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The Effect of Using Tall Windows in Buildings on the Thermal Load of the Building and Its Cost Analysis: A Comparative Case Study for Antalya and Erzurum

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Abstract: The 150 cm tall windows that used as the standard in residential buildings are now being replaced by 220 cm tall windows, which are rapidly becoming widespread. This study examined different window types according to both the type of glass used as well as the type of fill material used in double-glazed windows in order to show the effect of window selection on the energy consumption of the building. A comparison between Antalya and Erzurum was also made in the study. The study was carried out on a building model with seven floors and twenty-four apartments, each of which has five units. The window heights in each unit were assumed to be 150 cm and were defined as Type 0. Five additional building types were defined by increasing the window heights in each unit, respectively. Thermal load values were calculated for all six building types and compared with each other. As a result, a 46.7% increase in the window area causes a maximum heat loss of 9.6% in Erzurum and a maximum heat gain of 45.1% in Antalya. These values bring about an increase in the energy consumption by an average of USD 1465.32 per year in Erzurum and an average of USD 581.08 per year in Antalya.

Keywords: tall window buildings; low-emissivity-coated glass; energy consumption; cost analysis; comparison

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1. Introduction

Parallel to the increase in the world population and to developing technology, energy consumption is increasing day by day. As a result of the effects of developing technology on the construction sector, e.g., the needs of the growing population and rising standards of living, the number of buildings is increasing rapidly. Considering the energy consumption scheme in Turkey, 32% is consumed in residences including commercial and public services, 36% in industry, 27% in transportation, and 4% in agriculture. It has been determined that 48% of the energy consumed in buildings is used by air conditioning systems for heating and cooling purposes [1]. Although their rates differ depending on whether the architecture is multi-story or single-story, the thermal loads in buildings are mostly through external walls, windows, roofs, floors, and ventilation. The heat losses in buildings are approximately 51% from the opening such as windows and doors, 20% from the exterior door, 13% from the roof, and 16% from the concrete floor [2].

Windows, which are indispensable construction components, not only provide a pleasant appearance to the building but also have features such as creating a tranquil indoor environment for people's comfort and allowing light and air to enter the building, thus providing the connection between the indoors and outdoors [3–5]. The window systems commonly used in today's buildings are temperature-controlled windows, which are called double-glazed (or double-paned) windows, because two or more glass plates are separated from each other by a metal frame, creating a controlled volume between the panes, which can either be dehumidified or filled with various gases (mostly a combination of the two) [6]. The gap between the glasses varies between 6 and 20 mm, and this gap reduces heat transmission as it creates a heat buffer. In double-glazed windows, it is possible to lower the thermal transmittance further by filling the inter-pane volume with dehumidified air or noble gases such as argon, krypton, and xenon. Due to the high cost of noble gases compared to air, the use of windows filled with noble gases in buildings is very rare, except for in special applications [4,7].

In addition to the window size, the energy consumption of buildings depends on the physical properties of the selected windows, such as the frame material, gap width, type of filler gas, number of glass panes used, coating properties, frame design, etc., which have a significant effect on the thermal transmittance coefficient of the windows [2,8]. When the window applications used in residences today are examined, it is seen that the exterior facades feature large glass-covered areas and/or large windows are mostly preferred. There are many research studies and innovative window systems that will improve the thermal transmittance coefficient of windows in order to minimize the thermal gains and thermal losses resulting from the use of large-area windows. One of these is low-emissivity coating systems, also known as low-E coating or low-E, which aim to reduce high thermal losses through window surfaces by reducing thermal transmittance without changing the optical properties of the glass. This coating system reflects the sun's long wavelength rays in the invisible region (infrared) with a wavelength greater than 780 nm, while allowing the passage of short wavelength rays in the visible region with a wavelength of 380–780 nm [9].

Low-E applications were first introduced in the early 1980s [9]. Low-E glass technology is a coating obtained by applying various film layers of gold, silver, copper, aluminum, transparent metal, and/or metal oxide characterized with a thickness of less than 10 nm to one or all of the glass surfaces, outside or inside, to increase the insulation properties of plain or colored glasses, to control the heat or light transmittance of the glass according to the climate zone. Low-E coatings are available in two different types depending on the region and purpose of use: passive (allowing sunlight to penetrate in cold climates) and solar-controlled (preventing sunlight from entering in hot climates) [10]. They are also produced in two types, hard and soft, according to the degree of hardness of the coating. Hard coatings are based on tin oxide, while soft coatings consist of a thin layer of silver [9].

Windows have been the subject of many studies in the literature for different purposes due to their high energy consumption potential. For example, in one study, the relationship between the electrical energy required for the cooling of buildings and the type of large windows in buildings was analyzed to determine the optimum window type and its contribution to energy consumption [11]. In another study, the optimum window/wall ratio range was investigated by examining different window sizes [12]. Whereas other studies have addressed the advantages and disadvantages that may be brought on by higher window/wall ratios [13]. Simko and Moore emphasized the need for a clear understanding of the importance of windows in architecture and improved housing performance [14].

In this study, the effect of floor-to-ceiling tall windows, which are increasingly used in today's residential architecture, on building heat load and energy costs was investigated. The study was carried out on six different models with different window heights in the same architectural layout and the results were presented comparatively. In double-glazed window types, the effect of glass types being low-E glass or clear glass, and the effect of the inter-pane volume being filled with dehumidified air or argon gas were compared and reported.

2. Materials and Methods

This study examines the effect of window height and window type choices on building energy consumption in residential buildings located in two different cities with two different climatic characteristics in Turkey, i.e., in Antalya, one of the warmest provinces, and in Erzurum, one of the coldest provinces (Figure 1).

Figure 1. Antalya and Erzurum provinces (Turkey).

Antalya (36°53′14.64″ N, 30°42′27″ E), located in southern Turkey, is the 5th largest city in terms of population with an estimated population of 2,750,000. Antalya has a hot summer Mediterranean climate or a 'humid' dry summer subtropical climate. The climate is characterized by hot, dry summers and mild, rainy winters. Antalya is very sunny, with nearly 3000 h of sunshine per year [15]. The annual temperature distribution in Antalya is presented in Table 1 [16].

Table 1. Meteorological data for Antalya (1930–2021).

Value	Avg. Temp. (°C)	Avg. Highest Temp. (°C)	Avg. Lowest Temp. (°C)	Avg. Insolation Time (h)	Avg. Total Monthly Rainfall (mm)	Highest Temp. (°C)	Lowest Temp. (°C)
January	10	14.9	6	5.1	234.6	23.9	−4.3
February	10.7	15.6	6.4	5.8	152.1	26.7	−4.6
March	12.9	18	8.1	6.7	94	28.6	−1.6
April	16.4	21.4	11.2	8	49.4	36.4	1.4
May	20.6	25.6	15.2	9.8	32.1	41.7	6.7
June	25.3	30.7	19.6	11.4	11	44.8	11.1
July	28.5	34.1	22.8	11.8	4.5	45	14.8
August	28.4	34.1	22.8	11.3	4.5	44.8	13.6
September	25.2	31.2	19.5	9.8	16.6	42.5	10.3
October	20.6	26.6	15.3	7.9	67.9	38.7	4.9
November	15.5	21.3	10.8	6.3	132.1	33	0
December	11.6	16.7	7.6	4.9	261.2	25.4	−1.9
Annual	18.8	24.2	13.8	8.2	1060	45	−4.6

Erzurum (39°54′31″ N, 41°16′37″ E) is a city located in eastern Turkey, which is 1959 m above the sea level, and has approximately 750,000 inhabitants. Erzurum has a humid continental climate with very cold, snowy winters and warm, dry summers. Snow cover is frequent in winter, but the dry nature of the climate usually prevents large accumulation [17]. The annual temperature distribution in Erzurum is presented in Table 2 [18].

