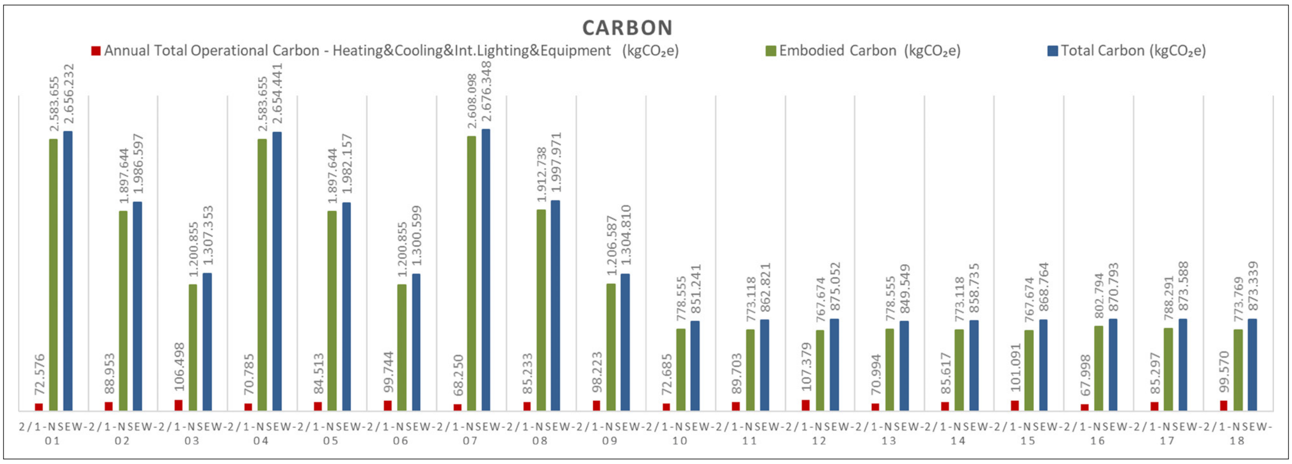

Figure 15. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 2/1 horizontal rectangle and windows on four facades (North, South, East, West).

South, East, West facade windows with form factors 1/2, 2/1, 1/1, respectively.

- Figures 5, 14, 23 show the calculation results of Annual Heating, Cooling, and Total Heating and Cooling Operational Carbon Emissions of building scenarios with North, South, East, West facade windows with form factors 1/2, 2/1, 1/1, respectively.
- Figures 6, 15, 24 show the calculation results of Operational Carbon from Annual Heating, Cooling, Interior Lighting, and Interior Equipment energy consumption, Embodied Carbon, and Total Operational and Embodied Carbon Emissions of building scenarios with North, South, East, West facade windows with form factors 1/2, 2/1, 1/1, respectively.
- Figures 7, 16, 25 show the calculation results of Annual Heating, Cooling, and Total Heating and Cooling Energy consumption of building scenarios with North, South facade windows with form factors 1/2, 2/1, 1/1, respectively.
- Figures 8, 17, 26 show the calculation results of Annual Heating, Cooling, and Total Heating and Cooling Operational Carbon Emissions of building scenarios with North, South facade windows with form factors 1/2, 2/1, 1/1, respectively.
- Figures 9, 18, 27 show the calculation results of Operational Carbon from Annual Heating, Cooling, Interior Lighting, and Interior Equipment energy consumption, Embodied Carbon, and Total Operational and Embodied Carbon Emissions of building scenarios with North, South facade windows with form factors 1/2, 2/1, 1/1, respectively.
- Figures 10, 19, 28 show the calculation results of Annual Heating, Cooling, and Total Heating and Cooling Energy consumption of building scenarios with East, West facade windows with form factors 1/2, 2/1, 1/1, respectively.
- Figures 11, 20, 29 show the calculation results of Annual Heating, Cooling, and Total Heating and Cooling

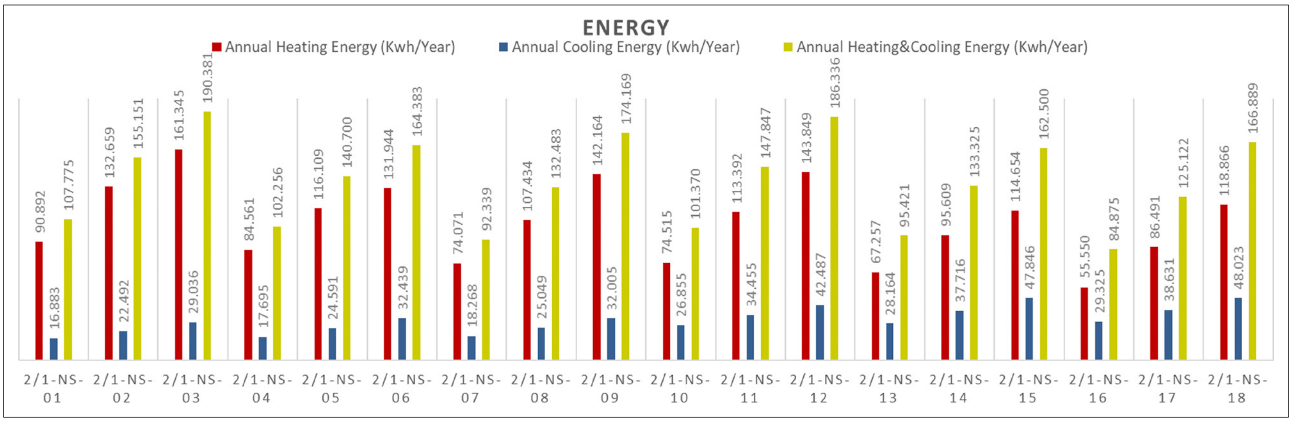

Figure 16. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 2/1 horizontal rectangle and windows on two facades (North, South).

