The effect of window proportions in low-rise residential buildings on annual energy consumption in humid temperate climate (case study: Rasht city in Iran)

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The proportions of exterior windows in low-rise residential buildings are crucial for optimizing energy consumption. This study investigates and optimizes these proportions for buildings in the temperate climate of Rasht City, Iran. A building was simulated in DesignBuilder software to explore how different window-to-wall ratios affect energy consumption. Using a parametric algorithm, the percentage of windows on each building facade was varied from 10% to 100%, and heating, cooling, and lighting loads were calculated. The results revealed that optimizing window proportions can significantly reduce annual energy consumption. For the north-facing facade, the optimal window-to-wall ratio is between 26% and 33%. On the south side, the most efficient window proportion is 21%–25%, resulting in the lowest energy consumption of 2,102 kWh/m² per year. The optimal window proportions for the east and west facades are 54%–57%, and 58%, respectively. The study found a strong correlation between energy consumption and the window-to-wall ratio for the south-facing facade, with a correlation coefficient of 0.97. For the north, east, and west facades, the correlation coefficients are 0.72, 0.17, and 0.33, respectively. These findings can predict energy consumption for residential buildings in Rasht and similar climates. Optimizing window proportions is an effective strategy to reduce energy use and enhance residents' quality of life, applicable to both new constructions and renovations of existing buildings.

KEYWORDS

window-to-wall ratio, optimization, energy consumption, residential building, Rasht

1 Introduction

Energy consumption in buildings accounts for about 40% of global energy use, with 60% of this related to heating and cooling, especially in the residential sector. Similarly, in Iran, buildings are a significant contributor to energy consumption (Asfour, 2020; Noaman et al., 2022; Spanodimitriou et al., 2022). Highlight the significant demand for cooling and heating savings in buildings, reinforcing the importance of energy-efficient design (Albatayneh et al., 2021; He et al., 2021; Sakhaei et al., 2020). This is particularly relevant given the rising global energy demand, which underscores the necessity of transitioning to renewable energy sources. Among these, solar photovoltaic (PV) technology has emerged as a leading solution for large-scale electricity generation (Mardani et al., 2024)

The increasing global energy demand necessitates a shift towards renewable energy sources, with solar photovoltaic technology being a prominent option for large-scale electricity generation.

Considering the increase in land population and urbanization growth up to 80% in 2030 and the increase in total energy demand in buildings between 110%–150% by 2050 and 160%–220% by 2095 compared to 2005, reducing energy consumption through improving efficiency Building energy has been considered (Mahiwal et al., 2021). Hoseinzadeh (2019) highlighted that half of the energy consumed by buildings is lost through windows. The study of smart windows in Iran for energy optimization across various climates and the analysis of cooling energy consumption strategies in different Iranian cities underscore the importance of optimizing the window-to-wall ratio. Addressing this issue is essential for improving energy efficiency in buildings. The optimal ratio of the outer window of the building to the wall is to reduce the annual energy consumption of the building, which should be applied in the early stages of building design (Goia, 2016). An essential point in the design process to determine the optimal percentage of external windows is to pay attention to the urban topology and the characteristics of the environment around the building (Košir et al., 2017). It should be noted that the optimal ratio of exterior windows to receive daylight is not equal to its value for minimum energy consumption (Byggregler and Författningssamling, 2009). The type of glass, its shape, and the location of the radiator should be taken into account so that with the correct placement of the external opening, the annual energy loss of the building through the thermal bridge can be reduced by half (Marino et al., 2017; Misiopecki et al., 2017; Ghanbari et al., 2022).

A study evaluated the increase in the ratio of outdoor windows in the north face and its decrease in the south face of 20 residential buildings. The results showed that for the stability of the building, small and large windows should be used in the north and south front, respectively. Also, the dimensions of the effective external opening do not significantly affect heating, while this value is significant on the cooling load (Halawa et al., 2017; Zare et al., 2022). Another study in residential buildings in cold climates showed that using solutions such as taking advantage of internal heat produced by equipment and people, obtaining solar heat, and triple-layered glass has greatly reduced heat loss. In addition, using the more oversized exterior windows on the north front used more suitable daylight conditions. Other results show that using larger north window dimensions has led to a slight increase in the heating load. On the other hand, more oversized windows on the south face of the building increase the ventilation speed, and awnings should also be used (Persson et al., 2006; Azizibabani et al., 2021).

In another study, Goia (2016) compared low-emissivity three-pane windows, three-pane clear windows, low-emission double-pane windows, and clear double-pane windows with five types of single-pane windows for a residential building in Rome, Italy. The results showed that the outer window of the building with an area ratio of less than 0.2 had the best performance. A study in a temperate oceanic climate for an office building showed that the optimal ratio is between 35% and 45% and does not depend on the facade and orientation of the building. Also, the overall energy consumption of the building depends a little on the efficiency of the air conditioning system and the geometry of the building. On the

other hand, it depends on the shading system, and the internal heat load changes significantly (Goia et al., 2013; Motie et al., 2023).

Research in the cold climate of Europe, between 35 and 60° north, showed that the most suitable ratio of Bjorn windows to the wall is between 30 and 45 percent (Goia, 2016). In Europe, the use of an elongated form has been proposed to receive more solar heat. Also, the square plan with a 50% exterior window ratio on the south front and without a canopy was introduced as one of the best models. However, in the case of extensive use of window surfaces with movable awnings, energy consumption has been minimized (Košir et al., 2017). In a study in Indonesia, Lee et al. (2013) found that changing the characteristics of exterior window glass affects the amount of visible light and absorption of thermal energy. Shell design guidelines for five climates are provided. According to ASHRAE's classification in climates 1 and 2, the most advantages are related to using windows in the north, south, west, and east facades, respectively. Also, in the regions of 3–5 ASHRAE, it is related to the view of the south front, north front, west front, and east front. The recommended ratio of the outer windows' dimensions to the building's outer wall on all fronts is 25%.

Various studies have used various optimization algorithms to improve the performance of the building shell; the genetic algorithm is one of them, which aims at optimal design to minimize the energy consumption of the building. A genetic algorithm study evaluated residential buildings with L-shaped, rectangular, plus, H-shaped, trapezoidal, and T-shaped forms. The effect of the ratio and type of external glass was analyzed in it. The results showed that trapezoid and rectangle forms had the best cost and life cycle performance. In addition, the square form performs best in all climates with minimum cost (Tuhus-Dubrow and Krarti, 2010). Amaral et al. (2016) in research optimized the window dimensions of a space in the Portuguese climate in terms of thermal comfort. The investigated variables were window dimensions, canopy type, and opening orientation. The parametric results showed that the west and north-east directions are inappropriate, and three-paned glass should be used in the north face. Also, a canopy does not affect the thermal performance of a triple-glazed window. On the other hand, it provides the possibility of using a window with wider dimensions.

Recently, using Design Builder software, the optimal dimensions of the exterior windows of the building in different climates have been investigated. Marino et al. (2017), in a study using Dizan Builder software with the Energy Plus engine, optimized the building shell in 12 Italian climates. The results showed that in all studied climates, the percentage of window to wall with 25.9% with poor insulation and 23.5% with proper insulation is the most optimal ratio. In another study, the percentage of external windows on the energy consumption of an office building in Libya was evaluated with Energy Plus software. The results showed that with the increase in the percentage of the window, the heating load decreased, and the cooling load increased between 6% and 180% (Alghoul et al., 2017).

