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# Optimizing Window Thermophysical Properties for Reducing Energy Demands, Energy Costs, and Greenhouse Gas Emissions in Residential Buildings of Türkiye

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A R T I C L E   I N F O

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A B S T R A C T

This study aimed to reevaluate the reference thermophysical property of windows (U-value) prescribed by the TS825 Thermal Insulation Requirements in Buildings standard based on three separate thermophysical categories (U-value, SHGC, and T-vis) with an aim to suggest an optimum window option to improve the sustainability of residential buildings in Türkiye align with the Goals 11, 12, and 13 of 2030 Sustainable Development Goals (SDGs). Accordingly, the energy performance of reference window type indicated by TS825 standard was tested for a sample residential building in Istanbul, using the DesignBuilder building energy simulation tool. Afterwards, in alignment with Goal 11, various new window types were proposed, and their impact on the annual energy demand of a sample building was analyzed. In the second phase, the effects of these window systems on energy costs were investigated vis-a-vis Goal 12. Finally, in the third phase, their impact on greenhouse gas emissions was assessed with a view to Goal 13. This study's hypothesis that the constant U-value approach in the TS825 standard does not adequately meet energy efficiency requirements across climatic conditions can significantly contribute to sustainable buildings. It provides outcomes to help policymakers optimize energy use and update standards toward Türkiye's 2030 SDGs.

# Türkiye'deki Konut Binalarında Enerji İhtiyaçlarını, Enerji Maliyetlerini ve Sera Gazı Emisyonlarını Azaltmak için Pencere Termofiziksel Özelliklerinin Optimize Edilmesi

M A K A L E   B İ L G İ S İ

***Anahtar Kelimeler:***
2030 Sürdürülebilir kalkınma hedefleri
Pencere
Enerji performansı
Enerji maliyeti
Sera gazı emisyonu

Ö Z E T

Bu çalışma, TS825 Binalarda Isı Yalıtım Kuralları standardında tanımlanan pencereler için referans alınan U-değerini yeniden değerlendirmektedir. Değerlendirme, yalnızca U-değeriyle sınırlı kalmayıp, güneş ısı kazanç katsayısı (SHGC) ve gün ışığı geçirme çarpanı (T-vis) gibi üç temel termofiziksel parametreyi de kapsamaktadır. Amaç, Türkiye'deki konut binalarının sürdürülebilirliğini artırmak üzere, 2030 Sürdürülebilir Kalkınma Hedefleri'nın (SKH) 11., 12. ve 13. hedefleri doğrultusunda en uygun pencere tipini belirlemektir. Bu kapsamda, TS825 standardındaki referans pencere tipi ile önerilen alternatifler, İstanbul'da bulunan örnek bir konut binasında, DesignBuilder enerji simülasyon programı kullanılarak test edilmiştir. Çalışmanın ilk aşamasında, 11. hedef doğrultusunda önerilen pencere tiplerinin yıllık enerji ihtiyacına etkisi analiz edilmiştir. İkinci aşamada, bu sistemlerin enerji maliyetlerine etkisi 12. hedef kapsamında incelenmiş; üçüncü aşamada ise sera gazı emisyonları üzerindeki etkileri 13. hedef bağlamında değerlendirilmiştir. Elde edilen sonuçlar, TS825'teki sabit U-değeri yaklaşımının farklı iklim koşulları için yeterli olmadığını ortaya koymakta ve enerji verimliliği standartlarının güncellenmesine yönelik politika yapıcılara stratejik öneriler sunmaktadır.

## NOMENCLATURE

| | | | |
|---|---|---|---|
| SDGs | Sustainable development goals | U-value | Overall heat transfer coefficient |
| SHGC | Solar heat gain coefficient | W | Air-filled window |
| RW | Reference window | WA | Argon-filled window |
| T-vis | Visible light transmittance | WK | Krypton-filled window |

## INTRODUCTION

The International Energy Agency (IEA) reported that today buildings globally account for the consumption of 37% of the total energy produced, 40% of the energy resources, 38% of the $CO_2$ emission, and 40% of waste (IEA, 2021). The energy consumption by buildings has gradually increased with the surge in construction activities. Furthermore, the fact that fossil fuels are used as the main source of energy, is associated with further dependence on foreign sources of energy, which increases the energy-related financial burden of countries. Türkiye is largely dependent upon energy imports. Fossil fuels dominate the energy supply in Türkiye, accounting for 83% of the total primary energy supply (TPES) in 2019, which is roughly equal to coal, oil, and natural gas, and accounts for 73% of total final consumption (TFC) in 2018 (IEA, 2021). Türkiye is geographically located in the temperate climatic zone. Therefore, the heating period lasts longer compared to the cooling period and the annual heating need of buildings in Türkiye is generally considered very high, regardless of the climatic region and accounts for 70% of the total energy consumed. The heat losses in buildings is originated from roofs (7%), external walls (40%), floors (6%), doors (17%), and windows (30%) (Mantotherm, 2023; TSE, 2008).