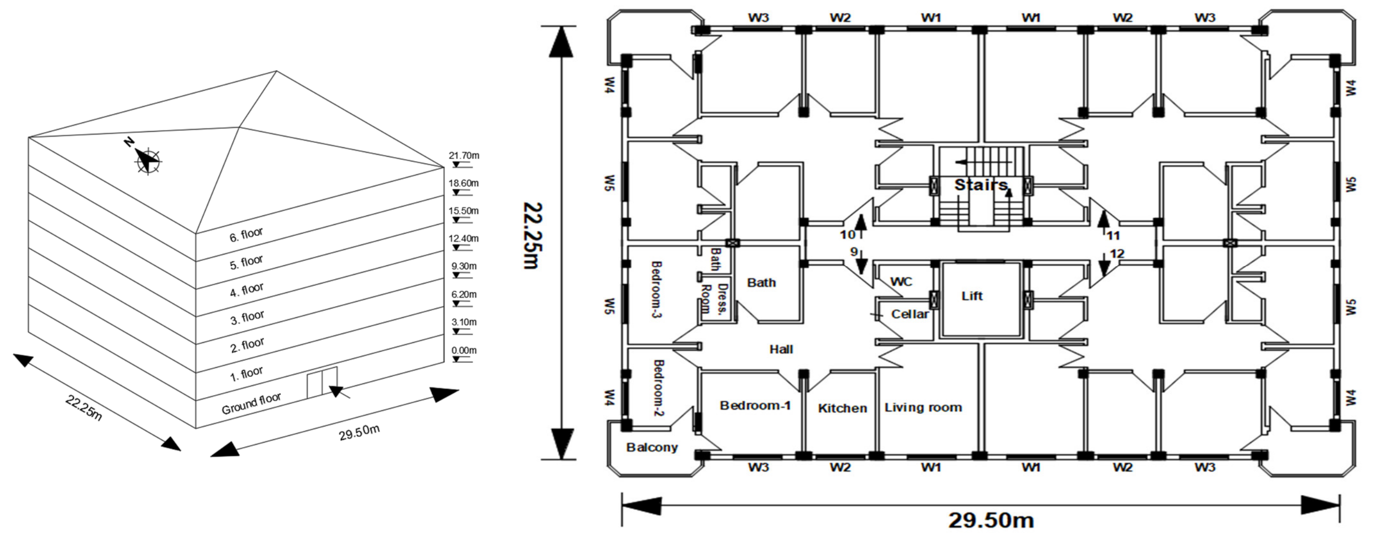
This whole study was carried out on a typical building project that is widely used in residential buildings. This study consists of determining the building architecture, determining the building types, selecting the window type, calculating the thermal loads (heat loss and heat gain) for each building type, and calculating the energy costs according to the thermal loads.

Table 2. Meteorological data for Erzurum (1929–2021).

Value	Avg. Temp. (°C)	Avg. Highest Temp. (°C)	Avg. Lowest Temp. (°C)	Avg. Insolation Time (h)	Avg. Total Monthly Rainfall (mm)	Highest Temp. (°C)	Lowest Temp. (°C)
January	−9.1	−4	−13.9	3.3	21.9	8	−36
February	−7.7	−2.3	−12.6	4.4	25.9	10.6	−37
March	−2.4	2.6	−7.1	5.2	35.4	21.4	−33.2
April	5	11	0	6.3	53.8	26.5	−22.4
May	10.7	16.9	4.4	8	72.4	29.6	−7.1
June	14.9	21.8	7.3	10.3	48.4	32.7	−5.6
July	19.2	26.6	11.1	11.2	27	35.6	−1.8
August	19.5	27.2	11.2	10.7	18.1	36.5	−1.1
September	14.8	22.7	6.4	9.1	24.3	33.3	−6.8
October	8.2	15.2	1.7	6.9	47.4	27	−14.1
November	1.1	6.9	−3.8	4.9	33.2	20.7	−34.3
December	−5.8	−1	−10.3	3.2	22.1	14	−37.2
Annual	5.7	12	−0.5	7	429.9	36.5	−37.2

2.1. Building Design

Despite the regional and cultural differences between Antalya and Erzurum provinces, the architectural layout was used in order to compare the results. In this study, a residential building model with a total of 24 apartments, consisting of 6 normal floors with 4 apartments on each and 1 ground floor was selected. The apartments are symmetrical and each apartment has a living room, kitchen, and 3 bedrooms. The aspects of the apartments are south-west for apartment 1, north-west for apartment 2, north-east for apartment 3, and south-east for apartment 4. There is a garage on the ground floor, and the floor height is 280 cm. The building site plan and apartment layout plan are shown in Figure 2.

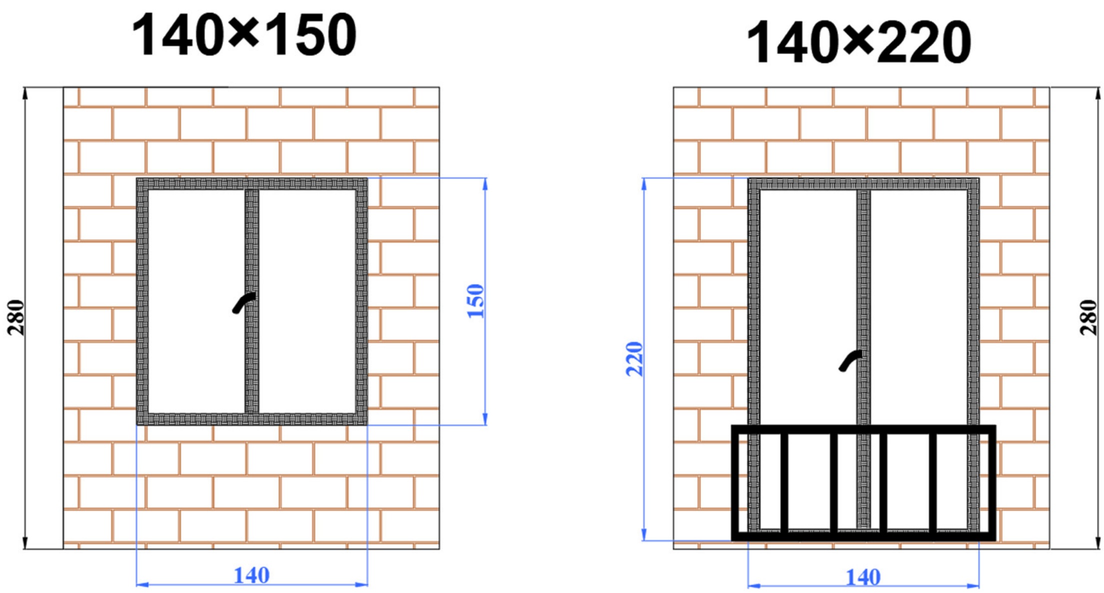


(**a**) (**b**)

Figure 2. Designed building (**a**) layout plan and (**b**) architectural project.