In a study, Krarti et al. (2005) analyzed the variables of the percentage of exterior window area, type of glass, and building geometry on the amount of electrical energy consumption in the American climate. The results showed that increasing the coefficient of transmitted light leads to an increase in the benefits of daylight. Latitude has a relatively small effect on the amount of daylight, and in all spaces, the coefficient of transmitted light greater than 0.3 has led to a decrease in the amount of energy return. The purpose of

FIGURE 1
Climatical zoning of Iran (Pilechiha et al., 2020).

designing wider openings in the outer walls of residential buildings is to receive more daylight, which leads to more heat loss and solar absorption (Bruno, 2017). In addition, the window area should not be less than ten percent of the interior floor area to use daylight (Byggregler and Författningssamling, 2009; Goharian et al., 2022).

An essential point in the design process to determine the optimal percentage of external windows is to pay attention to the urban topology and the characteristics of the environment around the building (Košir et al., 2017; Goharian et al., 2023). It should be noted that the optimal ratio of exterior windows to receive daylight is not equal to its value for minimum energy consumption (Byggregler and Författningssamling, 2009). The type of glass, its shape, and the location of the radiator are things that should be taken into account in such a way that with the correct placement of the external opening, the amount of annual energy loss by the building through the thermal bridge can be reduced by half (Marino et al., 2017; Misiopecki et al., 2017; Goharian et al., 2023).

According to reviewed studies, determining the optimal percentage of windows on different sides of a building significantly impacts internal thermal comfort, resident satisfaction, and overall energy consumption. Research is ongoing in various climates to identify the optimal percentage of external openings. However, there is a gap in research regarding the optimal window-to-wall ratio for residential buildings in Rasht City, which has a moderate and humid climate.

This research aims to identify the optimal percentage of windows on the four sides of residential buildings in Rasht, providing valuable guidance for designers and architects to achieve sustainable design. Additionally, the study seeks to determine the correlation coefficient between building energy consumption and the percentage of exterior windows. This correlation will help estimate and predict energy consumption, contributing to sustainability in both new and existing buildings.

2 Description of the climate region

The first step to designing a sustainable architecture is to study the desired climate. According to Kopen's climate classification, Iran has four climates: temperate and humid, hot and humid, cold and hot and dry (Kottek et al., 2006). Rasht has a temperate Caspian and semi-Mediterranean climate (Figure 1), which has hot and humid summers and cold and wet winters. The city of Rasht, the capital of Gilan Province in northern Iran, is located at a latitude of 37° 12′N and a longitude of 49° 39′E. Situated at an elevation of 36.7 m above sea level, Rasht experiences a humid and moderate climate due to its geographical location. The city is significantly influenced by the Caspian Sea, resulting in frequent rainfall and high humidity in the region (Jahanbani et al., 2011; Alamdari et al., 2022).

Figure 2 shows the cytometric chart of Rasht according to the ASHRAE standard 55 version 2004 output of the climate advisor software. According to Figure 2, thermal comfort exists 7% of the year without a specific design strategy. While 33.8% of the period of the year is created by using passive solar solutions, thermal comfort is created, 10.1% of which is by creating a canopy on the window. Also, according to the desired climate, 24% of the year, dehumidification is needed to achieve thermal comfort in the indoor space.

The direction of the wind flow in the year from different directions, and its intensity is shown in Figure 3, which is the
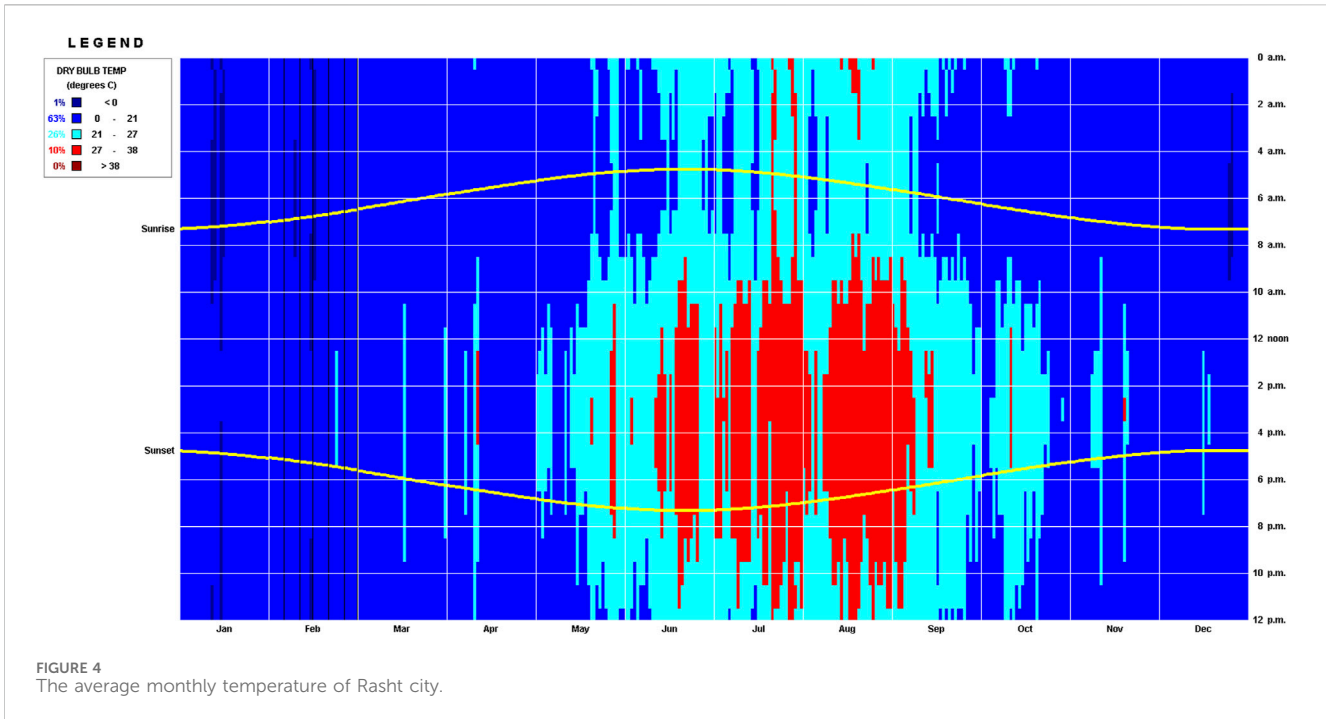
FIGURE 2
Rasht psychrometric chart.