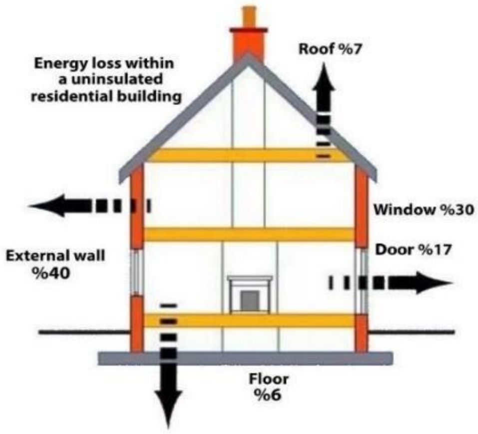



**Figure 1.** Heat loss rates in a residential building without insulation (Mantotherm, 2023; TSE, 2008).

In Türkiye, TS825 Thermal Insulation Requirements in Buildings standard is in place to prescribe the rules for calculations associated with the net heating energy demand and the highest allowable heating energy in buildings. This standard was incorporated into the zoning regulations by the Ministry of Environment, Urbanization and Climate Change in 1985. The purpose of this standard was to limit the amount of energy used for heating purposes in buildings in Türkiye with an aim to save energy and provide the standard calculation method and values for use in calculating the net heating energy demand (TSE, 2008). There are three versions of the TS825 standard published in 2008 and 2013 and 2024. The ministry does not mandate the use of the 2013 version of this standard. In addition, it is anticipated that the adaptation processes necessary for the effective implementation of the newly published version in 2024 will be completed by the first half of 2025 by the construction sector. Consequently, the 2008 version remains the most widely adopted standard in the sector. One of the important differences between these versions is the U-value of the windows as per the window-to-wall ratio (WWR). A more flexible approach was adopted for the window U-value in the 2008 version. In other words, no lower threshold was specified for window U-value, even if the WWR was high. Nevertheless, in the 2013 version, in cases where the WWR exceeds 60%, the U-value of the glass must be lower. This revision was intended to increase energy efficiency and improve the thermal insulation performance of buildings in Türkiye. If the WWR is below 60%, the U-value criteria of the 2008 version apply. In this case, a more flexible approach can be adopted, and the U-value values in the 2008 version can be harmonized. However, in all cases, it is important to choose glass with lower U-values where possible to improve energy efficiency. Pursuant to the TS825 standard published in 2008, Türkiye is divided into 4 different degree day regions by heat preservation and the standard prescribed the monthly average outdoor temperature ($t_d$) and average monthly solar radiation intensity values for use in calculations for all the degree day regions (TSE, 2008). The reference values (lower limits) of total heat transfer coefficients of the building envelope (exterior walls, floors, roofs, and windows) for each climatic zone (U-values) are set by this standard (Table 1).

**Table 1.** Reference U-values determined for degree day regions (TSE, 2008).

| *Regions* | $U_D$ ($W/m^2K$) | $U_T$ ($W/m^2K$) | $U_t$ ($W/m^2K$) | $U_P$ ($W/m^2K$) |
|---|---|---|---|---|
| *1. Region* | *0.70* | *0.45* | *0.70* | *2.4* |
| *2. Region* | *0.60* | *0.40* | *0.60* | *2.4* |
| *3. Region* | *0.50* | *0.30* | *0.45* | *2.4* |
| *4. Region* | *0.40* | *0.25* | *0.40* | *2.4* |

The U-values given in Table 1 are expanded below:

- $U_D$: Overall heat transfer coefficient of the external walls
- $U_T$: Overall heat transfer coefficient of the roofs
- $U_t$: Overall heat transfer coefficient of the floor adjacent the ground
- $U_P$: Overall heat transfer coefficient of the windows

As seen in Table 1, the U-values for exterior walls, roofs, and floors vary by region; nevertheless, it is remarkable that the U-values for windows remain constant. This standard prescribes the reference U-value for windows as 2.4 $W/m^2K$; nevertheless, the fact that the U-value of envelope areas, including windows, where heat losses and gains are rather high across the year, varies depending on the degree day region, will undoubtedly contribute in an increase in the energy conservation of buildings in Türkiye. A number of previous studies in the relevant literature suggested that windows selected specific to the climatic region improved the energy performance of buildings. Some of those studies are referred to below.

A study by Bektaş and Aksoy (2005) reported that windows, functioning as to adequately illuminate the interior volumes and provide the visual connection between the interior and exterior, where the components of the building envelop with the highest heat loss. It is a common practice to use double-glazed units with an aim to decrease heat loss through windows. Nevertheless, despite almost all the new buildings feature double glazing, it is no longer sufficient alone for the purposes of thermal insulation. It is possible to save up to 50% energy upon adequate insulation of the building and using the appropriate materials. Another study suggested that the amount of heat loss through building windows was dependent upon certain parameters, including window-to-wall ratio (WWR), frame, and glass type, and reported that double-glazed window types were mostly used as an alternative to single-glazed window types in Türkiye. In the present study, insulated glasses were created in double-glazed windows by leaving an air gap between two glass plates and by keeping dehumidified air and inert gas in this air pocket, thus preventing heat losses (Koyun & Koç, 2017). Yaman (2023) suggested that it was critical to consider the energy performance of buildings, when determining the window-to-wall ratios on building facades. Different types of glass and window frames should be considered with an aim to achieve better results in terms of heat loss and gain. Ünver et al. (2020) reported that in order to reduce energy losses caused by windows, single glass units in today's buildings were then being replaced by units with heat-light control coating, which featured double or triple glass units. Use of glass units with heat-light control coating in buildings is associated with a significant reduction in heat loss due to windows compared to standard uncoated glass units. Another study suggested that compared to uninsulated glass, use of glasses with high visible light transmittance (T-vis) and glasses with increased thermal insulation properties (low-e, reflective, self-cleaning, etc.) were critical components in buildings in terms of energy gains (Leftheriotis & Yianoulis, 2012). Khataybeh and Akgüç (2023) highlighted the importance of using smaller windows and climate-responsive passive design strategies to improve energy efficiency in hot-dry regions.

In the light of above, windows play a major role in the annual heating and cooling needs and consumption in buildings. Therefore, it has become more important to make calculations on how heat losses and gains via windows have an impact on the energy performance of the building. The effect of windows on the energy performance of the building can be calculated by means of building simulation tools. Building energy simulation tools have recently become popular among architects and engineers that they can facilitate significant energy and cost savings during the early design phase of the building. In addition, building energy simulation tools have become an integral part of integrated design because such tools allow

- the development of different design strategies and testing the strategies prior to implementation;
- taking necessary measures to reduce energy consumption values upon intervention in the design process as necessary;
- testing whether the required comfort and indoor air quality values are met;
- designing mechanical systems fit for the building and developing control strategies; and
- reducing the life cycle costs of the building and ensuring sustainability (Akgüç, 2020).

A number of previous studies in the relevant literature investigated the effects of windows used in buildings on the energy performance of the building and improving the energy efficiency of the building by means of building energy simulation tools. Some of those studies are referred to below.