2.2. Determination of Building Types

The difference between the windows is shown in Figure 3, where a 220 cm tall window was used instead of 150 cm tall windows that are commonly used in residential buildings.



(**a**) (**b**)

Figure 3. Window types (**a**) h = 150 cm and (**b**) h = 220 cm.

In order to examine the effect of window height on building energy consumption, 6 different building types with different window heights were designed. In Type 0 building, which is the reference building, all window heights are 150 cm. In Type 1 building, only the living room features 220 cm tall windows; whereas in Type 2 building, the living room and kitchen feature 220 cm tall windows; in Type 3 building, the living room, kitchen, and bedroom 1 feature 220 cm tall windows; in Type 4 building, the living room, kitchen, and bedroom (1 and 2) feature 220 cm tall windows; and finally, in Type 5 building, the living room, kitchen, and bedrooms (1–3) feature 220 cm tall windows.

The building types defined in this study and window sizes used in each unit are presented in Table 3.

Table 3. Building types according to window size.

Building Types	Living Room (W1)		Kitchen (W2)		Bedroom 1 (W3)		Bedroom 2 (W4)		Bedroom 3 (W5)		Total Number of Windows				Total Window Area (m^2)	Increase in Total Window Area (%)
	280 × 150	280 × 220	140 × 150	140 × 220	140 × 150	140 × 220	140 × 150	140 × 220	140 × 150	140 × 220	280 × 150	280 × 220	140 × 150	140 × 220		
Type 0	•		•		•		•		•		24		96		302.4	-
Type 1		•	•		•		•		•			24	96		349.44	15.6%
Type 2		•		•	•		•		•			24	72	24	372.96	23.3%
Type 3		•		•		•	•		•			24	48	48	396.48	31.1%
Type 4		•		•		•		•	•			24	24	72	420.00	38.9%
Type 5		•		•		•		•		•		24		96	443.52	46.7%

2.3. Selection of Window Types

In order to examine the effect of window choice on the thermal energy of the building, different types of windows were defined, according to both the type of glass used (low-E glass and clear glass) and the type of filling material used (air and argon). Window types are presented in Table 4 [19].

Table 4. Selected window types.

Building Type	Feature	U (Wm^{-2} K^{-1})
Type A	Air-filled, PVC-framed, double-glazed [a], and clear glass	2.60
Type B	Air-filled, PVC-framed, double-glazed [a], and low-emissivity-coated glass	1.70
Type C	Argon-filled, PVC-framed, double-glazed [a], and clear glass	2.55
Type D	Argon-filled, PVC-framed, double-glazed [a], and low-emissivity-coated glass	1.50

[a] 4 + 16 + 4 window type.

2.4. Determination of Construction Component

Before determining the thermal loads of the buildings for every building type, the structural components were formed in accordance with the Turkish Standards (TS). The compatibility of the determined building components was checked with the TGUB analysis software developed by the Turkish Autoclaved Aerated Concrete Association [20]. The structural components determined according to thermal comfort conditions and as per TS are presented in Table 5 [21].

Table 5. Thermal transmittance coefficients of construction components.

Construction Component	U (Wm^{-2} K^{-1}) Erzurum	U (Wm^{-2} K^{-1}) Antalya	Construction Component	U (Wm^{-2} K^{-1}) Erzurum	U (Wm^{-2} K^{-1}) Antalya
External wall 1	0.401	0.535	Window 1	2.6	2.6
External wall 2	0.3598	0.4311	Window 2	1.7	1.7
Column and beam	0.491	0.682	Window 3	2.55	2.55
Internal wall	1.288	1.288	Window 4	1.5	1.5
Internal door	2	2	Floor-1	0.275	0.359
Balcony door	3.5	3.5	Floor-2	0.618	0.75
External door	4	4	Ceiling	0.387	0.579

TS EN 13162 mineral and vegetable fiber rockwool with a thermal conductivity coefficient of 0.035 Wm^{-1} K^{-1}, produced in compliance with the standards, was used as insulation material [22]. Since the climates of the cities selected in the study are different, the construction components used are also different. The reason for this is that the most economical construction components that conform to the TS in terms of the amount of condensation that occur in the construction component during heat transfer through the building envelope is selected. While the external walls consist of 4 cm insulation material and 23 cm bricks in Antalya province, a 6 cm insulation was employed on the sandwich-type external walls in Erzurum.

2.5. Calculation of Thermal Loads

2.5.1. Heat Loss

The heat loss (Q_{loss}), also known as the heating load of the building, is calculated using Equation (1) [19].

$$Q_{loss} = Q_{loss,0}(1 + Z_D + Z_H + Z_W) \quad (1)$$

Here, $Q_{loss,0}$ is non-incremental heat loss value, Z_D is the direction factor, Z_H is the effect of window height, and Z_W is the combined effects during the design. The $Q_{loss,0}$ is calculated as the sum of heat losses of the construction components in Equation (2) [19].

$$Q_{loss,0} = \sum_j U_j A_j (T_{i,air} - T_{0,air}) \quad (2)$$

Here, the index j denotes construction components, such as external wall, internal wall, and window. U_j, A_j, $T_{i,air}$, and $T_{0,air}$ are, in respective order, the thermal transmittance coefficient of construction components (Wm^{-2} K^{-1}), the surface area of construction components (m^2), indoor air temperature (K), and outdoor air temperature (K) [19].

2.5.2. Heat Gain

The heat gain value of the buildings (Q_{gain}) is the sum of total outdoor heat gain of building, $Q_{outdoor}$, and total indoor heat gain of building, Q_{indoor}, and is calculated with Equation (3) [2,23].

$$Q_{gain} = \sum Q_{outdoor} + \sum Q_{indoor} \tag{3}$$

$Q_{outdoor}$ is the sum of total conduction heat of construction components ($Q_{conduction}$), total radiation heat from windows ($Q_{radiation}$), and the heat gain with fresh air (Q_{fresh_air}). $Q_{outdoor}$ is calculated with Equation (4) [2,23].

$$Q_{outdoor} = \sum Q_{conduction} + \sum Q_{radiation} + \sum Q_{fresh\_air} \tag{4}$$

Q_{indoor} is the sum of total heat from humans (Q_{human}), total heat from lamps (Q_{lamp}), and total heat caused from the use of equipment ($Q_{equipment}$), such as computers, refrigerators, and televisions. Q_{indoor} is calculated with Equation (5) [2,23].

$$Q_{indoor} = \sum Q_{human} + \sum Q_{lamp} + \sum Q_{equipment} \tag{5}$$

2.6. Determination of Systems Costs

In all systems that use energy, continuously or periodically, the cost of energy consumption should be evaluated together with the initial investment cost when analyzing the economics of the system. The total cost of any energy system consists of the initial investment cost and operating costs, which includes maintenance–service costs, labor costs, and energy consumption costs.

2.6.1. Initial Investment Costs

The initial investment cost of any system includes all costs (including the costs of device, equipment, assembly, and structure) incurred until the system is actively operating, that is, until it performs its task. While examining differences in the initial investment costs caused by the window height, not only the differences of building components, such as windows, walls, and paints, but also the differences of the initial investment costs of energy systems due to changes in thermal loads are calculated.