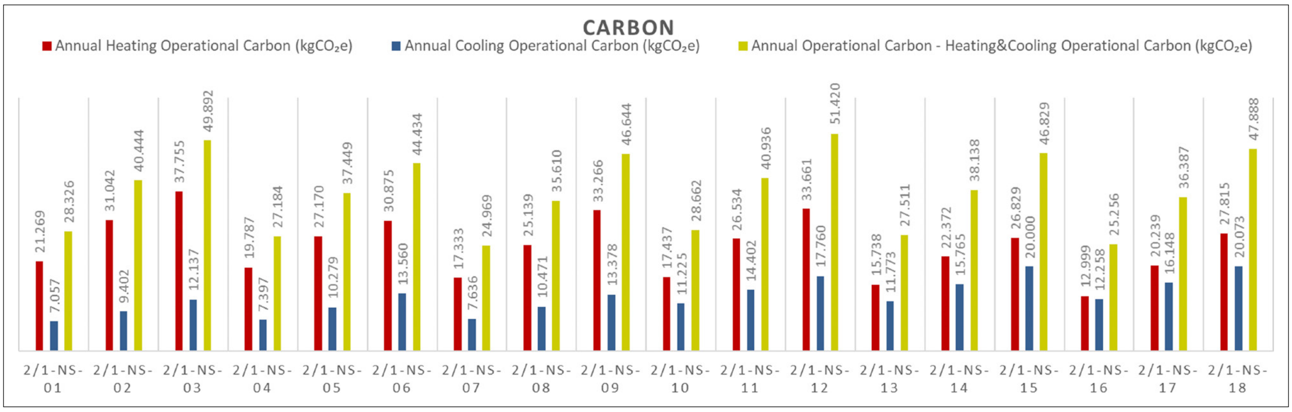

Figure 17. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 2/1 horizontal rectangle and windows on two facades (North, South).

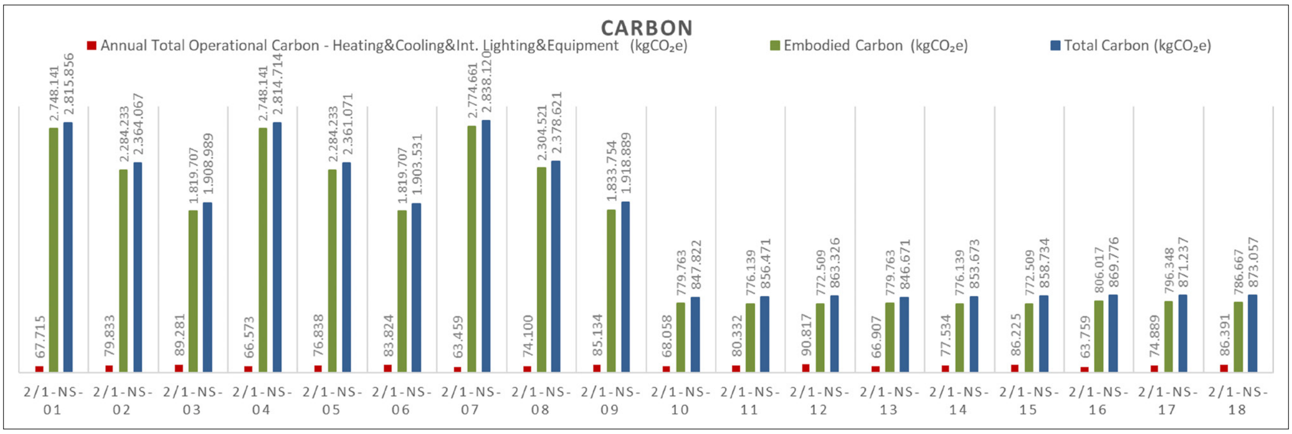

Figure 18. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 2/1 horizontal rectangle and windows on two facades (North, South).

Operational Carbon Emissions of building scenarios with East, West facade windows with form factors 1/2, 2/1, 1/1, respectively.

- Figures 12, 21, 30 show the calculation results of Operational Carbon from Annual Heating, Cooling, Interior Lighting, and Interior Equipment energy consumption, Embodied Carbon, and Total Operational and Embodied Carbon Emissions of building scenarios with East, West facade windows with form factors 1/2, 2/1, 1/1, respectively.