A study compared different types of windows by various characteristics, including the U-value, solar heat gain coefficient (SHGC), and T-vis by means of building energy simulation tools for a sample building modeled for different climate types of the Asian continent. As a result, WWR on the northern façade of buildings should be below 25% and that reducing thermal conductivity in triple glazing provided higher savings for the purposes of the heating energy demand of the building (Lee et al., 2013). Another study suggested that keeping under control the heat losses and gains from the building envelope in buildings in Türkiye was a crucial requirement for Türkiye, considering the increasing building stock. The main purpose of this study was to investigate the effect of double glazing on building energy consumption using experiment and simulation tools in hot-humid climatic regions, where the cooling load was considered higher. According to the results of that study, it was seen that lower values of SHGC of the outer glass type and the U-value and SHGC of the inner glass type in double glazing made a significant contribution to reducing the cooling load of the building (Özbalta & Yıldız, 2020). Another study investigated a university building in Samsun as the case study building, based on testing window types with different U-values (triple low-e, single clear, double low-e and double clear) to see their effects on the heating energy of the building. In that study, it was aimed to save energy in buildings in Türkiye by improving the heating energy performance of the existing building stock. As a result, the window type with the lowest U-value (1.55) for the building in question was the triple low-e glass type (Gülaçmaz & Başdemir, 2022). Yıldız et al. (2011) compared the effect of the change in WWR in different orientations on energy consumption for different types of glass in an educational building in Izmir, Türkiye using the EnergyPlus tool. In the above study, an increase in the WWR from 10% to 60% on the eastern, western, and southern facades with the use of double glazing was associated with an increase in the total energy consumption by 6.5%, 4.9% and 3.2%, respectively, while the use of low-e coated glass decreased the said rate by 4.5%, 3.2% and 0.3%, respectively. Another study investigated a sample office building hypothetically located in the Brazilian and German climatic zones modeled by Daysim and Radiance lighting simulation tools. Translucent photovoltaic panels were used in the windows on four different facades of the building to compare the energy produced by each panel. The results suggested that the eastern and western facades provided the highest energy production in all climatic regions by means of transparent photovoltaic panel use (Didoné & Wagner, 2013). An Estonian study concluded using building energy simulation tools that the WWR values of 22-24% were associated with the highest energy performance in double and triple glazing in a cold climatic region (Thalfeldt, et al., 2013). Lee et al. (2013) analyzed optimum window characteristics, including WWR, U-value, SHGC and T-vis, for office buildings located in the Asian region. The results were suggestive of the fact that the optimum WWR should be 25% and that high amounts of energy savings could be achieved in hot to cold climatic regions, if and when SHGC and T-vis values were kept in the range of 0.25-0.45. Another study for United Kingdom and Brazil investigated the ideal window area in buildings with integrated lighting system design with an aim to estimate the potential energy savings in lighting. The results indicated that the larger and narrower the room, the larger the ideal window area and the lower the energy consumption per $m^2$ (Ghisi & Tinker, 2005). The effects of various combinations of building geometry, window opening size, and glass type on daylight performance were investigated for four geographic locations in the United States. The analyses included different window types as well as various WWRs. The results indicated that for most commercial buildings with a glass U-value of above 0.5, daylight did not provide a significant additional lighting energy saving upon an increase in the WWR above 0.5 (Krarti et al., 2005). Zhang et al. (2017) reported that the energy demand for heating and lighting could be reduced by 24-28% as a result of their optimization studies on spatial configurations in school buildings aimed to minimize energy use for heating and lighting. The effect of the integration of different glass types with a daylight automation system on the energy and daylight performance of the building was analyzed for a traditional Harput house located in the cold climatic region in Türkiye. As a result, the use of low-e coated and argon-filled triple windows together with the daylight automation system increased the energy performance of the building by 8.2%. Furthermore, the high T-vis value of the glass contributed to the increase in the illumination level of the interior spaces (Akgüç & Atik, 2023).

A review of above referred studies indicated that appropriate window recommendations were made with an aim to improve the energy performance of buildings, taking into account climatic zones and building types. Nevertheless, the TS825 standard recommended the same window U-value for four different degree day regions in Türkiye. Therefore, the point of departure of this study was to query the degree to which the TS825 standard's constant window U-value approach fulfills the energy efficiency requirements of different climate regions. Accordingly, the present study aimed to categorize the window thermophysical properties, which are considered constant for all degree day regions in the TS825 standard, by U-value, SHGC and T-vis to suggest optimum windows that would improve the energy efficiency of residential buildings in the 2nd degree day region in Türkiye. Additionally, this study analyzed how the recommended window options would contribute to Türkiye's progress towards the 2030 Sustainable Development Goals (SDGs). Istanbul, which has the highest population density and building typology in Türkiye, was selected as the pilot region for the purposes of the present study. A sample residential building for Istanbul, located in the 2nd degree day region, was modeled and the energy performances of different types of glass and frames selected for this building were tested using the DesignBuilder energy simulation tool. The sample building examined in this study is not classified as a case study building. This building has been modelled with consideration of single-family houses within the existing building stock of Istanbul, and the thermophysical properties of the building envelope have been modeled in accordance with the TS825 standard. Furthermore, the schedules for occupancy, lighting, and equipment of this building have been modeled with reference to the ASHRAE 90.1 standard. As a result of these performance tests, optimum types of glass and frames to reduce the annual energy demand, $CO_2$ emissions and energy costs of sample residential buildings located in the 2nd degree day region were recommended, taking into consideration the annual heating and cooling needs of the sample building. Within the framework of this research, the improvements made in the field of building sustainability are of significant importance for Türkiye's progress towards the 2030 SDGs. Specifically, these improvements align with the 11th goal, 'Sustainable Cities and Communities,' the 12th goal, 'Responsible Consumption and Production,' and the 13th goal, 'Climate Action,' as defined for 2030. In this context, the novelty of the study is that a new approach was suggested for Türkiye can achieve the 11th, 12th, 13th goals of the 2030 SDGs by proposing window types, which improved the sustainability of residential buildings in Istanbul, with rapidly increasing population and energy demands. Therefore, the study was structured into three main phases. In the first phase, analyses were conducted to reduce the annual heating and cooling energy requirements of the building in alignment with the 11th goal of the 2030 SDGs. The window types that most effectively mitigate these energy demands were identified. In the second phase, the impact of the selected window types on the building's annual energy costs was examined in detail within the framework of the 12th goal of the 2030 SDGs. Thus, the window types that demonstrated optimal performance in the first phase were reevaluated to ascertain whether they maintained their superiority over alternative window types, facilitating energy performance and cost optimization among the options. In the third phase, the influence of the selected window types on the building's annual greenhouse gas emissions was analyzed in accordance with the 13th goal of the 2030 SDGs. In this context, the implications of the identified window types for environmental sustainability were also assessed, investigating whether the window types that exhibited the highest performance in the first and second phases continued to demonstrate superiority at this stage. This article includes detailed analyzes and comparative results of different types of window components, with an aim to positively contribute to building science as to reducing the annual energy demand, $CO_2$ emissions and energy costs of sample residential buildings in moderate-humid climate regions.