2.6.2. Operating Costs

Operating costs consist of maintenance and service costs, energy consumption costs, and labor costs. In this study, only the energy consumption costs arising from the differences in thermal loads were calculated as operating costs since only the differential costs due to the effect of window size were examined. Maintenance–service and labor costs were not taken into account since the difference costs could not be incurred.

Since it is assumed that natural gas central heating system is used for heating and a domestic split air conditioner is used for cooling in the building types, the amounts of natural gas consumption and electrical energy are calculated while determining the amount of energy consumption by the systems.

The annual consumption of natural gas (B_y) was determined using Equation (6) [19].

$$B_y = \frac{3.6 Q_{loss} Z_d Z_a}{2 H_u \eta_t} \qquad (\text{kg year}^{-1} \text{ or m}^3 \text{ year}^{-1}) \tag{6}$$

where, Q_{loss} is the total heat loss, Z_d is the daily operating time (hour day^{-1}), Z_a is the annual operating time (day $year^{-1}$), H_u is the lower heating value (H_u = 8250 kcal m^{-3} for natural gas), and η_t is thermal efficiency of the heating system [19].

The amount consumption amount of electric energy ($Q_{electric}$) was determined with Equation (7) [19].

$$Q_{electric} = \frac{Q_{device} Z_d Z_a}{F_D} \quad (7)$$

where, Q_{device} is the capacity of device and F_D is diversity factor.

3. Results and Discussion

All standard values used in the calculations of the thermal loads were taken from the TS. Some important standard values used in the calculations and the assumptions made are listed below [19,22,23].

- The garage on the ground floor was also naturally air-conditioned.
- A central heating system with natural gas was preferred for the heating system.
- A split air conditioner was preferred for the cooling system.
- The building was a free-standing layout type.
- The heating system was selected so that the system runs continuously, with the set value turned down during night.
- The passive type in Erzurum and solar-controlled type in Antalya were selected as the window coating types.
- Ambient data assumed to be for Erzurum and Antalya, respectively;
- $T_{0,air}$ is −21 °C and +3 °C (winter);
- $T_{0,air}$ is +30 °C and +39 °C (summer);
- $T_{i,air}$ is +25 °C and +29 °C (summer);
- φ_{out} is 55% and 45% (summer);
- φ_{in} is 60% and 35% (summer).
- All thermal loads are presented in kcal h^{-1} in the calculations.
- In Erzurum, the heating system was considered to operate for 8 months, October–May, and the cooling system operated for only one month, August.
- In Antalya, the heating system was considered to operate for 5 months, November–March, and the cooling system operated for 4 months, June–September.
- In the solar irradiation calculations, the shading factor was taken as 0.9 for windows with clear glass, and 0.5 for windows with low-E glass.

3.1. Heat Loss

The results obtained in this study that addressed the six different building types and four different window types in two different climate zones are presented comparatively. The thermal losses of the buildings were calculated separately for each apartment and are presented graphically. A sample calculation is presented in Table 6. The total heat loss values of the apartments are presented in Figure 4 for Erzurum and in Figure 5 for Antalya for each window type and building type.

Table 6. Head loss values of Type A according to building types (Erzurum).

Floor	Apartment Number	Type A					
		Type 0	Type 1	Type 2	Type 3	Type 4	Type 5
1	1	6169.4	6349.6	6435.3	6525.5	6620.0	6714.5
	2	6418.1	6616.1	6710.2	6809.2	6903.7	6998.2
	3	6418.1	6616.1	6710.2	6809.2	6903.7	6998.2
	4	6169.4	6349.6	6435.3	6525.5	6620.0	6714.5
2	5	5300.3	5480.5	5566.3	5656.4	5750.9	5845.5
	6	5473.2	5671.2	5765.3	5864.3	5958.8	6053.3
	7	5549.1	5747.0	5841.1	5940.1	6034.6	6129.2
	8	5300.3	5480.5	5566.3	5656.4	5750.9	5845.5
3,4	9,13	5477.7	5666.7	5756.7	5851.2	5950.2	6049.1
	10,14	5473.2	5671.2	5765.3	5864.3	5958.8	6053.3
	11,15	5549.1	5747.0	5841.1	5940.1	6034.6	6129.2
	12,16	5300.3	5480.5	5566.3	5656.4	5750.9	5845.5
5	17	5300.3	5480.5	5566.3	5656.4	5750.9	5845.5
	18	5473.2	5671.2	5765.3	5864.3	5958.8	6053.3
	19	5549.1	5747.0	5841.1	5940.1	6034.6	6129.2
	20	5300.3	5480.5	5566.3	5656.4	5750.9	5845.5
6	21	7168.5	7348.7	7434.5	7524.6	7619.1	7713.7
	22	7417.3	7615.2	7709.3	7808.3	7902.8	7997.4
	23	7417.3	7615.2	7709.3	7808.3	7902.8	7997.4
	24	7168.5	7348.7	7434.5	7524.6	7619.1	7713.7
Total		141,193.0	145,748.6	147,915.3	150,193.1	152,470.9	154,748.7