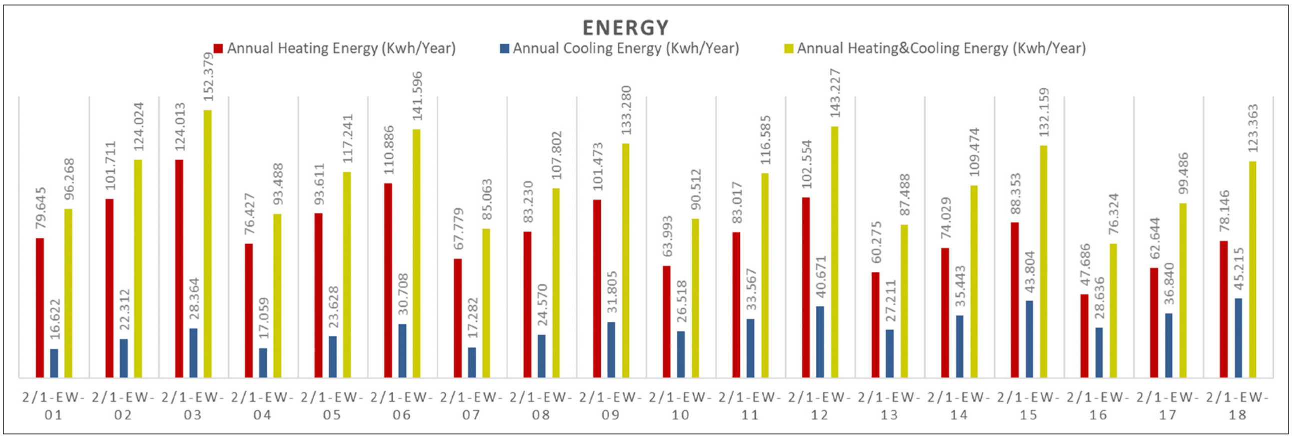

Figure 19. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 2/1 horizontal rectangle and windows on two facades (East, West).

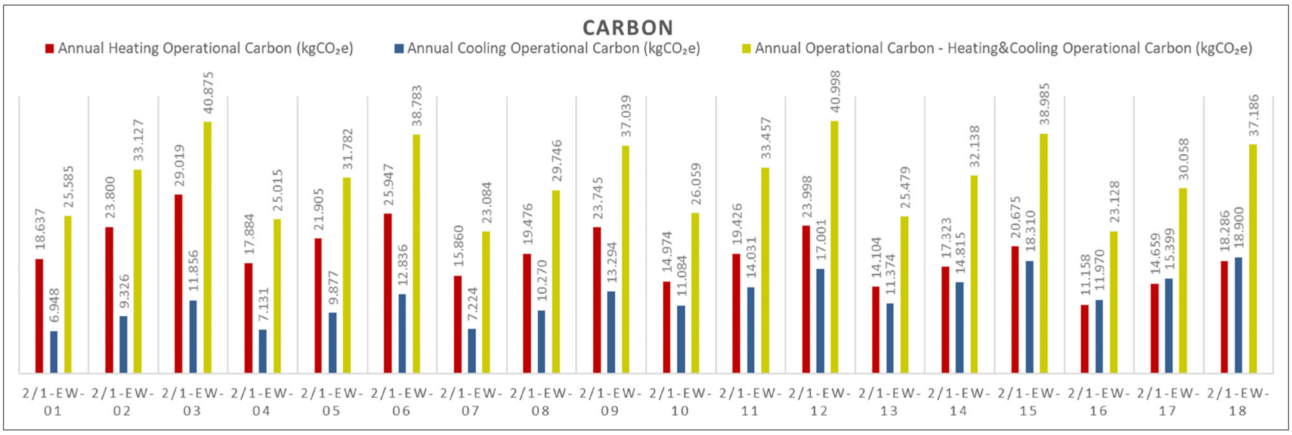

Figure 20. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 2/1 horizontal l rectangle and windows on two facades (East, West).

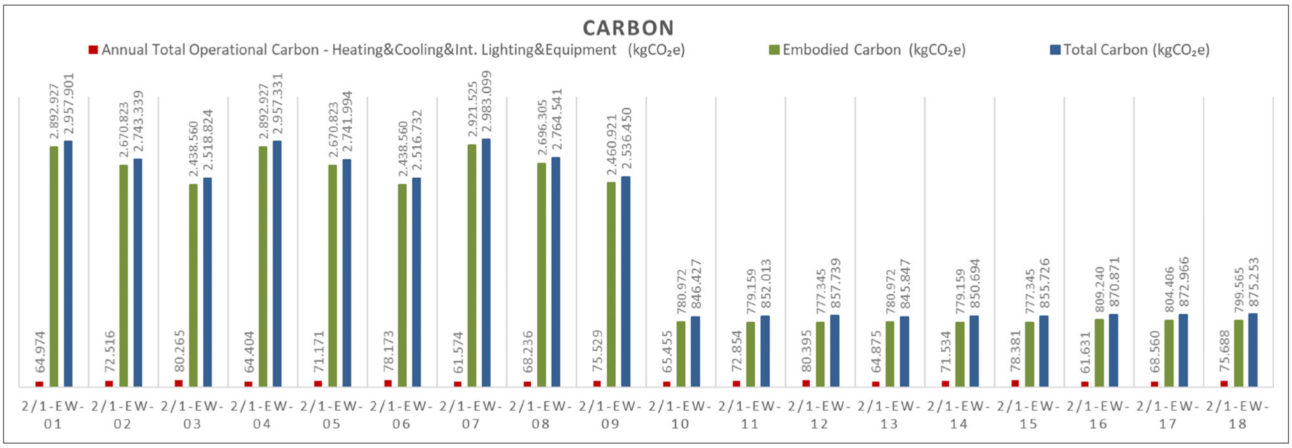

Figure 21. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total Operational and Embodied Carbon Emissions of building scenarios with building form factor 2/1 horizontal rectangle and windows on two facades (East, West).