## RESEARCH METHODOLOGY

For the purposes of the study, first, the role of residential buildings in energy consumption across the world and in Türkiye was reviewed in line with the technical data from IEA, to see the distribution of energy consumption of residential buildings in Türkiye. TS825, i.e., the national building standard in Türkiye, divides the country into degree day regions in consideration of climatic data. The standard recommended U-values of the exterior walls, floors and roofs of buildings to calculate the annual heat gains and losses of the buildings on a region-specific basis, taking into account the climatic data. Nevertheless, the recommendations of the standard were only limited to the U-values for windows, which was considered constant for each degree day region. A review of previous data showed that the Istanbul, which was located in the 2nd degree day region according to TS825 had the densest population and building stock in Türkiye. A scientific study to investigate and suggest the ways to improve the energy efficiency of the existing building stock in Istanbul may contribute not only in decreasing the cost of energy in Türkiye, but also minimize the country's external dependence on fossil fuels and reduce Istanbul's carbon footprint.

Within the scope of this research, window (glass + frame) suggestions were introduced to help reduce the annual energy demand, $CO_2$ emissions and energy costs of a sample residential building in Istanbul on the basis of climatic parameters and building type. Therefore, the methodology of this study was classified into three main phases. In the first phase, the studies were conducted for diminishing the annual heating and cooling energy demand of the building align with the 11th goal of 2030 SDGs. Today, the effect of the building envelope on the energy performance of the building can be determined by building simulation tools with results very close to actual implementation. Therefore, a sample building was first modeled using the DesignBuilder building simulation tool and the dynamic behavior of the building under climatic data throughout the year was investigated. Then, 20 different window types, which were considered to help improve the energy efficiency of the sample building, were determined and the effect of the gas gaps of different thicknesses (8mm, 12mm and 16mm) for those windows and the different gases used in those gaps (air, argon and krypton) on the energy performance of the building was tested using the DesignBuilder building simulation tool. Furthermore, the effects of different frame types on the energy performance of the building were also included in above tests. As a result of the energy performance tests in the scope of the study, the optimum window type for a sample residential building in Istanbul, located in the 2nd degree day region of the pursuant to the TS825 standard, and the U-value, SGHC, and T-vis values of the selected window type were determined. The selection of window types in this study was based on a comprehensive review of previous studies and a detailed thermophysical analysis. Numerous studies in the literature suggested that argon- and krypton-filled glazing significantly enhanced energy efficiency due to their superior insulating properties. With their low thermal conductivity, these gases minimize heat transfer within the glazing system, thereby reducing the overall energy demand of buildings. Beyond the influence of gas fillings, the selection process meticulously considered the fundamental thermophysical properties of glazing. Key parameters such as U-value, SHGC, and T-vis were carefully analyzed to determine the most optimal combinations. The primary objective was to minimize heat losses while maximizing solar gains, thereby optimizing both heating demand in winter and cooling loads in summer. These selection criteria helped establish a holistic framework aimed at reducing energy consumption, lowering energy costs, and mitigating greenhouse gas emissions in residential buildings in Istanbul. Consequently, this study not only provides insights as regards the individual building scale but also contributes to a broader sustainability perspective by offering strategic recommendations for energy-efficient glazing solutions.

With its user-friendly interface, DesignBuilder simulation tool allows modeling of almost all types of buildings, from single family residences to large-scale mixed buildings. The aforementioned graphical interface presents the calculated results for buildings to the user in the form of daily, monthly, and annual data with tables and graphs. The tool also allows the determination of the brightness levels of the spaces upon analysis of the natural and artificial lighting of the buildings and the analysis of the speed and temperature of the airflows occurring in the spaces during natural ventilation by means of 3D graphics through CFD simulations. DesignBuilder simulation tool uses the calculation infrastructure of the EnergyPlus building simulation tool to calculate the energy performance of buildings. EnergyPlus is a sophisticated software that calculates building heating and cooling loads by mathematical algorithms, including transfer function, finite differences, and finite elements. Both of these simulation tools were tested by a number of other research studies, which confirmed their accuracy. Both of these tools are based on a detailed-dynamic methodology stated in EN 13790 - Energy performance of buildings - Calculation of energy use for space heating and cooling. This International Standard gives calculation methods for assessment of the annual energy use for space heating and cooling of a residential or a non-residential building, or a part of it, referred to as "the building". This method includes the calculation of:

a) the heat transfer by transmission and ventilation of the building zone when heated or cooled to constant internal temperature;
b) the contribution of internal and solar heat gains to the building heat balance;
c) the annual energy demands for heating and cooling, to maintain the specified set-point temperatures in the building – latent heat not included; and
d) the annual energy use for heating and cooling of the building, using input from the relevant system standards referred to in this International Standard.

In the second phase, the impact of the selected window types, in line with the 12th goal of the 2030 SDGs, on the annual energy costs of the building is analyzed in detail. This analysis aims to reveal the effectiveness of the window types that most significantly improve the building's annual energy performance, as identified in the first step, in enhancing energy costs. Thus, it is tested whether the window types that demonstrated the best performance in the first step still exhibit superiority over other window types in the second step, enabling the optimization of energy performance and energy costs among the windows. In this step, first, relevant calculations were made to see how the selected window types changed the annual cost of natural gas used for heating the building. For the purposes thereof, the annual natural gas requirement of the building (ANGRB) obtained as kWh in m³ was expressed, using the following formula:

$$\mathrm{ANGRB}\ (\mathrm{m}^3) = \frac{\mathrm{ANGRB}\ (\mathrm{kWh})}{10.64} \tag{1}$$

Istanbul Gas Distribution Industry and Trade Incorporated Company (İGDAŞ) 2023 natural gas $m^3$ unit price average in Table 2 was used to express the annual natural gas requirement of the building in TL and Euro currencies. According to data from the Central Bank of the Republic of Türkiye, the average exchange rate of the Euro in 2023 was 26 TL (T.C. Merkez Bankası, 2023).

**Table 2.** Monthly change in the $m^3$ unit price of natural gas in 2023 (İGDAŞ, 2023).

| *Month* | *Unit Price of Natural Gas (TL/m³)* | *Unit Price of Natural Gas (Euro/m³)* |
|---|---|---|
| *January* | *4.58* | *0.176* |
| *February* | *4.59* | *0.177* |
| *March* | *4.62* | *0.178* |
| *April* | *4.63* | *0.178* |
| *May* | *4.65* | *0.179* |
| *June* | *4.66* | *0.179* |
| *July* | *4.71* | *0.181* |
| *August* | *4.73* | *0.182* |
| *September* | *4.79* | *0.184* |
| *October* | *4.85* | *0.187* |
| *November* | *4.88* | *0.188* |
| *December* | *4.90* | *0.188* |