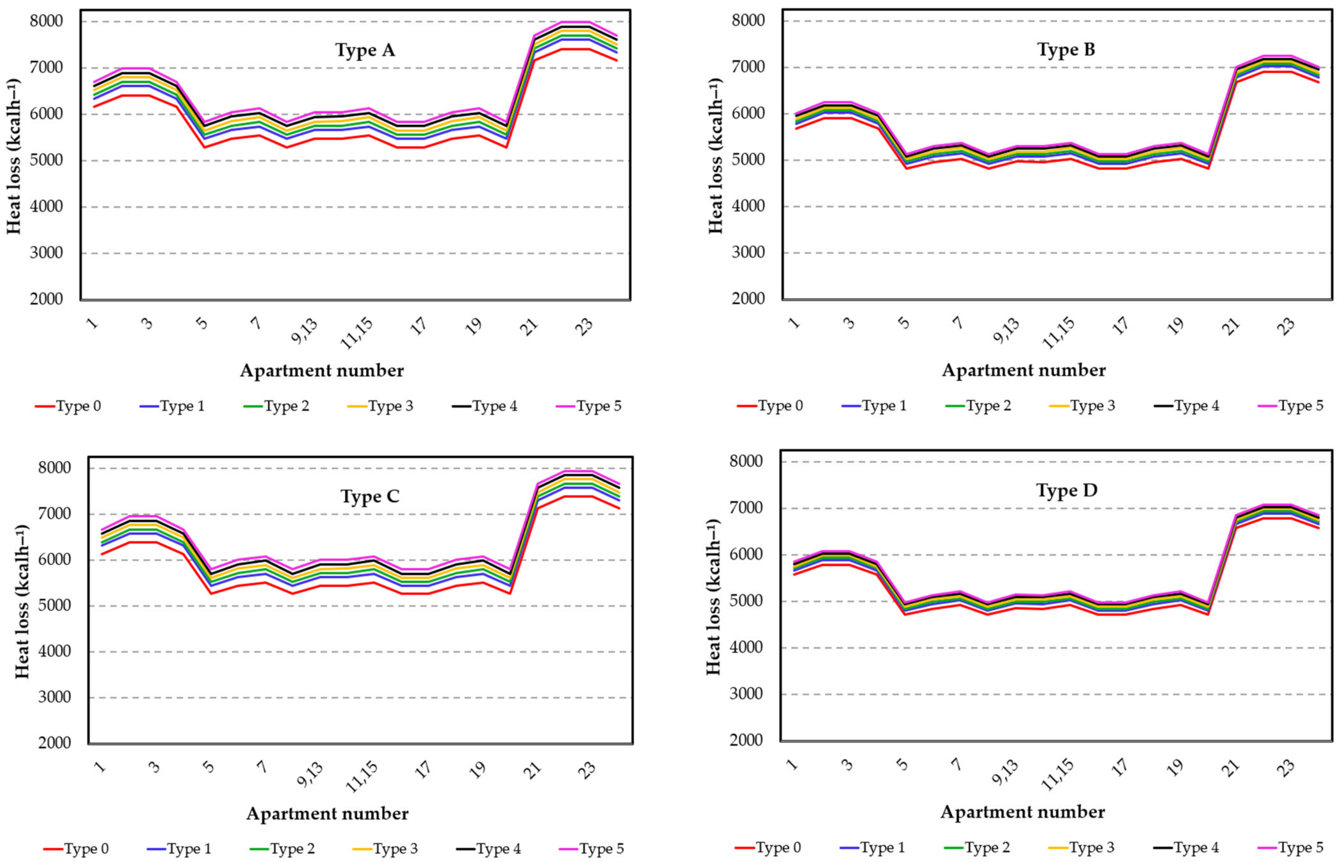


Figure 4. Comparison of heat loss according to window type for Erzurum.

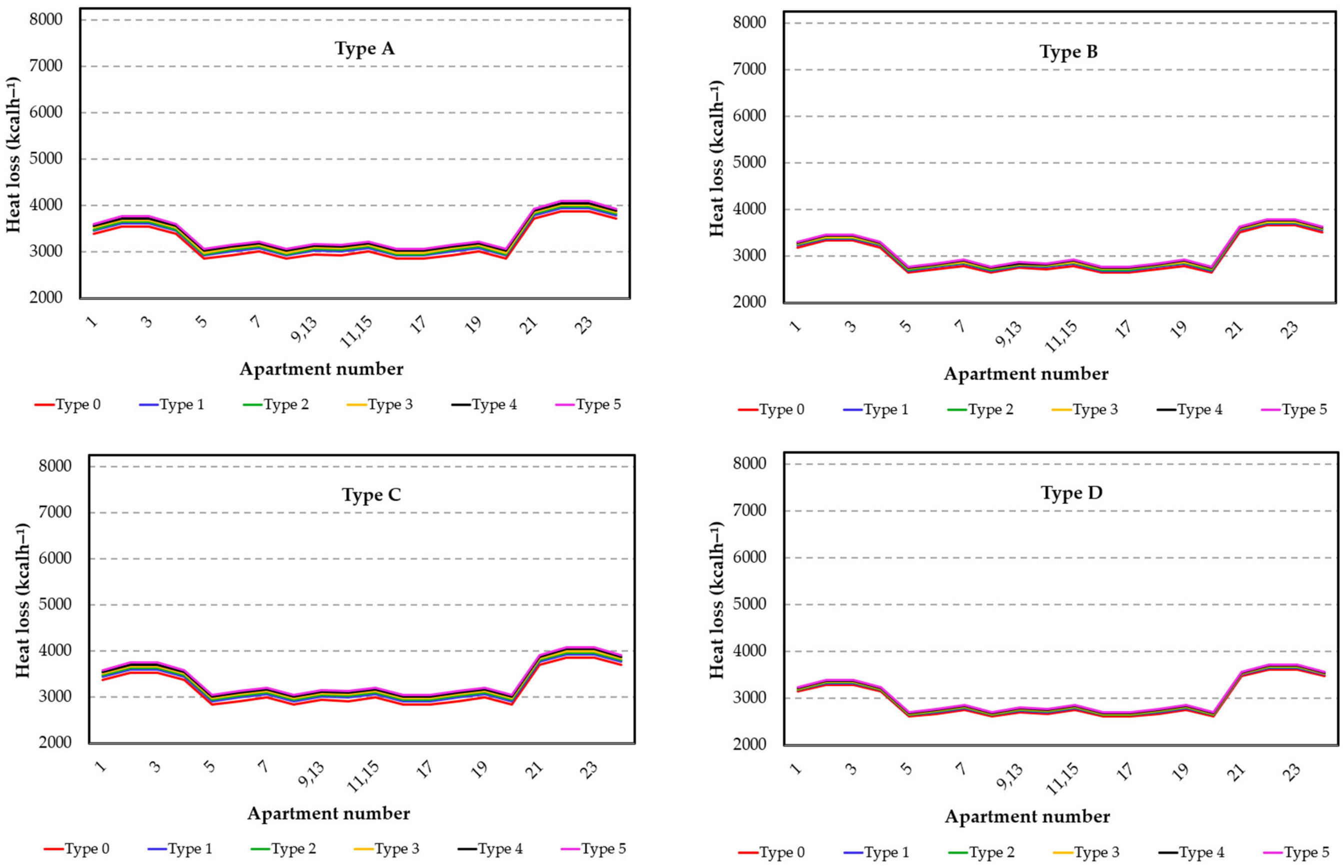


Figure 5. Comparison of heat loss according to window type for Antalya.

When Figures 4 and 5 are analyzed, the following can be observed:

- It is seen that the heat loss in the apartments numbered 1, 2, 3, and 4 on the first floor above the unheated volume (garage) is much higher than the heat loss in the apartments on the intermediate floors.
- It is also observed that the heat loss in the apartments on the top floor is much higher than for the apartments on the intermediate floors due to the heat loss through the roof.
- Similarly, although located on the same floor, this difference in apartments with different heat loss values varies depending on the direction of the apartment.
- It is seen that the heat loss values in Type 1, 2, 3, 4, and 5 buildings, which show a gradual transition from a 150 cm tall window to a 220 cm tall window, are more distinctly spaced in Type A and C windows, whereas they are narrower in Type B and D windows with low-E glass.
- The positive effect of low-E technology in windows on heat loss is evident in Type B and D.

In order to graphically illustrate the effect of low-Es, a Type 0 building with all the windows measuring 150 cm in height was compared with a Type 5 building with all the windows measuring 220 cm in height. The comparison for Erzurum is presented in Figure 6 and the comparison for Antalya is presented in Figure 7.

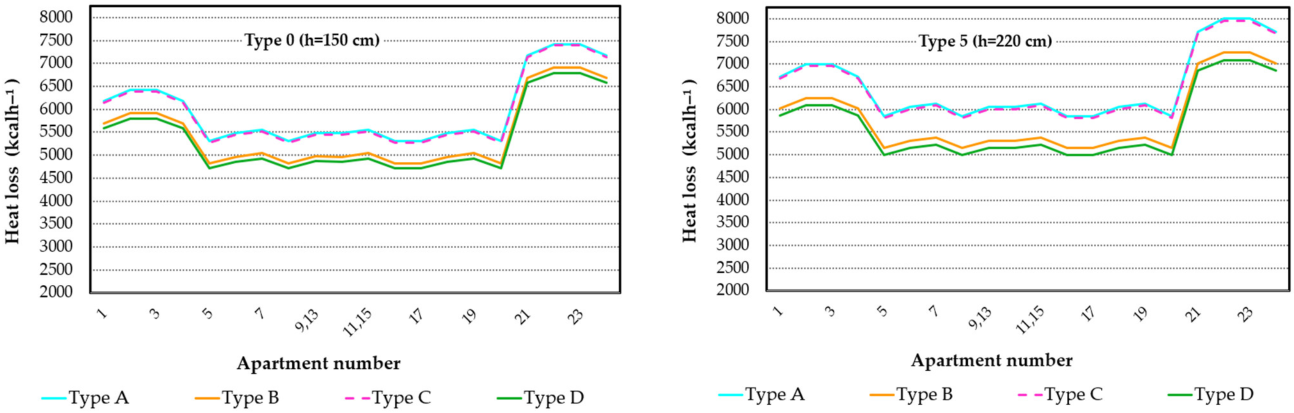


Figure 6. Comparison of window types according to window height (Erzurum).