FIGURE 3
Annual wind flow diagram of Rasht city.
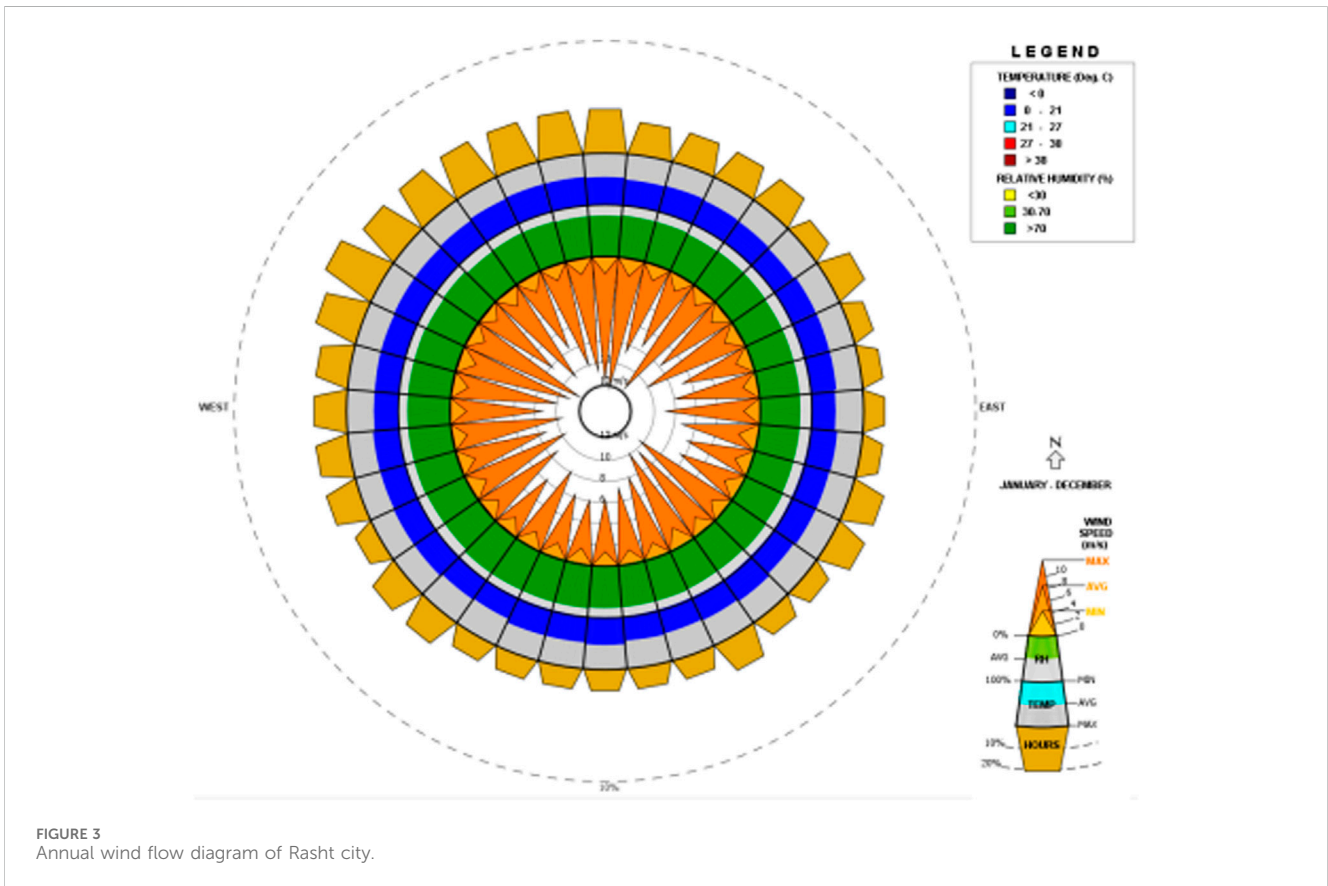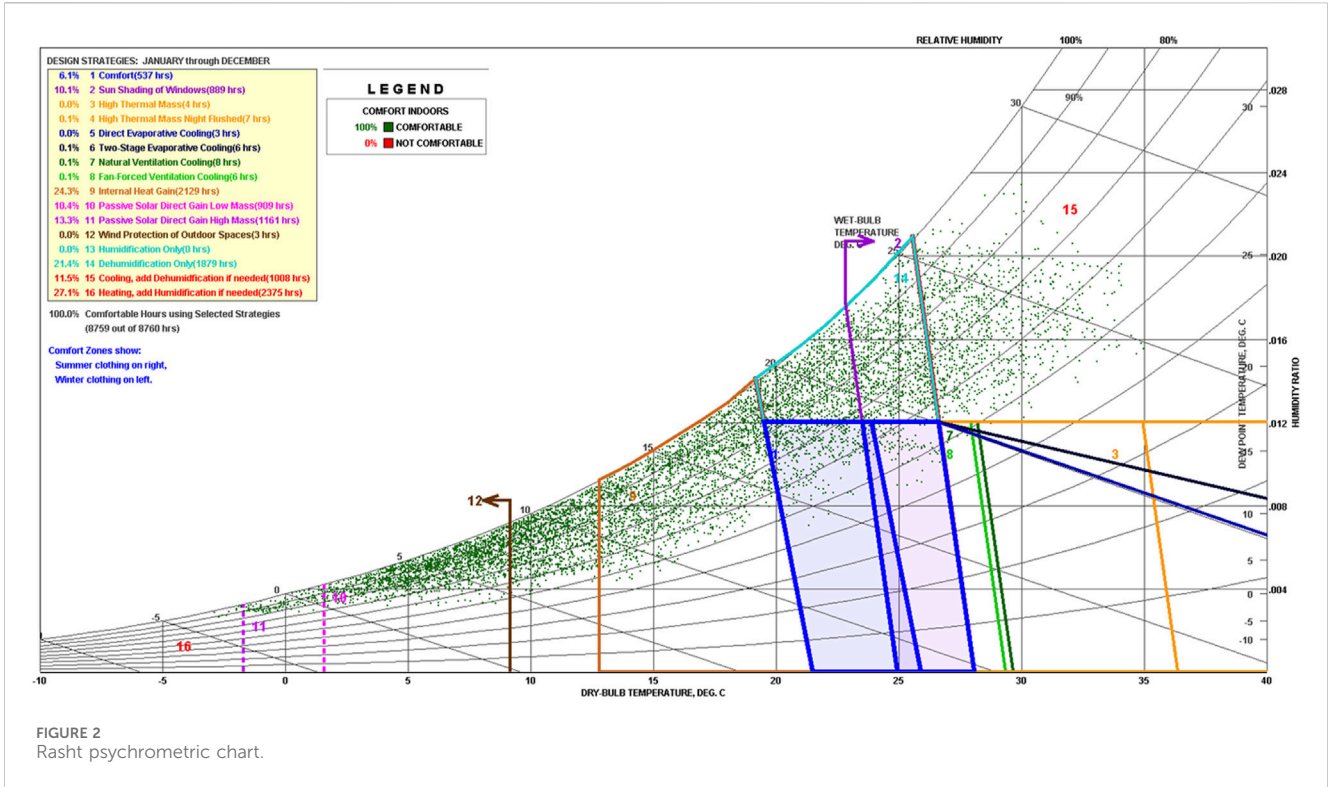
FIGURE 4
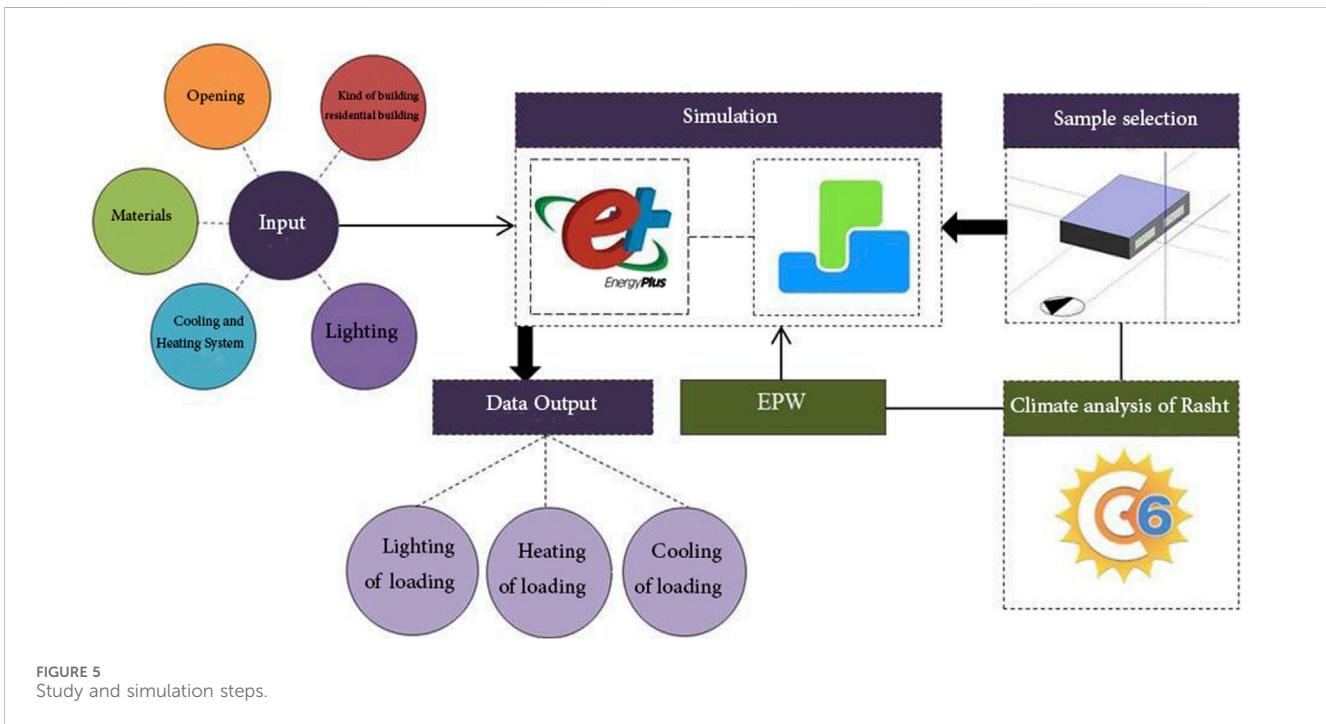The average monthly temperature of Rasht city.