The findings given in Figures 4–30 are analyzed for the building scenarios with building form factors of 1/2 (Vertical Rectangle), 2/1 (Horizontal Rectangle), and 1/1 (Square), and windows on four facades (North, South, East, West), and for the building scenarios with windows on two facades (North, South) and (East, West),

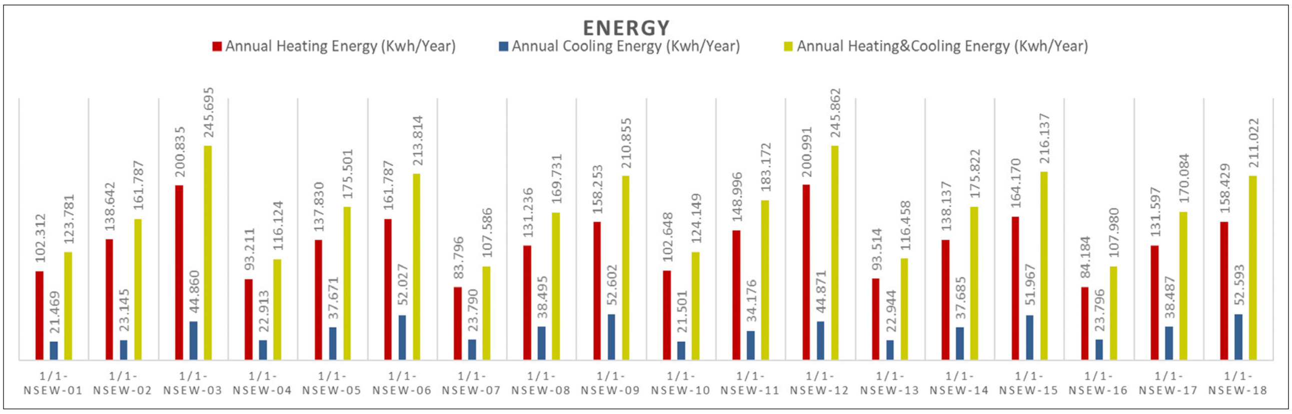

Figure 22. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 1/1 square and windows on four facades (North, South, East, West).

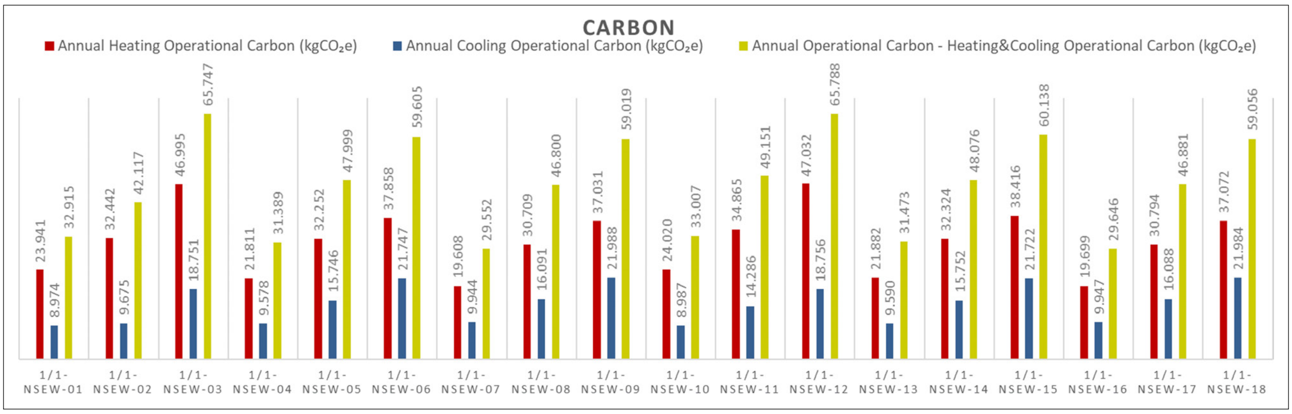

Figure 23. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 1/1 square and windows on four facades (North, South, East, West).

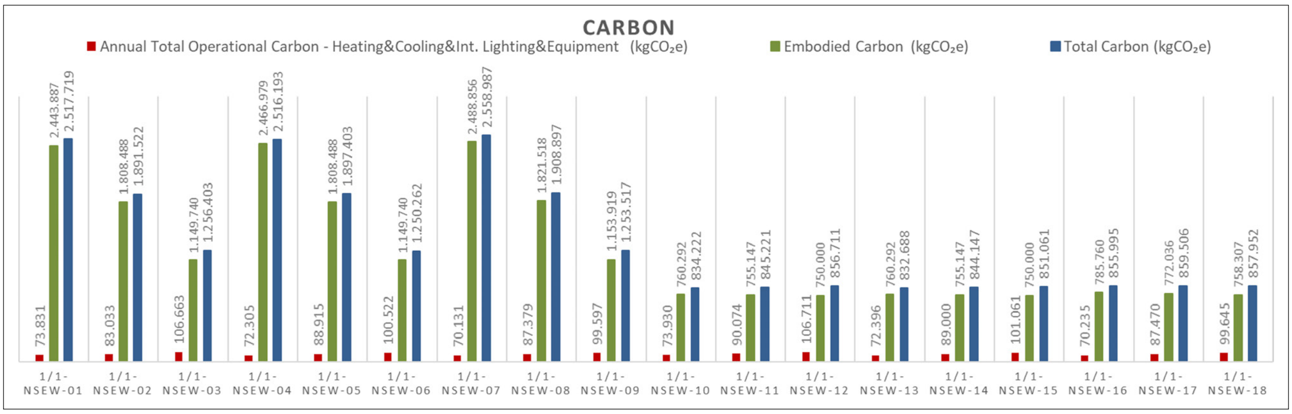

Figure 24. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 1/1 square and windows on four facades (North, South, East, West).