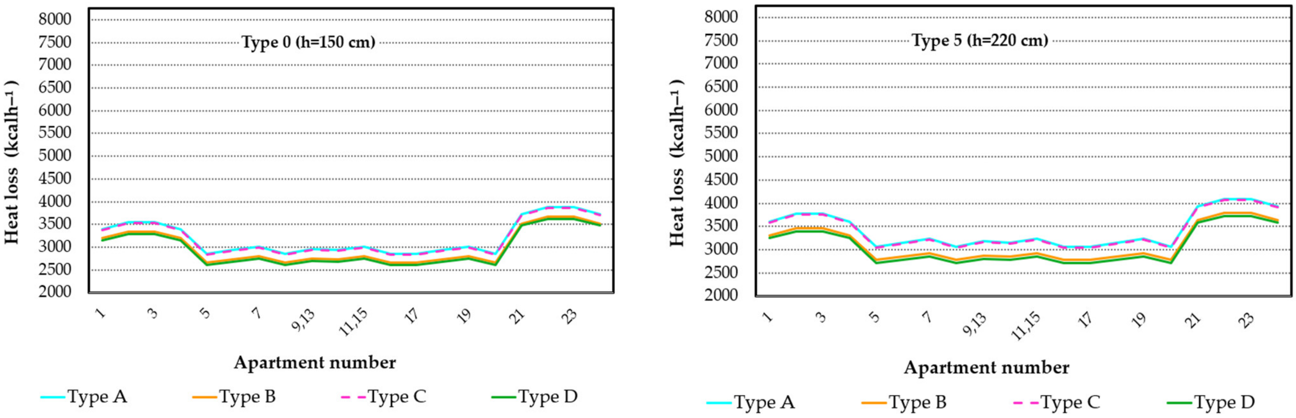


Figure 7. Comparison of window types according to window height (Antalya).

Examining Figures 6 and 7, the following can be observed:

- The heat loss values of windows with clear glass are significantly higher than of windows with low-E glass.
- Since the U values of Type C and Type A windows defined in Table 4 are very close to each other, the lines appear almost adjacent to each other in the graph.
- In Erzurum, which has a colder climate, the heat loss in apartments is higher than in Antalya due to the larger ΔT values.
- There is a noticeable increase in heat loss with an increasing window height.
- The difference in heat loss between apartments on the same floor, i.e., the fluctuation in the figure, is also larger in Erzurum. This shows the importance of solar energy in cold climates.

The heat loss values of each building type and window type, and the percentage of the change with respect to the reference building, Type 0, are presented in Table 7 for Erzurum.

Table 7. Heat loss values for Erzurum.

Building Type	Window Type							
	Type A		Type B		Type C		Type D	
Type 0	141,193.0	-	129,304.2	-	140,532.5	-	126,662.3	-
Type 1	145,748.6	3.2%	131,995.4	2.1%	144,984.5	3.2%	128,939.1	1.8%
Type 2	147,915.3	4.8%	133,275.3	3.1%	147,101.9	4.7%	130,021.9	2.7%
Type 3	150,193.1	6.4%	134,620.8	4.1%	149,328.0	6.3%	131,160.3	3.6%
Type 4	152,470.9	8.0%	135,966.4	5.2%	151,554.0	7.8%	132,298.7	4.4%
Type 5	154,748.7	9.6%	137,312.0	6.2%	153,780.0	9.4%	133,437.1	5.3%

When Table 7 is analyzed, it is an expected result that the heat loss values will also increase with an increasing window area according to the building types. The main purpose of this study is to examine and quantify the relationship between these increases. The 46.7% increase in the window area in the Type 5 building caused the highest increase in thermal loss in the Type A building with clear glass and the lowest increase in the Type D building with low-E glass. Although the Type A and Type C values are close to each other, the difference between Type B and Type D is large. This is due to the argon used to fill the inter-pane volume. In addition, the effect of using low-E glass in windows is also clearly seen in Type B and Type D. Type B is lower than Type A under the same conditions and Type C is lower than Type D.

The heat loss values of each building type and window type, and the percentage of the change with respect to reference building, Type 0, are presented in Table 8 for Antalya.

Table 8. Heat loss values for Antalya.

Building Type	Window Type							
	Type A		Type B		Type C		Type D	
Type 0	75,816.1	-	70,943.7	-	75,545.4	-	69,860.9	-
Type 1	77,589.9	2.3%	71,944.4	1.4%	77,276.3	2.3%	70,689.9	1.2%
Type 2	78,372.5	3.4%	72,385.9	2.0%	78,039.9	3.3%	71,055.6	1.7%
Type 3	79,259.4	4.5%	72,886.3	2.7%	78,905.3	4.4%	71,470.0	2.3%
Type 4	80,146.3	5.7%	73,386.6	3.4%	79,770.8	5.6%	71,884.5	2.9%
Type 5	81,033.2	6.9%	73,887.0	4.1%	80,636.2	6.7%	72,298.9	3.5%

When the values in Table 8 are compared with Table 7, it is seen that the increase rates are close to each other among different building types, whereas they are quite different among the different window types. In Antalya, which has a warmer climate, despite the use of construction components with higher thermal transmittance, the heat loss values and the change in values are approximately 50% less than in Erzurum. This shows the effect of temperature differences on the heat loss value as well as the importance of construction components.

The relationship between the increase in the window areas and heat loss values is presented in Figure 8, comparing Erzurum and Antalya.

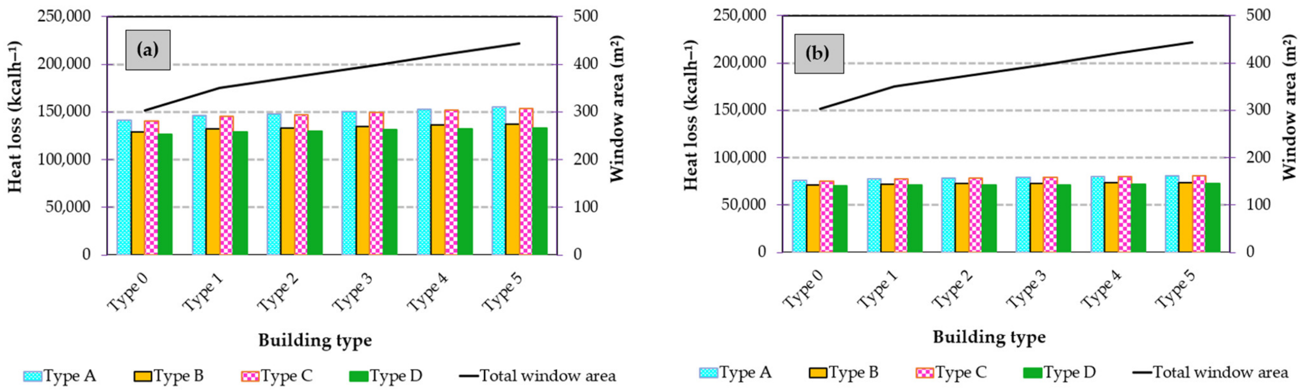


Figure 8. Comparison of heat loss values (**a**) Erzurum and (**b**) Antalya.