FIGURE 5
Study and simulation steps.

dominant wind from the northwest. Also, the average temperature of Rasht during the year 1390–1400 in the months of the year is shown in Figure 4. The minimum and maximum temperatures in the year are −4 and 35°C, respectively, which occurred in January and August. The months of July, August, and September are considered as warm months (Figure 4).

3 Research method

The research steps and methods used in this study are shown in Figure 5. First, to determine the optimal percentage of windows in the outer walls of a residential building, a space with dimensions of 4 m * 6 m and a height of 4 m was selected as a residential space. This space has an east-west extension (Figure 6).
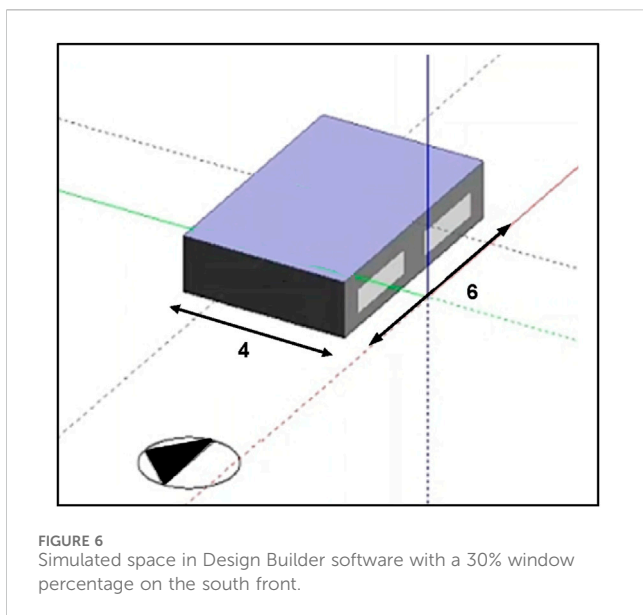
FIGURE 6
Simulated space in Design Builder software with a 30% window percentage on the south front.

TABLE 1 Characteristics of the studied building.

Components	Specifications
Account Type	Residential building
Location	Rasht, Iran
Number of floors	1
Height of each floor	4 m
orientation	Eastern Western
Lighting	300 Lux
Occupancy capacity (persons)/m2	2 (ASHRAE standard)
Infiltration	0.5 AC/h

3.1 Simulation tools

DesignBuilder is a sophisticated graphical interface specifically created to facilitate EnergyPlus simulations. As a state-of-the-art software tool, it enables comprehensive analysis of building energy consumption, CO_2 emissions, lighting, and thermal comfort performance. The platform is designed to streamline the building simulation process, allowing users to efficiently compare the functionality and performance of various design alternatives, ensuring timely and cost-effective results. By integrating rapid building modeling with advanced dynamic energy simulation capabilities, DesignBuilder offers an intuitive interface and innovative productivity features, making it accessible for users with varying levels of expertise to model complex structures with ease. Additionally, it serves as the first fully integrated user interface for the EnergyPlus dynamic thermal simulation engine (Choudhary, 2015). Design Builder software was used to evaluate the impact of the percentage of external windows to the external wall on the building's energy consumption, which has an energy analysis plus engine. EPW climate file was also used to define Rasht The software can analyze and calculate lighting, daylight, cooling, and heating

loads. In the simulation scenarios, the heating setpoint was set to 22°C and the cooling setpoint to 24°C, by ASHRAE standards. Additionally, ASHRAE standards specify that the recommended illumination level for residential spaces is 300 lux.

The specifications of the simulated space are given in Table 1. According to the ASHRAE standard, the heating point was 22°C, and the cooling point was 24°C. The materials used in the sample space are given in Table 2. In the intended space, the glasses were considered as double-glazed glass. The thickness of each glass is mm3, the thickness of the air layer between them is 6 mm, and its heat transfer coefficient is W/m2K3/3.