The recent unfavorable economic policies in place in Türkiye have inflicted price increases each month, as seen in the 2023 monthly natural gas unit prices above. TS825 2. The right window selection in this study on residential buildings in the degree day region will both provide maximum benefit from passive systems and contribute to the improvement of cooling and heating performances along with the increase in energy efficiency of residential buildings. This will be associated with improvements in natural gas and electricity bills, as seen in the performed tests. The cost calculations were based on the monthly average of 2023 for the $m^3$ unit price of natural gas. Accordingly, the average $m^3$ unit price of natural gas was 4.71 TL. The Value Added Tax (VAT) was added to the annual natural gas cost of the building in order to obtain the final annual cost of natural gas. For the purposes of this study, a VAT rate of 18% was applied. Furthermore, in order to express the annual natural gas requirement of the sample building in kWh, the energy value of 1 $m^3$ natural gas was retrieved from the data of the Energy Market Regulatory Authority (EPDK). According to EPDK, 1 $m^3$ (Standard cubic meter) natural gas refers to the amount of natural gas that fills a volume of 1 $m^3$ at 15°C and 1.01325 bar absolute pressure, does not contain water vapor, and has an Upper Calorific Value of 9155 kcal. The energy value of 1 $m^3$ of natural gas is 10.64 kWh (EPDK, 2023). Therefore, the energy value of natural gas in the denominator of the above equation was taken as 10.64 kWh. Secondly, how the selected window types changed the annual cost of electrical energy used to cool the building was calculated in this step. In this calculation, the annual total electricity requirement of the building was first determined, and the relevant value was divided by 12 to determine the building's average monthly electricity requirement. Upon determining the monthly requirement of the building, the Türkiye Electricity Distribution Cooperation (TEDAŞ) data in Table 3 was used to calculate the electricity cost in TL. Based on the 2023 data; the price of 1 kWh of electricity is calculated at a unit price of 1.47 TL with a low tariff application up to a total of 240 kWh per month for TEDAŞ Residential Subscribers, while in cases where more than 240 kWh is used, the unit price of electricity is calculated at a rate of 2.21 TL with a high tariff application (Solar AVM, 2023). The VAT rate is included in the unit costs used in electricity cost calculations.

**Table 3.** Electricity unit prices depending on consumption amount in 2023 (EPDK, 2023).

| *Electricity Consumption Range* | *Unit Price (TL)* | *Unit Price (Euro)* |
|---|---|---|
| *1 – 240 kWh* | *1.47* | *0.057* |
| *over 240 kWh* | *2.21* | *0.085* |

In this step of the study, how the selected window types changed the annual greenhouse gas emissions of the building from electricity and natural gas was calculated. The Türkiye Electricity Production and Electricity Consumption Point Emission Factors Information Form published by the Republic of Türkiye Ministry of Energy and Natural Resources on August 8, 2022 was taken as reference in order to include the greenhouse gas emission factor originating from electricity use in the calculations (Solar AVM, 2023). The electricity consumption point emission factors as per this form are divided into two: electricity consumption points connected to the transmission line and electricity consumption points connected to the distribution line. The greenhouse gas emission factor related to the electricity use of buildings is represented by the consumption point emission factor connected to the distribution line in this form. This factor is 0.481 $tCO_2/MWh$ and represents the amount of total greenhouse gas emissions in terms of $CO_2$ released per unit of electricity consumption. Subsequently, the Turkish Emission Inventory published by the Ministry of Energy and Natural Resources in April 2023 was taken as reference in order to include the greenhouse gas emission factor originating from natural gas in the calculations (T.C Enerji ve Tabii Kaynaklar Bakanlığı, 2023). The natural gas emission factor for 2021 is 55.46 tons/TJ in the table titled "Table 3.18: $CO_2$ emission factors used for source category 1.A.1.a, 1990-2021" in this inventory. In order to convert this value to $tCO_2/MWh$, it will first be necessary to convert 1 TJ to kWh (1 TJ = 277777.78 kWh). Furthermore, the greenhouse gas emission factor from natural gas was 0.2 $tCO_2/MWh$. The annual energy performance, energy costs, and greenhouse gas emissions of all the selected window types were compared based on the calculations carried out through the three main phases that constituted the method of this study. As a result, window types with optimum performance in all three steps were determined for a sample residential building in Istanbul located in the second-degree day zone as per TS825. The flowchart of the method used in this research is as follow.

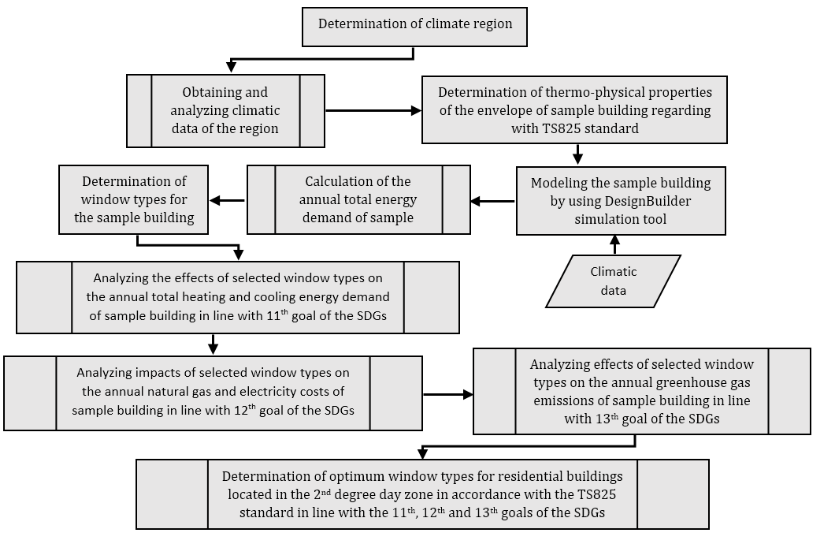
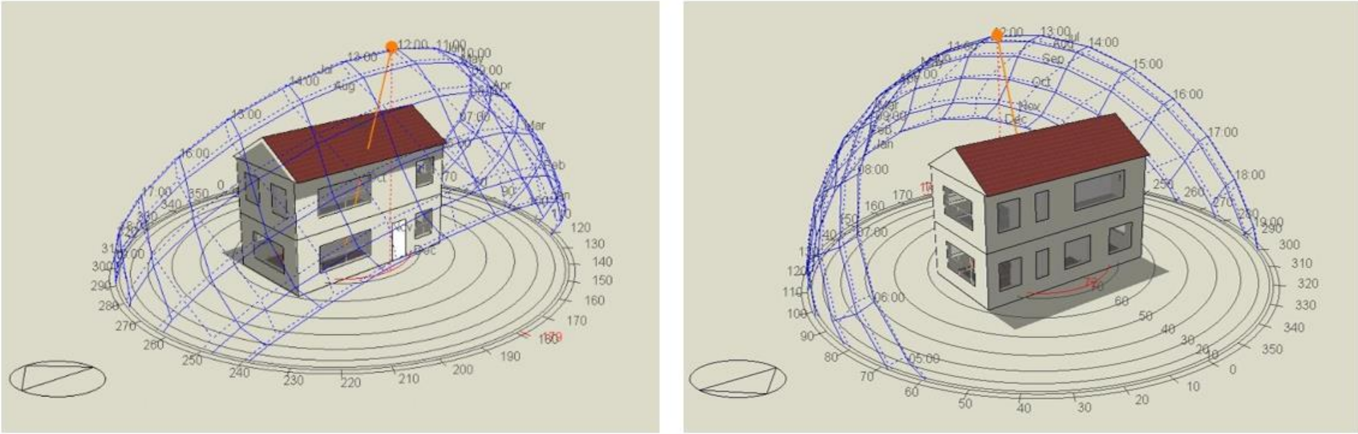