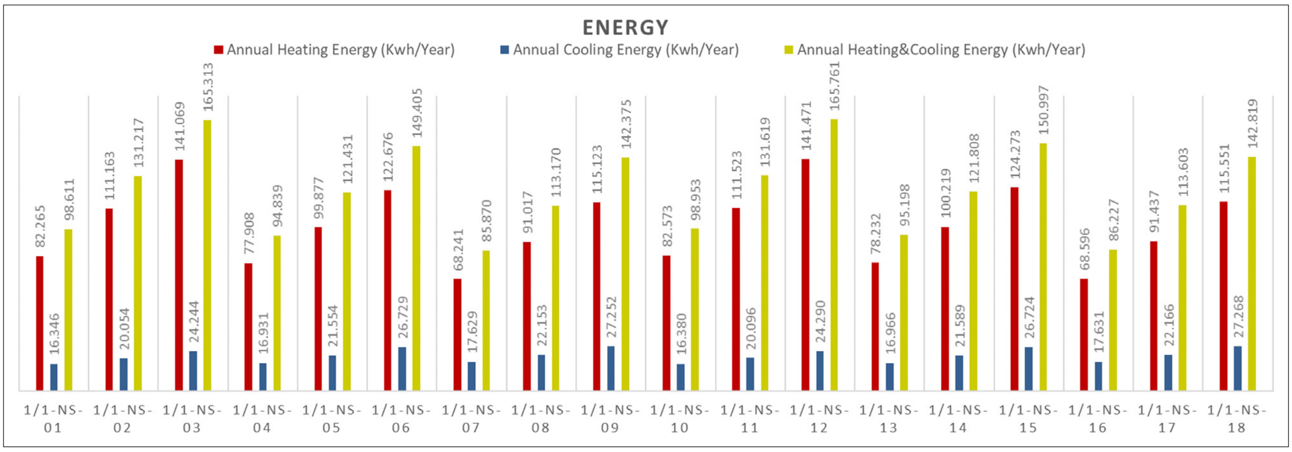

Figure 25. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 1/1 square and windows on two facades (North, South

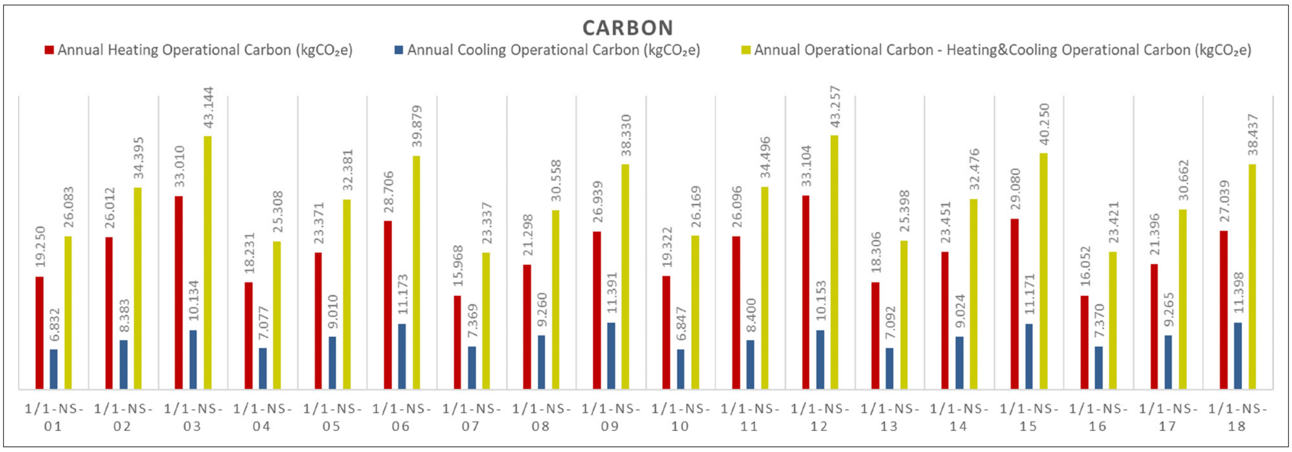

Figure 26. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 1/1 square and windows on two facades (North, South).

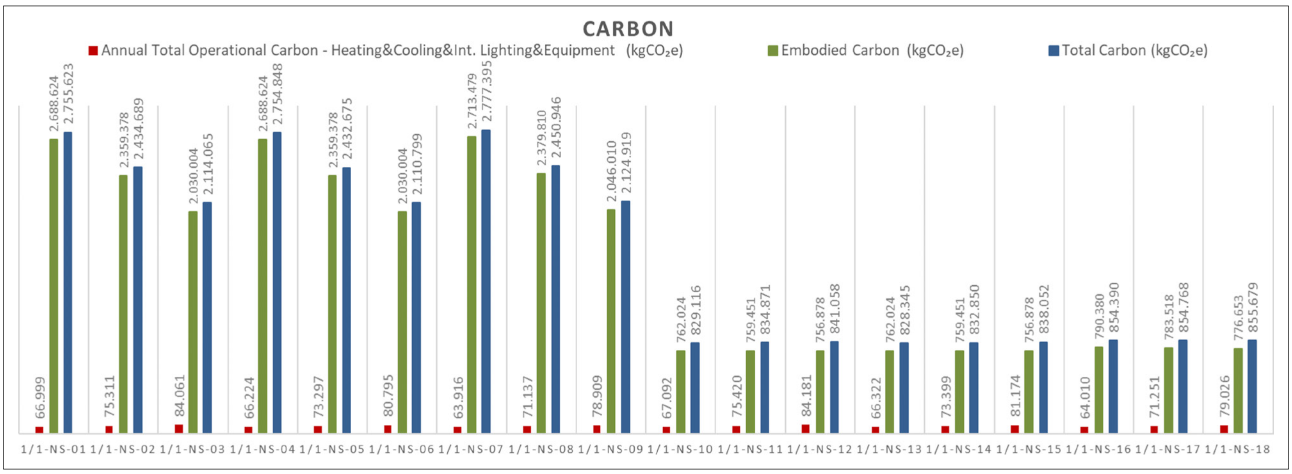

Figure 27. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 1/1 square and windows on two facades (North, South).