3.2 Validation software

Design Builder is a reputable commercial software for building energy simulation, offering comprehensive and dynamic capabilities. Its credibility is validated through the BESTest method, developed by the International Energy Agency to evaluate the accuracy and validity of energy simulation tools. The BESTest protocol is recognized as a standard benchmark for assessing building energy simulation capabilities. Design Builder is widely cited in scientific papers as a reliable energy simulation tool and is based on the extensively optimized EnergyPlus computational engine. Simulation results with EnergyPlus have been validated according to the "Industrial Test Standards" of the U.S. Department of Energy (Ilbeigi et al., 2020; Taleb and Sharples, 2011).
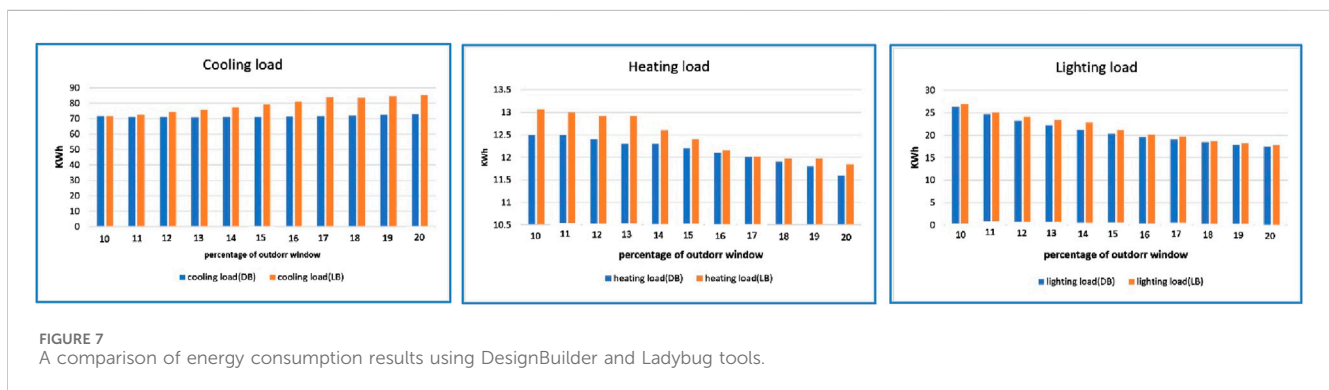
In this research, Ladybug software is used as a complementary tool to evaluate and compare simulation results with Design Builder. Initial modeling was conducted using Rhino software with dimensions of 4 m*6 m, as detailed in Table 1, followed by adjustments according to Table 2. The primary objective of the study is to optimize building window dimensions. For this purpose, 11 different scenarios of window-to-wall ratios were simulated and analyzed. The results show that the average cooling load calculated by Ladybug (78.98 kWh) and Design-Builder (71.49 kWh) differ by approximately 9.4%. Design Builder recorded 12.14 kWh for heating load calculations, while Ladybug recorded 12.44 kWh, resulting in a 2.5% difference. Electrical energy consumption also varied, with Design Builder recording 20.94 kWh and Ladybug 21.64 kWh, showing a 3.2% difference (Figure 7). These variations in results between the two software tools highlight their accuracy and reliability in simulations. The capability of these tools to optimize design and reduce energy consumption can be trusted for this research and similar projects, providing reliable results that enable more precise analysis and better decision-making for enhancing building energy performance.

3.3 Simulation modes

A parametric analysis using DesignBuilder software was conducted to determine the optimal percentage of exterior windows on all four sides of residential buildings in Rasht: south, north, east, and west. Initially, a building with dimensions of 4 m * 6 m was simulated using input data such as Rasht's climatic file, building materials, occupancy rates, lighting, and other building-specific details. The parameters for the analysis were configured accordingly.

TABLE 2 Specifications of the materials of the simulated sample space in the Design-Builder software (based on the ASHRAE standard).

	Layers	Thickness (mm)	U-value W/(m²K)	R$_c$-value (m²K)/W
Outer wall	Exterior bricklayer	100	0.35	2.85
	XPS polystyrene insulation	100		
	Concrete blocks	100		
	Gypsum plaster	10		
Rooftop	asphalt	10	0.47	2.09
	Fiberboard	10		
	XPS polystyrene insulation	40		
	Concrete	10		
	Gypsum plaster	15		
Window	Glass	3	0.42	2.2
	Gap	6		
	Glass	3		

FIGURE 7
A comparison of energy consumption results using DesignBuilder and Ladybug tools.

The first simulation was carried out on the building's south-facing side, where the window-to-wall ratio was varied from 10% to 100%. Annual cooling, heating, and lighting loads were measured for each percentage of windows. This process was repeated for the north, east, and west facades, and the corresponding data was gathered. By comparing the results, the optimal window percentage for each facade was identified. Finally, to achieve the objective of studying the correlation between energy loads (cooling, heating, and lighting) and the percentage of exterior windows, a correlation coefficient was calculated. This analysis helps predict energy consumption in both existing and planned buildings, guiding sustainable design solutions.

4 Data analysis and results

After simulating the desired building, the amount of solar gain, cooling load, heating load, and annual lighting consumption of the building was calculated for different percentages of windows in the four sides of the office building for Bushehr, Shiraz, and Tabriz.

4.1 Solar gain

The increase in temperature in an object, building, or space caused by the sun's radiation is called solar gain, which is one of the critical factors in the cooling load of the building. In addition, the solar gain coefficient is one of the essential characteristics of the exterior windows of the building, which refers to the transmission of solar energy by the window with all its components, including the materials used in the frame and glass (Baenas and Machado, 2017; Sharbafian et al., 2024). The amount of solar gain received annually in the studied space for different window percentages on four sides of residential buildings in Rasht City is shown in Figure 8. To determine the amount of solar gain of the building with 10% exterior windows on the south side of the studied space, it is 18.28 kWh/m. This value has reached 101/27 kWh/m with a window percentage of 50%. The amount of solar gain with 10% of the outer window on the north side of the building is also 21.8 kWh/m, and with 100% of the window, it reaches 87.26 kWh/m, which experiences a 90.7% increase in solar gain (Figure 8). The amount of solar gain for the percentage of western and eastern windows is almost the same. According to Figure 8, the amount of solar gain of the building with
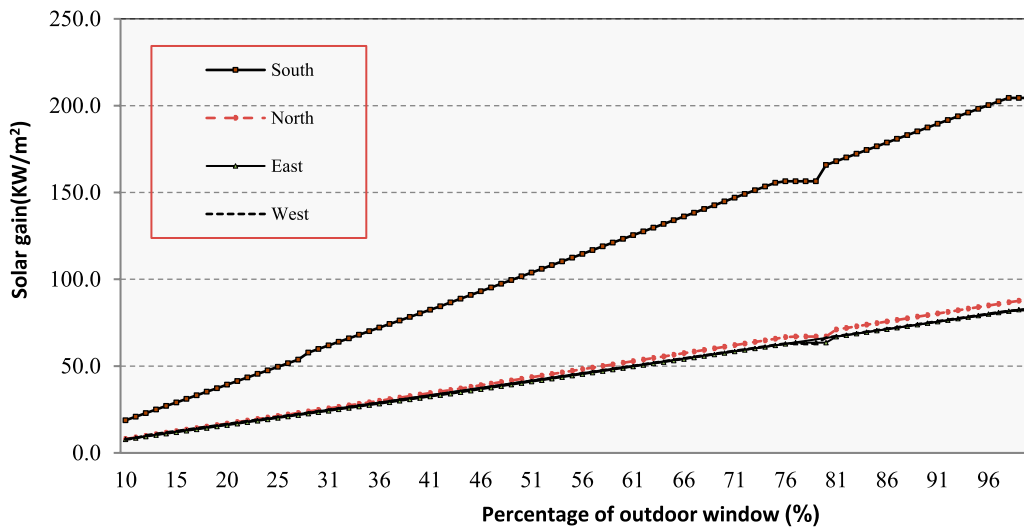
FIGURE 8
The amount of annual solar gain with the percentage of different windows on different fronts of residential buildings in Rasht.
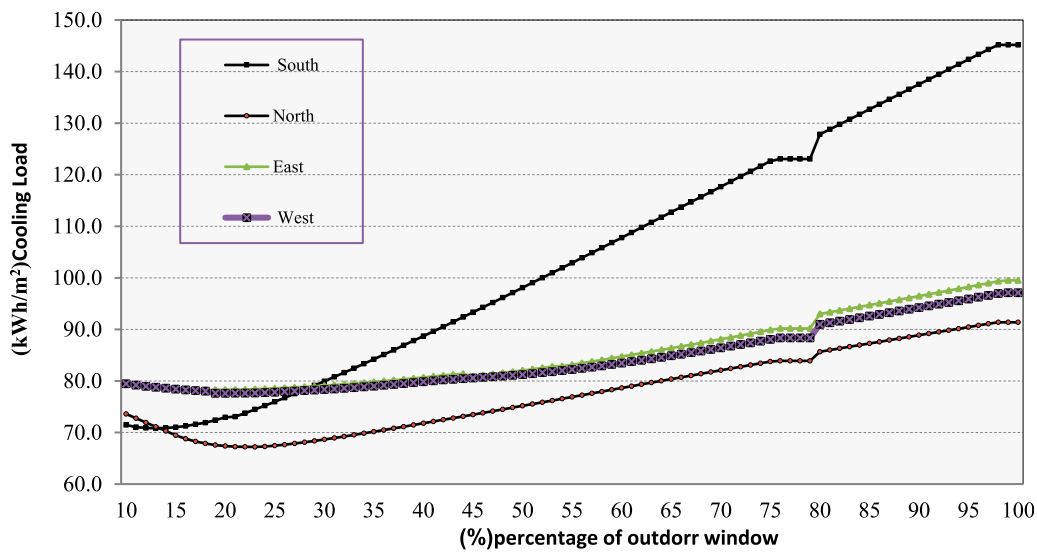