**Figure 2.** Flowchart of the methodology used in this study.

## DETERMINING THE SAMPLE BUILDING AND DEVELOPING THE ENERGY MODEL

### Modeling of the Sample Building

Located on both the European and Asian continents, Istanbul is included in the Marmara region of Türkiye. It has a transitional climate between the Mediterranean and the Black Sea and is features moderately humid climatic characteristics. For the purposes of the present study, a 5-metre wide and 10-metre long, 2-floor sample residential building in Istanbul was modeled using the DesignBuilder building energy simulation tool. The ground floor and first floor of the building are 50$m^2$ each and the total area of the building is 100$m^2$. TS825 standard was taken as a basis in modeling the building's exterior wall, floor, roof, and window materials. Furthermore, the ASHRAE 90.1 standard was taken into consideration in modeling the activity levels of building users, user density, lighting, and equipment usage time schedules.



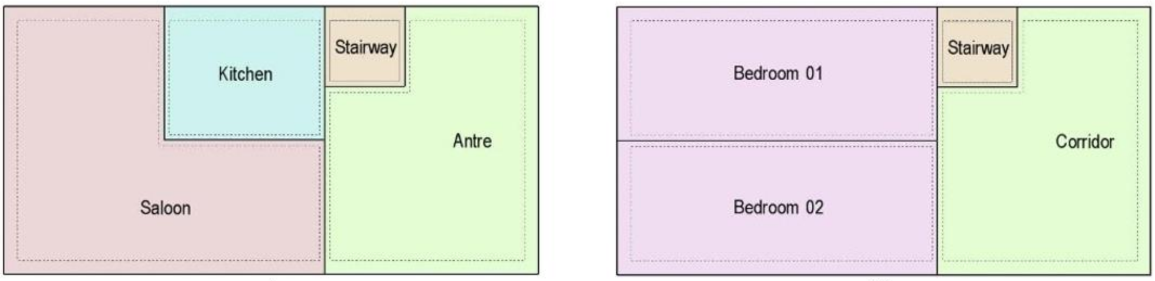
a) b)

**Figure 3.** DesignBuilder model view of a) south-west and b) north-east orientation of the sample building

Figure 4 shows the schematic representations of ground floor and 1st floor plans of the sample building, respectively. Considering that a family of 4 individuals lived in the sample building, the ground floor hosted the common use areas, including living rooms, kitchen and entrance units, while an entrance hall, a master bedroom with private areas, and a bedroom used by two children were placed on the 1st floor. Each of the designed spaces had different functions, since they had different occupancies, lighting and interior equipment schedules. Therefore, each space in the building was modeled with a different thermal zone consideration. To create the energy model of the building, first the building geometry was modeled followed by the building's shell materials, usage schedules, activity levels of users, thermostat temperatures of thermal zones, electrical loads of lighting and interior equipment. Figure 5 shows the wall, floor, and roof layers of the sample building. Material layering and layer thicknesses were designed on the basis of the U-values referenced in TS825 for buildings located in the 2nd degree day region. Thermophysical properties (U-value, SGHC, and T – vis) of the modeled building envelope were set by considering Table 1, and these properties are shown in Table 4. As can be seen, the U-values of the opaque and transparent components of the sample building provided the reference U-values of the TS825 standard; nevertheless, this standard did not specify a reference value for SHGC and T-vis for the windows. Therefore, the reference values of SHGC and T-vis coefficients of the windows of the sample building were set to the values shown in Table 4 for the purposes of the present study. Besides, it was assumed that the WWR of the building was 30% and all the window frames were wooden. Therefore, the U-value of the reference window of the sample building was integrated into the building energy model by considering the 2008 version of the TS825 standard in this study. In this study, all analyses related to energy performance, energy cost, and greenhouse gas emissions were conducted based on a scenario which considered the sample building's WWR as 30%.

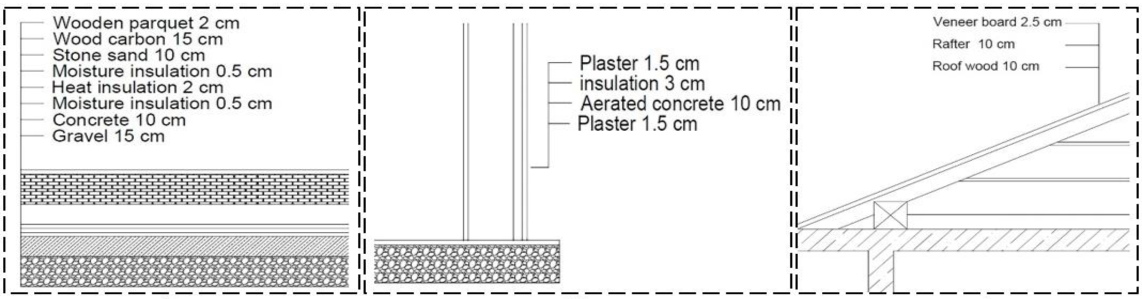
**Table 4.** Thermophysical properties of the Shell components of the sample building.

| *Components of the building envelope* | *U – value ($W/m^2K$)* | *SHGC* | *T – vis* |
|---|---|---|---|
| *External Wall* | *0.520* | - | - |
| *Floor* | *0.310* | - | - |
| *Roof* | *0.393* | - | - |




a) b)

**Figure 4.** Model view of a) ground and b) first floor plan of the sample building.




a) b) c)

**Figure 5.** Layering of a) floor, b) wall, and c) roof of the sample building.

Below are the occupancy, lighting and interior equipment schedules of the thermal zones of the sample building modeled with DesignBuilder by considering ASHRAE 90.1. ASHRAE Standard 90.1. It provides minimum requirements for energy-efficient designs for buildings except low-rise residential buildings, and frequently used as a reference standard in energy modeling and code compliance. Table 5 presents the usage schedules of thermal zones. Tables 9, 10, 11, and 12 include the lighting schedules of thermal zones. The time period shown in the tables represents daily usage throughout the year.