In Figure 8, which visually represents the values given in Tables 8 and 9, it is seen that the values in Erzurum are higher than the values in Antalya. It is also clear from the figure that the increase in the windows with clear glass is greater than the increase in the windows with low-E glass.

3.2. Heat Gain

In this study, which was conducted to examine the effect of the use of tall windows in residential buildings on building thermal loads, the Q_{indoor} values, which were the same for all building and window types, were not included in the calculations. Therefore, only the $Q_{conduction}$ and $Q_{radiation}$ values of the building were analyzed.

The gain values by conduction and the percentage of the change with respect to the reference building, Type 0, are presented in Table 9 for Erzurum.

Table 9. Heat gain values by conduction for Erzurum.

Building Type	Window Type							
	Type A		Type B		Type C		Type D	
Type 0	13,732.44	-	12,620.02	-	13,670.64	-	12,372.81	-
Type 1	13,943.89	1.5%	12,725.62	0.8%	13,876.20	1.5%	12,454.90	0.7%
Type 2	14,049.61	2.3%	12,778.43	1.3%	13,978.99	2.3%	12,495.94	1.0%
Type 3	14,155.33	3.1%	12,831.23	1.7%	14,081.77	3.0%	12,536.98	1.3%
Type 4	14,383.69	4.7%	12,945.28	2.6%	14,303.78	4.6%	12,625.64	2.0%
Type 5	14,612.05	6.4%	13,059.34	3.5%	14,525.79	6.3%	12,714.29	2.8%

When the heat gain increase rates in Table 9 are examined, it can be seen through the difference between the Type A and Type B windows that there is less heat gain in the windows with low-E glass than in the windows with clear glass. Likewise, it is evident through Type A and Type C that the use of argon gas in the inter-pane volume brought on a smaller heat gain.

The gain values by conduction and the percentage of the change with respect to the reference building, Type 0, are presented in Table 10 for Antalya.

Table 10. Heat gains by conduction for Antalya.

Building Type	Window Type							
	Type A		Type B		Type C		Type D	
Type 0	18,298.10	-	17,185.68	-	18,236.30	-	16,938.48	-
Type 1	18,478.03	1.0%	17,259.77	0.4%	18,410.35	1.0%	16,989.05	0.3%
Type 2	18,568.00	1.5%	17,296.82	0.6%	18,497.38	1.4%	17,014.33	0.4%
Type 3	18,657.96	2.0%	17,333.86	0.9%	18,584.40	1.9%	17,039.61	0.6%
Type 4	18,852.28	3.0%	17,413.87	1.3%	18,772.37	2.9%	17,094.23	0.9%
Type 5	19,046.61	4.1%	17,493.89	1.8%	18,960.34	4.0%	17,148.84	1.2%

When the values in Table 10 are evaluated, it ca be seen that the heat gain values by conduction in Antalya are higher than Erzurum, but the rate of increase is lower. This situation causes an increase in the heat gain values due to the high ΔT of summer months in Antalya.

Another important parameter in the calculations of the heat gain values of buildings is the heat gain by radiation. The solar radiation data that belong to cities are shown in Figure 9 [24]. The heat gain by the radiation of buildings is presented in Table S1 for both cities.

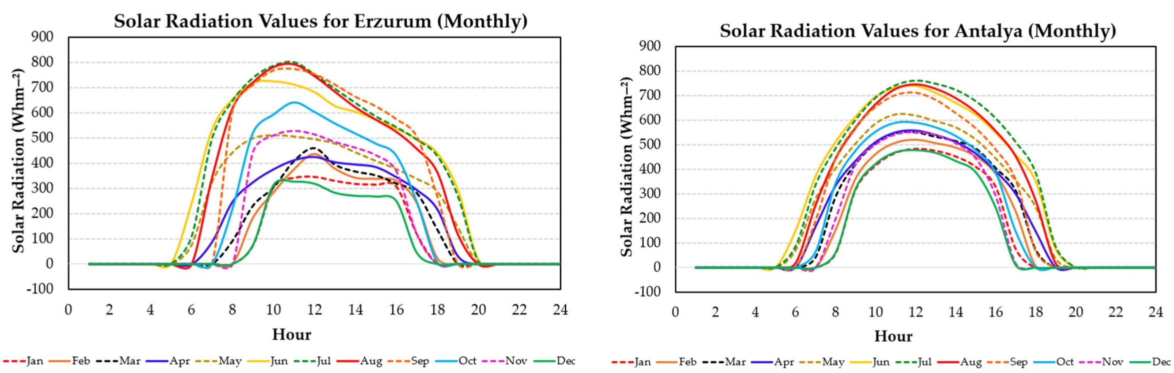


Figure 9. Solar radiation values of cities.

Erzurum, a cold city, is exposed to high solar radiation due to its altitude in the summer months. However, the low solar radiation data in winter months and its high altitude are the reasons for its low winter temperatures.

3.3. Costs Analysis

The use of 220 cm tall windows instead of 150 cm tall windows has an impact on the thermal loads of the buildings in terms of both the initial investment costs and the energy costs. For this reason, each cost has been discussed in detail while examining the results of this study. Since the building type, window type, and cost variety are large, the costs are shown in a table.

The obtained results are presented by taking the differential values according to the Type 0 building, which is defined as the reference building. The Type 0 building was taken as a reference and all relevant cost calculations were made as differences. There are two reasons for using differential values with respect to a reference building:

- Different results may be obtained in different studies since the thermal loads and related costs in buildings depend on many different parameters such as the size, architecture, and location of the building.
- In buildings with different base area to surface area proportions, the differential costs incurred by the change in the window size may become too small so that the implementation seems insignificant in comparison. Such situations will relatively reduce the emphasis on the importance of energy saving, which is the main objective of this study.

Before examining the cost difference tables according to the Type 0, it is recommended to examine Table 11, which describes the parameters in the cost tables. All the costs were obtained from [25].

Table 11. Parameters and details used in cost calculations.

Par. N.	Parameter Description	Properties	Price (USD)
P1	The difference in the cost of windows between tall windows and standard windows.	Type A	68.47
		Type B (Erzurum)	73.52
		Type B (Antalya)	95.21
		Type C	68.84
		Type D (Erzurum)	79.22
		Type D (Antalya)	95.58
P2	Cost of external wall area to be saved when tall windows are used.	External wall 1 (Erzurum)	60.44
		External wall 1 (Antalya)	56.92
P3	The difference in initial investment costs of equipment in the heating system due to change in window height. (Note: The changes in the heating system components are limited to changes in the radiator size as the amount of heat loss increase was not very large. $Q_{radiator}$ was taken to be 1350 kcal h^{-1}.)	Radiator (1 m)	80.25
P4	The difference in initial investment costs of equipment in the cooling system due to change in window height. (Note: Addition split-type air conditioners were preferred for change in the cooling system components.)	Capacity 2–2.5 KW	76.63
P5	The difference in the cost of the amount of natural gas used in the heating system.	1 m^3 natural gas (Erzurum) [a]	0.313985221
		1 m^3 natural gas (Antalya) [b]	0.307528729
P6	The difference in the cost of electricity consumed by the air conditioner used in the cooling system.	1 kWh electricity [c]	0.09241

[a] Reference [26]; [b] Reference [27]; and [c] Reference [28].