FIGURE 9
Annual cooling load with the percentage of different windows on different fronts of residential buildings in Rasht.

10% and 100% windows on the east side is 7.27 kWh/m and 82.29 kWh/m, respectively.

4.2 Cooling load

Figure 9 shows the cooling times with the percentage of different windows on the four sides of the building in Rasht. On the south front, the window with a ratio of 15%–20% with an average consumption of 71.25 kWh/m has the lowest cooling load due to the low solar gain with this window percentage (Figure 8). The north front of the building, with 22%–24% of the external window, has the lowest amount of cooling load with 62.22 kWh/m², and the highest

amount of cooling load belongs to 100% of the external window with the amount of 91.24 kWh/m². Also, according to Figure 9, For Rasht, the east side of the window has the lowest consumption with a ratio of 17%–21% with a consumption of 78.23 kWh/m. This amount for the west front of the building is a ratio of 19%–22% and an average amount of 77.26 kWh/m.

4.3 Heating load

Figure 10 shows the annual heating load of a residential building per square meter with the percentage of different windows for Rasht. On the south side of the building, with the increase in the percentage
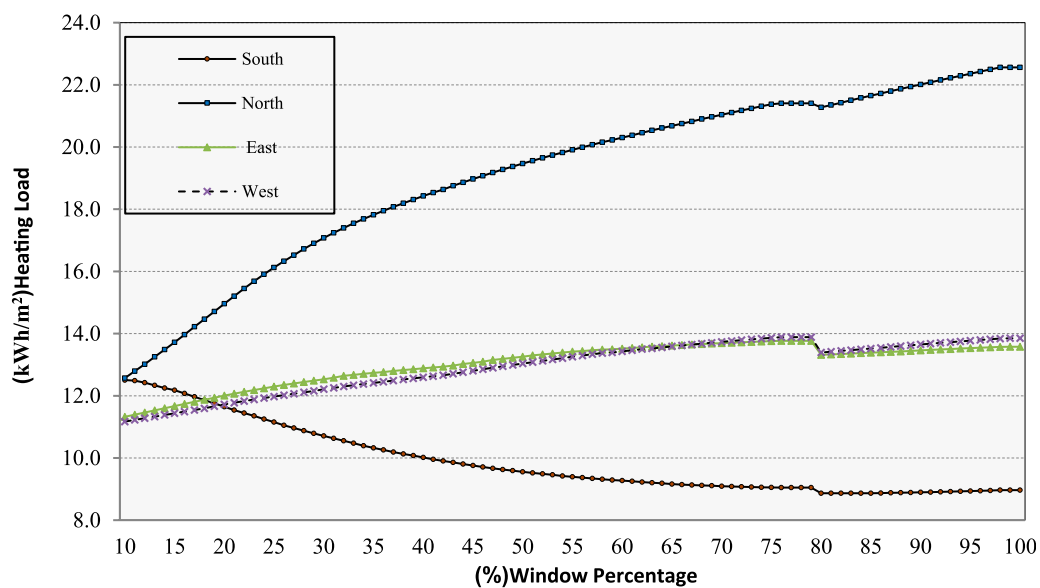
FIGURE 10
The amount of annual solar gain with the percentage of different windows on different fronts of residential buildings in Rasht.

of windows, the heating load has decreased due to receiving direct sunlight and increasing solar gain (Figure 7), which helps to increase the room's temperature. The southern front of the building has the lowest heating load at over 80%, with a consumption of 8.29 kWh/m^2. The east and west facades behaved almost the same, and with the increase in the percentage of windows, the heating load also increased. The cause of this issue is the increase in the window area, which has led to the wastage of energy.

On the other hand, the indirect reception of sunlight on these fronts helps increase the room's temperature, which is more suitable for lighting and daylight. That also applies to the northern front, shown in Figure 10. On the north front of the building, the heating load of the studied space with 10% of the external window is 12.26 kWh/m^2, which is 22.26 kWh/m^2 with 100% window.

4.4 Lighting load

The annual lighting consumption of the residential building for different window percentages for Rasht is shown in Figure 11. According to Figure 11, with the increase in the percentage of windows in all fronts, the lighting load has decreased because more natural light has entered the interior space, which has led to a decrease in lighting load. In Rasht, the annual lighting load of the building with 10% windows on the south and north fronts is 47.21 kWh/m^2, which is 17.21 kWh/m^2 with 70% exterior windows (Figure 11). Also, the annual lighting of the building with a 10% exterior window percentage on the east side is approximately 39.22 kWh/m^2, which is 12.25 kWh/m^2 with a 70% window, which has decreased by 68%. Also, on the west side of the building, the lighting load for 10% and 100% of the outer window is 26.23 kWh/m and 11.25 kWh/m, respectively.