**Table 5.** The occupancy schedule of bedrooms.

| *Time Period* | *Occupancy Rate* |
|---|---|
| *07:00* | *1* |
| *08:00* | *0.5* |
| *09:00* | *0.25* |
| *22:00* | *0* |
| *23:00* | *0.25* |
| *24:00* | *0.75* |

**Table 6.** The occupancy schedule of living room.

| *Time Period* | *Occupancy Rate* |
|---|---|
| *06:00* | *0* |
| *07:00* | *0.25* |
| *09:00* | *1* |
| *10:00* | *0.25* |
| *18:00* | *0* |
| *19:00* | *0.5* |
| *21:00* | *1* |
| *22:00* | *0.3* |
| *24:00* | *0* |

**Table 7.** The occupancy schedule of corridors.

| *Time Period* | *Occupancy Rate* |
|---|---|
| *07:00* | *0* |
| *08:00* | *0.5* |
| *09:00* | *1* |
| *10:00* | *0.5* |
| *17:00* | *0* |
| *18:00* | *0.25* |
| *19:00* | *0.5* |
| *20:00* | *0.75* |
| *22:00* | *1* |
| *23:00* | *0.75* |
| *24:00* | *0.25* |

**Table 8.** The occupancy schedule of kitchen.

| *Time Period* | *Occupancy Rate* |
|---|---|
| *07:00* | *0* |
| *10:00* | *1* |
| *19:00* | *0* |
| *23:00* | *0.2* |
| *24:00* | *0* |

**Table 9.** The lighting schedule of bedrooms.

| *Time Period* | *Lighting Usage Rate* |
|---|---|
| *07:00* | *0* |
| *10:00* | *1* |
| *19:00* | *0* |
| *23:00* | *0.2* |
| *24:00* | *0* |

**Table 10.** The lighting schedule of living room.

| *Time Period* | *Lighting Usage Rate* |
|---|---|
| *06:00* | *0* |
| *10:00* | *1* |
| *18:00* | *0* |
| *22:00* | *1* |
| *24:00* | *0* |

**Table 11**. The lighting schedule of corridor.

| *Time Period* | *Lighting Usage Rate* |
|---|---|
| *07:00* | *0* |
| *10:00* | *1* |
| *17:00* | *0* |
| *24:00* | *1* |

**Table 12.** The lighting schedule of kitchen.

| *Time period* | *Lighting Usage Rate* |
|---|---|
| *07:00* | *0* |
| *10:00* | *1* |
| *19:00* | *0* |
| *23:00* | *1* |
| *24:00* | *0* |

Tables 13, 14, 15, and 16 include the internal equipment schedules of thermal zones.

**Table 13.** The equipment schedule of bedrooms.

| *Time Period* | *Equipment Usage Rate* |
|---|---|
| *07:00* | *0.070* |
| *08:00* | *0.534* |
| *09:00* | *1* |
| *10:00* | *0.534* |
| *17:00* | *0.070* |
| *18:00* | *0.302* |
| *19:00* | *0.534* |
| *20:00* | *0.770* |
| *22:00* | *1* |
| *23:00* | *0.770* |
| *24:00* | *0.302* |

**Table 14.** The equipment schedule of living room.

| *Time Period* | *Equipment Usage Rate* |
|---|---|
| *06:00* | *0.081* |
| *07:00* | *0.311* |
| *09:00* | *1* |
| *10:00* | *0.311* |
| *18:00* | *0.081* |
| *19:00* | *0.540* |
| *21:00* | *1* |
| *22:00* | *0.357* |
| *24:00* | *0.081* |

**Table 15.** The equipment schedule of corridor.

| *Time Period* | *Equipment Usage Rate* |
|---|---|
| *07:00* | *0.046* |
| *23:00* | *1* |
| *24:00* | *0.332* |

**Table 16.** The equipment schedule of kitchen.

| *Time Period* | *Equipment Usage Rate* |
|---|---|
| *07:00* | *0.066* |
| *10:00* | *1* |
| *19:00* | *0.066* |
| *23:00* | *0.252* |
| *24:00* | *0.066* |

Table 17 defines the lighting power density (LPD) and interior equipment electrical loads of thermal zones.

**Table 17.** Lighting loads of thermal zones.

| *Thermal Zone* | *LPD [$W/m^2$]* | *Equipment Power [$W/m^2$]* |
|---|---|---|
| *Living Room* | *2.500* | *3.060* |
| *Kitchen* | *2.500* | *30.280* |
| *Corridor* | *2.500* | *2.160* |
| *Bedroom* | *2.500* | *3.580* |

The heating and cooling set-point temperature of those sections should also be identified with an aim to find the heating and cooling needs of each thermal zone. In this study, the cooling set-point temperature for all thermal zones and heating set temperature was set to 26°C and 19°C, respectively. The TS825 standard was taken as a basis to determine above temperature levels (TSE, 2008). The annual total energy demand of the sample building as modeled in DesignBuilder, upon simulation vis-a-vis Istanbul climatic conditions, is shown in Figure 13. Upon a review of this graph, the annual heating need and cooling need of the building was 53.90 kWh/m$^2$ and 24.30 kWh/m$^2$ respectively, where the annual lighting consumption, annual equipment consumption, and annual total energy demand of the building was 6.70 kWh/m$^2$, 9,01 kWh/m$^2$, and 93,93 kWh/m$^2$ respectively. As can be seen, the annual heating need of the building was higher compared to the cooling need. This was due to the fact that the selected sample building was modeled as a residential building, and both the thermophysical properties of the building envelope materials and the occupancy, lighting, and equipment densities were integrated into the model as such. In addition, the set-point temperatures of thermal zones were determined according to the thermostat temperatures for residential buildings as prescribed by the TS825 standard. As a result of all above, the annual heating need of the building was higher compared to the cooling need.