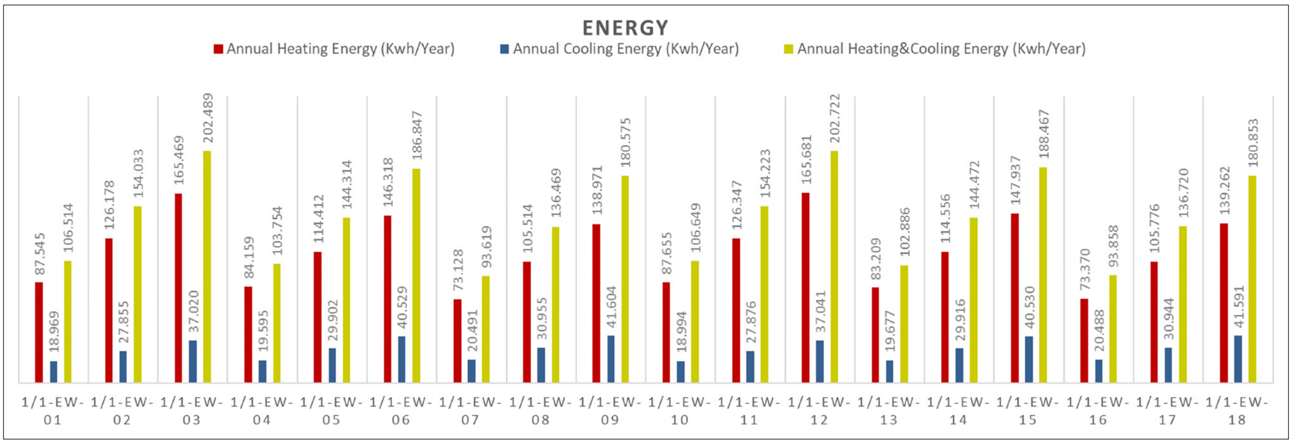

Figure 28. The calculation results of annual heating, cooling, total heating and cooling energy consumption of building scenarios with building form factor 1/1 square and windows on two facades (East, West).

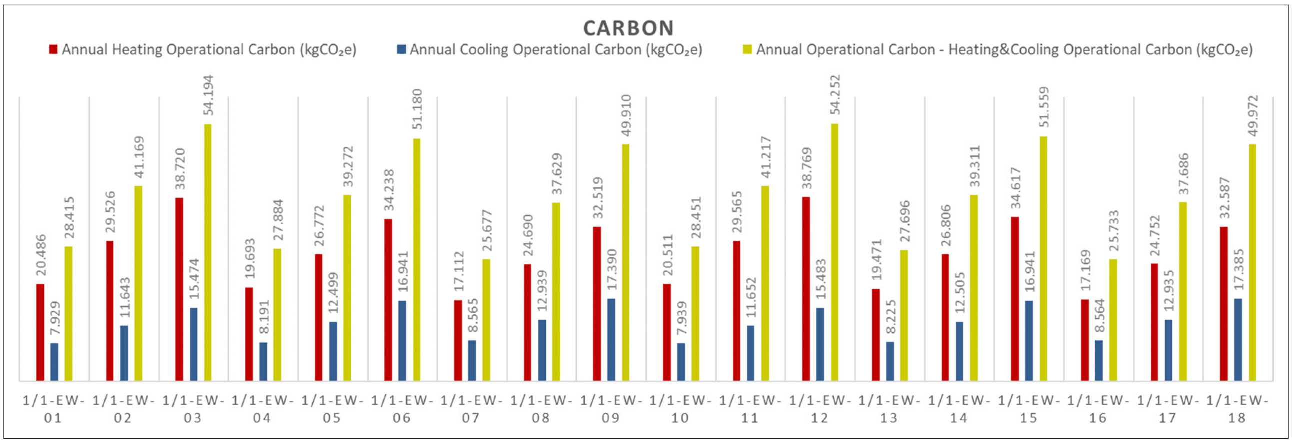

Figure 29. The calculation results of annual heating, cooling, total heating and cooling operational carbon emissions of building scenarios with building form factor 1/1 square and windows on two facades (East, West).