4.5 A total load of cooling, heating, and lighting

The total load of cooling, lighting, and cooling with different percentages of windows in the outer wall on the four sides of North, South, East, and West for a residential building in Rasht is shown in Figure 12. According to Figure 12, the residential building with 21%–25% windows on the south front of the residential building had the lowest energy consumption, which was 2,102 kWh/m^2. Also, for the northern front of the building, this amount was 2,103 kWh/m, which is 26%–33%. Also, it has been the most optimal in the eastern front, with 54%–57% with an annual energy consumption of 2,103 kWh/m. Also, the most optimal energy consumption mode on the west side is related to 58% of the outer window, 116.24 kWh/m^2.

4.6 Correlation coefficient between energy consumption and the window-to-wall ratio (WWR)

The correlation coefficients between the energy consumption of buildings with south, north, east, and west orientations and the optimal percentage of exterior windows (WWR) are presented in Table 3 and Figure 13. According to Table 3, the energy consumption of the building with south-facing windows is highly correlated with the window-to-wall ratio ($p < 0.0001$). Additionally, the energy consumption of the building with north-facing windows shows a significant correlation with the WWR, with a correlation coefficient of $r = 0.72$ and a slope of 0.19. The correlation coefficients for the energy consumption of buildings with east-facing and west-facing windows relative to the WWR are 0.17 and 0.33, respectively (Table 3). Regression lines and scatterplots illustrating the
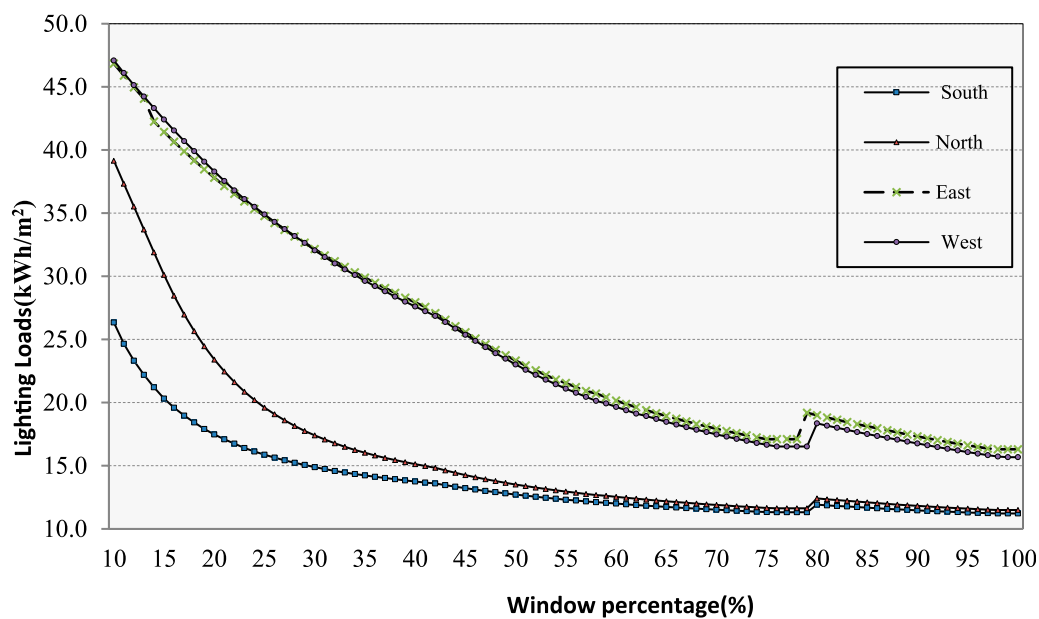
FIGURE 11
The amount of annual solar gain with the percentage of different windows on different fronts of residential buildings in Rasht.
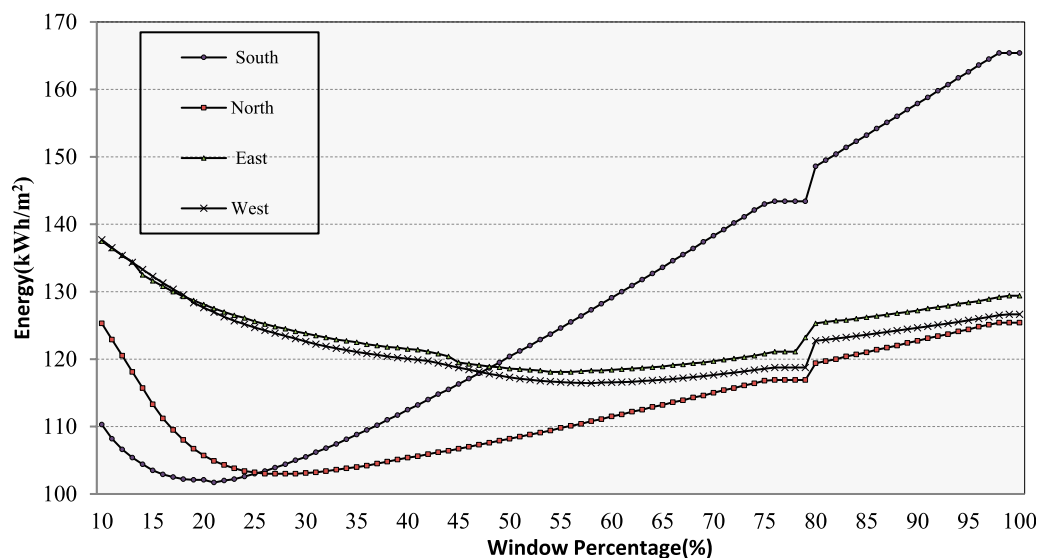

FIGURE 12
Annual energy consumption with the percentage of different windows on different fronts of residential buildings in Rasht.

relationship between building energy consumption and the exterior window-to-wall ratio are shown in Figure 13.