The cost difference analysis of all types is in Tables S1–S9. The comparisons for all types are presented in Table 12.

Table 12. Comparison of costs for all types (USD).

Window Types	Type 0 P2	P1	P3	Type 5 P4	P5	P6
Type A (Erzurum)	8528.81	9662.72	735.46	193.06	1603.34	325.13
Type A (Antalya)	8032.75	9662.72	184.87	609.40	372.53	284.39
Type B (Erzurum)	8528.81	10,375.61	436.93	105.49	947.54	165.35
Type B (Antalya)	8032.75	13,435.35	310.12	270.50	376.07	148.11
Type C (Erzurum)	8528.81	9715.35	717.14	192.18	1566.62	317.56
Type C (Antalya)	8032.75	9715.35	184.87	608.53	372.53	276.82
Type D (Erzurum)	8528.81	11,180.07	363.64	102.01	800.65	135.07
Type D (Antalya)	8032.75	13,487.98	240.54	267.01	376.07	117.82

According to Table 12, the cooling system costs in Antalya are lower than in Erzurum. When examining Table 12, it should not be forgotten that the values in here are obtained by taking the difference according to the Type 0 building.

4. Conclusions

In order to improve the visual attractiveness as well as create tranquil interior spaces, the use of larger windows in houses, especially tall windows that extend down to the base, is increasing day by day. In this study, the effect of using 220 cm tall windows instead of 150 cm tall windows, which used to be the standard in residential buildings, on the building's thermal load and energy consumption was examined.

For this study, first of all, an original building with 150 cm tall windows was designed. In order to comparatively examine the effect of changing the window size, five more different building types were designed in the same architectural layout. In addition to the total of six different building types with different tall window lengths, four different window types were designed, featuring different glass types (clear glass and low-emissivity-coated glass) and different gas fills in the inter-pane volume (air or argon). All the studies were carried out separately for Antalya, one of the hottest provinces in Turkey, and Erzurum, one of the coldest provinces in Turkey. When the increase in window size, the change in the thermal load on the building, and the economic effects of this change are examined, the following can be observed:

- The 46.7% increase in window area brought on an increase in the heat loss for the most window with clear glass, Type-A, and the least window with low-E glass, Type-D.
- When the thermal loss values are examined, it can be seen that the thermal loss values in Erzurum were approximately 50% higher than in Antalya. Antalya, which has higher temperatures than Erzurum both in the summer and winter, had lower thermal loss values due to lower ΔT values in the winter. However, as for the heat gain, the opposite is the case.
- When thermal gain values are examined:
    - It can be seen that the thermal gain value by conduction in Erzurum was approximately 25% less than in Antalya. Although the heat gain value in Antalya increased with the increased window area, the increase rates with respect to Type 0 were less in Erzurum due to the lower ΔT values.
    - Due to the effect of insolation during the day in Antalya, the amount of heat gained by irradiation in Antalya is higher than in Erzurum. The 46.7% increase in the window area resulted in an approximately 30% increase in heat gain by radiation.
- Since the thermal transmittance coefficients of windows with low-e glass are lower, they have a positive effect from 70% to 75% in thermal gain values and 50% to 60% in heat loss values.
- In cold climates such as Erzurum, the energy consumed by heating systems is always much higher than the energy consumed by the cooling system.

- In hot climates such as Antalya, the energy consumed by heating systems is always much lower than that consumed by the cooling system.
- The 46.7% increase in the window area led to an increase in energy consumption in both the heating system and the cooling system. This value is approximately 50% less in the case of windows with low-E glass.
- The average cost of energy consumption increased by USD 1465.32 per year in Erzurum and USD 581.08 in Antalya due to the increased window area. All these values were discussed in detail in the study.

The differences between this study and similar studies that have researched windows in buildings in the literature are described below.

1. This study used real window sizes from a real architectural project. However, in similar studies in the literature, approximate wall/window ratios were generally used, such as 10%, 20%, etc.
2. The costs are real values that are used in the markets.
3. In similar studies in the literature, the energy consumption values and costs caused by increased thermal loads due to an increased window area have been analyzed. Unlike the literature, this study also examined the differences in the initial investment cost caused by the increased capacities of the thermal system equipment due to increasing thermal loads.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13030731/s1, Table S1: The solar irradiation values for building and window types in Erzurum and Antalya; Table S2: Cost difference detail for Type A (Erzurum); Table S3: Cost difference detail for Type A (Antalya); Table S4: Cost difference detail for Type B (Erzurum); Table S5: Cost difference detail for Type B (Antalya); Table S6: Cost difference detail for Type C (Erzurum); Table S7: Cost difference detail for Type C (Antalya); Table S8: Cost difference detail for Type D (Erzurum); and Table S9: Cost difference detail for Type D (Antalya).

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Nomenclature

A_j	Surface area of construction components (m^2)
B_Y	Annual consumption amount of natural gas (kg year^{-1} or m^3 year$^{-1)}$
F_D	Diversity factor
h	Window height (m)
H_U	Lower heating value (kJm^{-3})
j	Construction components of building
$Q_{equipment}$	Heat gain from equipment (W)
$Q_{electric}$	Amount of electric energy consumption (kWh)
$Q_{conduction}$	Heat value by conduction (W)
Q_{device}	Heat gain from devices (W)
Q_{fresh_air}	Heat gain with fresh air (W)
Q_{gain}	Heat gain (W)
Q_{indoor}	Indoor heat gain (W)
Q_{lamp}	Heat gain from lamp (W)
Q_{loss}	Heat loss (W)

$Q_{loss,0}$	Non-incremental heat loss (W)
Q_{human}	Heat gain from humans (W)
$Q_{outdoor}$	Outdoor heat gain (W)
$Q_{radiation}$	Heat value by radiation (W)
$P1$	The difference in the cost of windows between tall windows and standard windows (USD)
$P2$	Cost of external wall area to be saved when tall windows are used (USD)
$P3$	The difference in initial investment costs of equipment in the heating system due to change in window height (USD)
$P4$	The difference in initial investment costs of equipment in the cooling system due to change in window height (USD)
$P5$	The difference in the cost of the amount of natural gas used in the heating system (USD)
$P6$	The difference in the cost of electricity consumed by the air conditioner used in the cooling system (USD)
$T_{o,air}$	Outdoor air temperature (K)
$T_{i,air}$	Indoor air temperature (K)
U_j	Thermal transmittance coefficient of construction components (Wm^{-2} K^{-1})
Z_a	Annual operating time (day year^{-1})
Z_D	Direction factor
Z_d	Daily operating time (hour day^{-1})
Z_H	Height effect
Z_W	Combined effect
η_t	Thermal efficiency
φ_{out}	Humidity value of outdoor
φ_{in}	Humidity value of indoor
Abbreviations	
W1, . . . , W5	Window1, . . . , Window5
TS	Turkish Standards
low-E	Low-emissivity coating

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