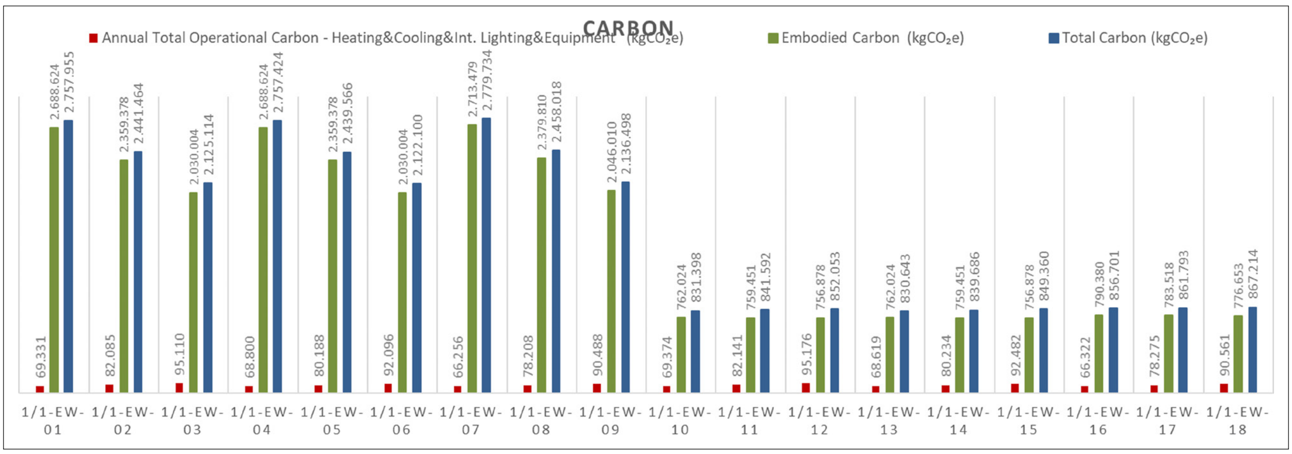

Figure 30. The calculation results of operational carbon from annual heating, cooling, interior lighting and interior equipment energy consumption, embodied carbon, total operational and embodied carbon emissions of building scenarios with building form factor 1/1 square and windows on two facades (East, West).

respectively. The results of the analyses are presented in the following sections.

Building Scenarios with Building Form Factor 1/2 Vertical Rectangular with Windows on Four Facades (N, S, E, W)

- As the window-to-wall ratio rises from 20% to 80%, the annual energy consumption increases. The most efficient scenarios are 1/2-NSEW-16 for heating, 1/2-NSEW-01 for cooling, and 1/2-NSEW-16 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 1/2-NSEW-16 for heating, 1/2-NSEW-01 for cooling, 1/2-NSEW-16 for total heating-cooling, and 1/2-NSEW-16 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is higher in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 1/2-NSEW-12 and 1/2-NSEW-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease significantly by up to 50% in scenarios with brick as the façade opaque material, while increasing slightly by 1–3% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 1/2-NSEW-13.

Building Scenarios with Building Form Factor 1/2 Vertical Rectangular with Windows on Two Facades (N, S)

- As the window-to-wall ratio rises from 20% to 80%, the annual energy consumption increases. The most efficient scenarios are 1/2-NS-16 for heating, 1/2-NS-01 for cooling, and 1/2-NS-16 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 1/2-NS-16 for heating, 1/2-NS-01 for cooling, 1/2-NS-07 for total heating-cooling, and 1/2-NS-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is greater in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 1/2-NS-12 and 1/2-NS-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease by up to 15% in scenarios with brick as the façade opaque material, while increasing slightly by 0.1–1% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 1/2-NS-13.

Building Scenarios with Building Form Factor 1/2 Vertical Rectangular with Windows on Two Facades (E, W)

- As the window-to-wall ratio rises from 20% to 80%, the annual energy consumption increases. The most efficient scenarios are 1/2-EW-16 for heating, 1/2-EW-01 for cooling, and 1/2-EW-16 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 1/2-EW-16 for heating, 1/2-EW-01 for cooling, 1/2-EW-07 for total heating-cooling, and 1/2-EW-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is higher in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 1/2-EW-12 and 1/2-EW-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease by up to 32% in scenarios with brick as the façade opaque material, while increasing slightly by 1.5–3% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 1/2-EW-13.

Building Scenarios with Building Form Factor 2/1 Vertical Rectangle with Windows on Four Facades (N, S, E, W)

- As the window-to-wall ratio rises from 20% to 80%, annual energy consumption increases. The most efficient scenarios are 2/1-NSEW-16 for heating, 2/1-NSEW-01 for cooling, and 2/1-NSEW-16 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 2/1-NSEW-16 for heating, 2/1-NSEW-01 for cooling, 2/1-NSEW-16 for total heating-cooling, and 2/1-NSEW-16 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is higher in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 2/1-NSEW-12 and 2/1-NSEW-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease significantly by up to 51% in scenarios with brick as

the façade opaque material, while increasing slightly by 0.5–3% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 2/1-NSEW-13.

Building Scenarios with Building Form Factor 2/1 Vertical Rectangle with Windows on Two Facades (N, S)

- As the window-to-wall ratio rises from 20% to 80%, annual energy consumption increases. The most efficient scenarios are 2/1-NS-16 for heating, 2/1-NS-01 for cooling, and 2/1-NS-16 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 2/1-NS-16 for heating, 2/1-NS-01 for cooling, 2/1-NS-07 for total heating-cooling, and 2/1-NS-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is greater in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 2/1-NS-12 and 2/1-NS-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total of annual operational and embodied carbon emissions decrease by up to 32% in scenarios with brick as the façade opaque material, while increasing slightly by 0.38–2% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 2/1-NS-13.

Building Scenarios with Building Form Factor 2/1 Vertical Rectangle with Windows on Two Facades (E, W)

- As the window-to-wall ratio rises from 20% to 80%, the annual energy consumption increases. The most efficient scenarios are 2/1-EW-16 for heating, 2/1-EW-01 for cooling, and 2/1-EW-16 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 2/1-EW-16 for heating, 2/1-EW-01 for cooling, 2/1-EW-07 for total heating-cooling, and 2/1-EW-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is greater in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 2/1-EW-12 and 2/1-EW-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease by up to 15% in scenarios with brick as the façade opaque material, while increasing slightly by 0.5–1% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 2/1-EW-13.

Building Scenarios with Building Form Factor 1/1 Square Building with Windows on Four Facades (N, S, E, W)

- As the window-to-wall ratio rises from 20% to 80%, annual energy consumption increases. The most efficient scenarios are 1/1-NSEW-07 for heating, 1/1- NSEW-01 for cooling, and 1/1-NSEW-07 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 1/1-NSEW-07 for heating, 1/1-NSEW-01 for cooling, 1/1-NSEW-07 for total heating-cooling, and 1/1-NSEW-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is higher in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 1/1-NSEW-12 and 1/1- NSEW-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease by up to 51% in scenarios with brick as the façade opaque material, while increasing slightly by 0.2– 2.7% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 1/1-NSEW-13.