The correlation coefficient between building energy consumption and the exterior window-to-wall ratio (WWR) for the four building orientations is presented in Table 3 and Figure 13. According to Table 3, building energy consumption (E) is significantly correlated with the WWR ($P < 0.0001$), with a correlation coefficient of 0.44. This data is valuable for predicting energy consumption in buildings with various facades and provides important insights for architects and designers (Figure 14).
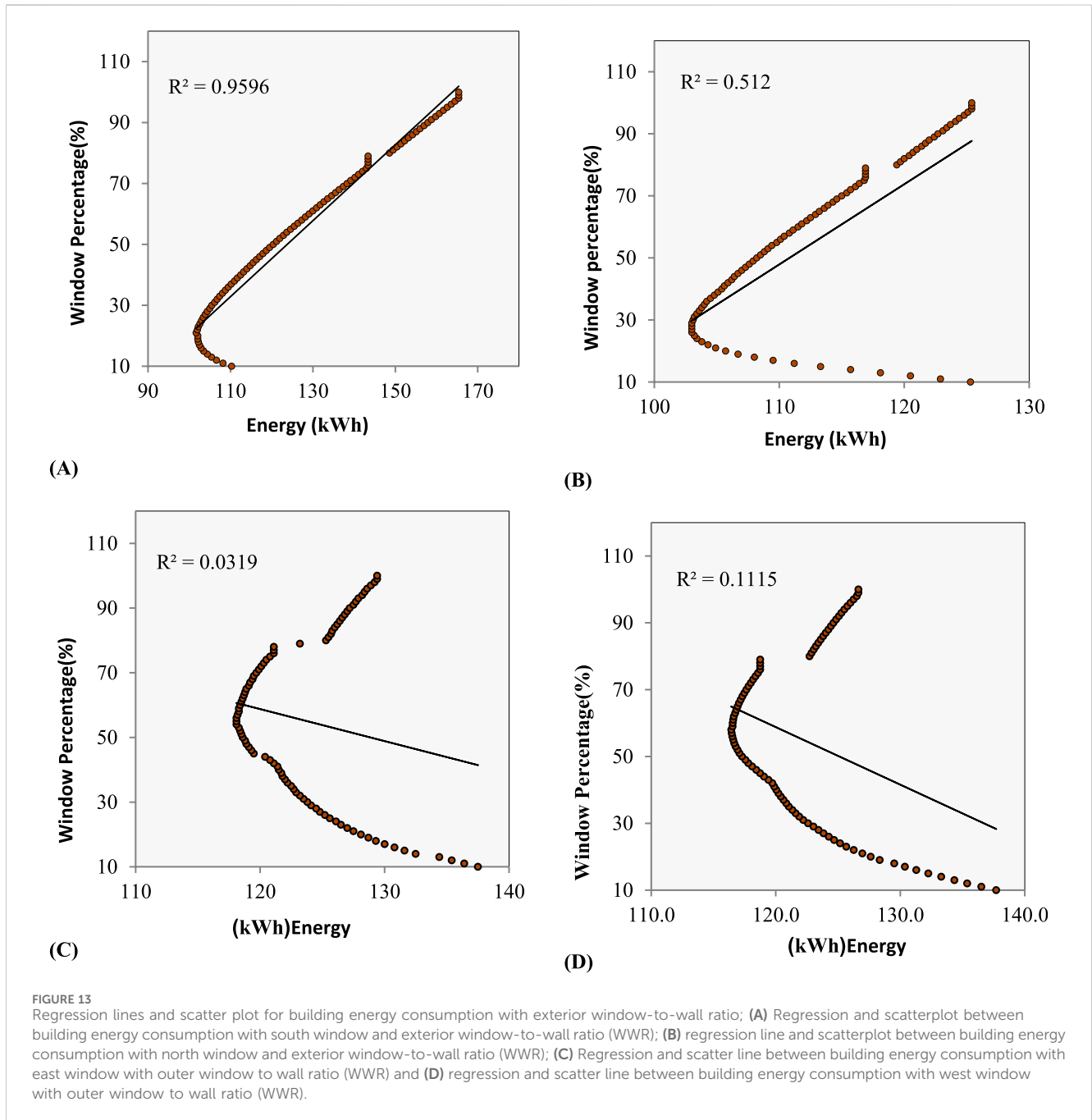
Additionally, it is useful for existing buildings, as it can guide redesigns and renovations aimed at enhancing energy efficiency.
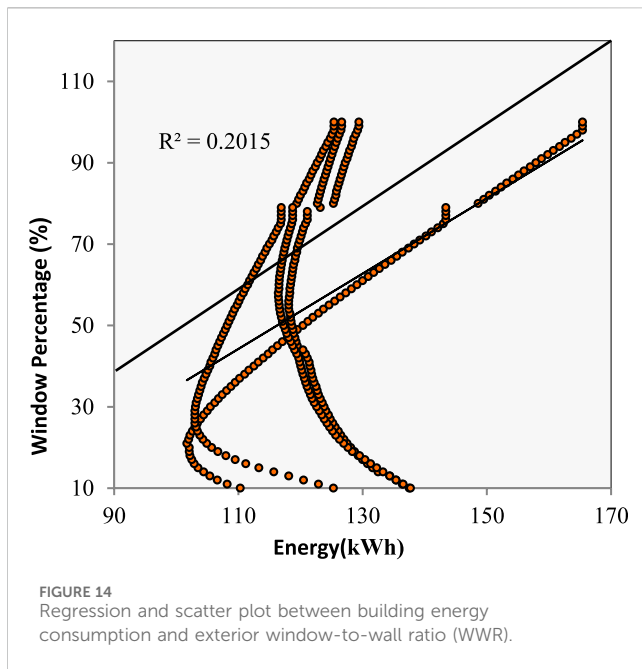
5 Conclusion

This research investigated and determined the optimal percentage of windows for the north, south, east, and west facades of residential buildings in Rasht, a city with a moderate climate. By analyzing the correlation between energy consumption

TABLE 3 Correlation results between building energy consumption and exterior window-to-wall ratio.

	R	R^2	Slope	p-value	Eq
Energy consumption of building with south window	0.97	0.95	0.76	<0.0001	$E_s = 0.76WWR + 85.4$
Energy consumption of building with north window	0.72	0.51	0.19	<0.0001	$E_N = 0.19WWR + 101.8$
Energy consumption of building with east window	0.17	0.03	−0.03	<0.009	$E_E = −0.03WWR + 125.6$
Energy consumption of building with west window	0.33	0.11	−0.06	<0.001	$E_W = −0.06WWR + 125.8$
Total building energy consumption	0.44	0.20	0.21	<0.0001	$E = −0.21WWR + 109.7$

FIGURE 13
Regression lines and scatter plot for building energy consumption with exterior window-to-wall ratio; **(A)** Regression and scatterplot between building energy consumption with south window and exterior window-to-wall ratio (WWR); **(B)** regression line and scatterplot between building energy consumption with north window and exterior window-to-wall ratio (WWR); **(C)** Regression and scatter line between building energy consumption with east window with outer window to wall ratio (WWR) and **(D)** regression and scatter line between building energy consumption with west window with outer window to wall ratio (WWR).

FIGURE 14
Regression and scatter plot between building energy consumption and exterior window-to-wall ratio (WWR).

and the window-to-wall ratio (WWR), the study aims to predict energy consumption for both existing and new residential structures, contributing to energy efficiency and sustainability.

Simulations were conducted using DesignBuilder software, focusing on solar gain, cooling load, heating, and lighting consumption across various window configurations. The key findings are:

- For the north side, the optimal window percentage was between 26% and 33%, with an energy consumption of 2,103 kWh/m^2 per year.
- For the south side, the optimal window percentage was 21%–25%, resulting in the lowest energy consumption of 2,102 kWh/m^2 per year.
- On the east side, the optimal window percentage ranged from 54% to 57%, with an annual energy consumption of 2,103 kWh/m^2.
- On the west side, the optimal window percentage was 58%, with an energy consumption of 116.24 kWh/m^2 per year.

The correlation coefficient between energy consumption and WWR was found to be 0.97 for the south-facing windows, indicating a strong relationship. For north-facing windows, the correlation coefficient was 0.72. The coefficients for the west and east facades were 0.33 and 0.17, respectively. Overall, the correlation coefficient for building energy consumption with WWR was 0.44.

These findings are valuable for predicting and optimizing energy consumption in buildings with various facades, providing useful insights for architects and designers. The research also highlights the potential for redesign and renovation of existing buildings to improve energy efficiency.

Given the significant energy consumption in the building sector, with a substantial portion lost through windows, these results can guide the adoption of optimal window proportions in residential buildings in Rasht and similar climates in Iran. Utilizing these findings contributes to sustainable architecture and reduces environmental impacts associated with greenhouse gas emissions. The methodology applied in this research could also be adapted for use in other climates.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Funding

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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