Building Scenarios with Building Form Factor 1/1 Square Building with Windows on Two Facades (N, S)

- As the window-to-wall ratio rises from 20% to 80%, the annual energy consumption increases. The most efficient scenarios are 1/1-NS-07 for heating, 1/1-NS-01 for cooling, and 1/1-NS-07 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 1/1-NS-07 for heating, 1/1-NS-01 for cooling, 1/1-NS-07 for total heating-cooling, and 1/1-NS-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is higher in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 1/1-NS-12 and 1/1-NS-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease

by up to 23% in scenarios with brick as the façade opaque material, while increasing by 0.2–1.4% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 1/1-NS-13.

Building Scenarios with Building Form Factor 1/1 Square Building with Windows on Two Facades (E, W)

- As the window-to-wall ratio rises from 20% to 80%, annual energy consumption increases. The most efficient scenarios are 1/1-EW-07 for heating, 1/1-EW-01 for cooling, and 1/1-EW-07 for total heating-cooling.
- Annual operational carbon emissions increase when the window-to-wall ratio rises from 20% to 80%. The most efficient scenarios are 1/1-EW-07 for heating, 1/1-EW-01 for cooling, 1/1-EW-07 for total heating-cooling, and 1/1-EW-07 for total heating, cooling, interior lighting, and interior equipment.
- As the window-to-wall ratio increases, the reduction in embodied carbon emissions is greater in scenarios with brick as the opaque material compared to those with aerated concrete. The most efficient scenarios in terms of embodied carbon emissions are 1/1-EW-12 and 1/1-EW-15 with aerated concrete as the opaque material.
- As the window-to-wall ratio increases, the total annual operational and embodied carbon emissions decrease by up to 23% in scenarios with brick as the façade opaque material, while increasing slightly by 1.2– 2.5% in scenarios with aerated concrete as the façade opaque material. The most efficient scenario in terms of total carbon emissions is 1/1-EW-13.

CONCLUSION

According to the assumptions made within the scope of the study and the scenarios created, the findings obtained from the calculations for the new office buildings to be built in Erzurum are presented below:

- The majority of total heating and cooling energy consumption (62%–86%) results from heating.
- As the window-to-wall ratio in the façade increases, the quantity of heating and cooling energy consumed, and consequently, the operational carbon emissions, rise.
- As the window-to-wall ratio increases, the amount of embodied carbon decreases.
- With regard to total carbon emissions (i.e., the sum of operational carbon and embodied carbon), the proportion of operational carbon in scenarios employing brick as the opaque façade material ranges from 2.5% to 5%, while the proportion of embodied carbon ranges from 95% to 97.5%. For scenarios employing aerated concrete as the opaque façade material, the share of operational carbon is approximately 8–10%, while the share of embodied carbon is 90–92%.
- Energy consumption and carbon emissions are assessed based on the form factor and orientation of the window. According to the evaluation of the findings:
  - For buildings with windows on four facades (N, S, E, W):
    - Scenario 2/1-NSEW-16 for energy consumption.
    - Scenario 2/1-NSEW-16 for operational carbon emissions.
    - Scenarios 1/1-NSEW-12 and 1/1-NSEW-15 for embodied carbon.
    - Scenario 1/1-NSEW-13 for total carbon emissions.
  - For buildings with windows on two facades (N, S):
    - Scenario 1/2-NS-16 for energy consumption.
    - Scenario 1/2-NS-07 for operational carbon emissions.
    - Scenarios 1/1-NS-12 and 1/1-NS-15 for embodied carbon.
    - Scenario 1/1-NS-13 for total carbon emissions.
  - For buildings with windows on two facades (E, W):
    - Scenario 2/1-EW-16 for energy consumption.
    - Scenario 2/1-EW-07 for operational carbon emissions.
    - Scenarios 1/1-EW-12 and 1/1-EW-15 for embodied carbon.
    - Scenario 1/1-EW-13 for total carbon emissions provide minimum values.

The results of the study show the impact of design parameters related to the building envelope of office buildings on energy consumption and carbon emissions. Energy-efficient and low-carbon buildings play an important role in solving environmental problems and reducing energy consumption and overall carbon emissions. For this reason, office buildings, especially those that are occupied for long periods and have high artificial energy consumption, should be carefully designed. In this context, appropriate design and material selection of the building envelope will contribute to a significant reduction in energy consumption for heating and cooling while providing the required climatic comfort for the occupants. This will also help to minimize operational and embodied carbon emissions of the building.

In other words, if the properties of the building envelope are properly determined, the energy performance of the building can be significantly improved, and the amount of energy consumption and carbon emissions can be reduced.

This paper presents the findings of a study that aims to evaluate the heating and cooling performance, operational carbon emissions, and embodied carbon emissions of new office buildings in Erzurum in the case of detached layout construction in line with the assumptions. These results and evaluations will reduce the artificial energy consumption required for heating and cooling, as well as carbon emissions during operation and embodied carbon. However, in order to reach more general conclusions, it would be beneficial to apply the study to different climate zones and scenarios.

It is evident that studies conducted under diverse scenarios can facilitate the development of sustainable, energy-efficient, and low-carbon emission building designs and create a more sustainable built environment. As a consequence, these studies will contribute to the achievement of national and international goals related to the protection of the natural environment, efficient use of resources and materials, reduction of carbon emissions, and prevention of climate change.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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