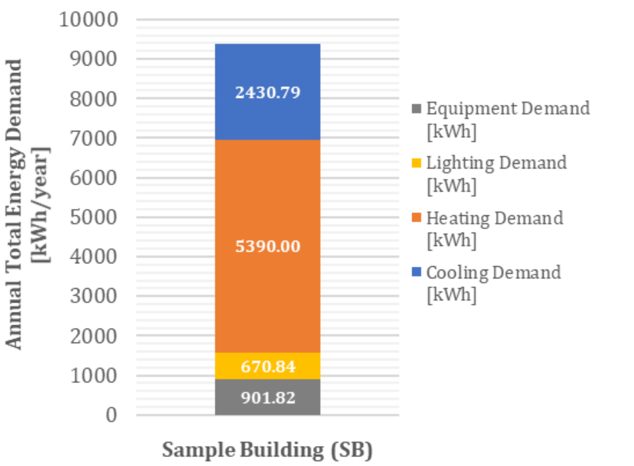



**Figure 6.** Calculation of the annual total energy demand of the sample building

## DETERMINATION OF WINDOW TYPES ACCORDING TO THEIR THERMOPHYSICAL PROPERTIES

The U-value of a building's envelope plays a crucial role in determining its heating and cooling demands. In the context of building science, the U-value quantifies the heat transfer through various building elements such as walls, floors, roofs, and windows, indicating their efficiency in insulating against heat loss. Essentially, a higher U-value signifies poorer thermal performance of the building component. There are many studies on improving the thermal performance of building envelope and one of them is the research of Akgüç et al. In this research, the exterior walls of the office part in Pratt & Whitney Turkish Engine Center were covered by building integrated photovoltaic system (BIPVS) by using TRNSYS building simulation tool. In this way, heat losses from the building envelope were reduced during the heating period, and the electricity produced by BIPVs had a significant impact on reducing the annual energy cost of the building (Egrican & Akguc, 2011). Among the building envelope components, windows have the highest thermally transmittance and therefore has the weakest thermal resistance properties in a given building, with thermos-physical properties of SHGC and T-vis in addition to the U-value. In Figure 7, the overall response of window glazing to solar radiation is illustrated.

The present study aimed to reduce the annual total energy demand of the sample building selected for the Istanbul climatic region by the use of suggested windows. Especially given Istanbul's climatic characteristics and the fact that the sample building was considered a residential building, it would be appropriate to suggest windows with an aim to reduce the annual heating need of the building.

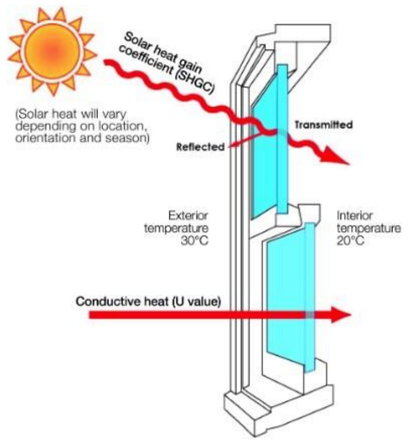



**Figure 7.** Basic properties of glass (U.S of Department Energy, 2023).

Table 18 includes the thermophysical properties of the window types recommended for the sample building. The window (RW) in the first row of the table is determined as the reference window that would meet the window U-value as prescribed in the TS825 standard. All the windows from W01 to W20 were considered to help reduce the annual total energy demand of the sample building, and the U-value of all of those windows were below the U-value of the RW. This was aimed to achieve the goal of improving the energy efficiency of the building upon decrease in the heat losses of the sample building during the heating period.

In deciding the windows recommended in the table, not only the U-value but also the SHGC and T–vis parameters were taken into consideration. As seen in Table 18, although the U-values of certain windows were quite close to each other, the respective SHGC and T–vis values differed. This was scheduled to test the impact of the U-value of the proposed windows, as well as their SHGC and T-vis values, on the energy performance of the building. Therefore, the main goal of the present study was to investigate the appropriate SHGC and T–vis for residential buildings located in the Istanbul climatic region of Türkiye and to develop a new approach to improve the thermophysical properties of window glass recommended by the TS825 standard.

The window glasses selected for the purposes of the study from clear, low-e coated, and polymer glass materials, and the glasses recommended in Table 18 were categorized by their material properties. Clear glasses feature low reflectivity due to their low iron content and thus allow maximum sunlight to pass through. Need for unnecessary use of artificial lights is therefore removed. This type of glasses allows light transmittance at approximately 90%. In addition to light transmittance, they have greater heat gain compared to float glass, which can be beneficial in countries with low or sub-zero temperatures throughout the year or during prolonged periods within a given year.

**Table 18.** Thermophysical properties of air-filled (16 mm) double-glazed window (glass + timber frame) types proposed for the sample building.

| *Proposed Windows* | *Glazing Type* | *Thickness of External Glass [mm]* | *Gap* | *Thickness of Internal Glass [mm]* | *U-value [W/m²K]* | *SGHC* | *T - vis* |
|---|---|---|---|---|---|---|---|
| *RW* | *Clear* | *13.600* | *16mm air* | *13.600* | *2.390* | *0.494* | *0.659* |
| *W01* | *Low-e* | *6.350* | *16mm air* | *13.600* | *2.382* | *0.160* | *0.100* |
| *W02* | *Low-e* | *3.059* | *16mm air* | *3.850* | *2.264* | *0.350* | *0.395* |
| *W03* | *Low-e* | *3.059* | *16mm air* | *7.030* | *2.233* | *0.394* | *0.414* |
| *W04* | *Low-e* | *2.184* | *16mm air* | *2.184* | *2.144* | *0.684* | *0.713* |
| *W05* | *Polymer* | *12.119* | *16mm air* | *12.119* | *2.131* | *0.519* | *0.255* |
| *W06* | *Low-e* | *3.080* | *16mm air* | *3.080* | *1.963* | *0.686* | *0.645* |
| *W07* | *Low-e* | *3.060* | *16mm air* | *3.060* | *1.886* | *0.400* | *0.608* |
| *W08* | *Low-e* | *5.880* | *16mm air* | *5.880* | *1.850* | *0.535* | *0.802* |
| *W09* | *Polymer* | *19.612* | *16mm air* | *19.612* | *1.826* | *0.665* | *0.528* |
| *W10* | *Low-e* | *6.000* | *16mm air* | *6.000* | *1.813* | *0.187* | *0.192* |
| *W11* | *Low-e* | *11.652* | *16mm air* | *11.652* | *1.803* | *0.241* | *0.319* |
| *W12* | *Low-e* | *6.000* | *16mm air* | *6.000* | *1.802* | *0.227* | *0.233* |
| *W13* | *Low-e* | *5.880* | *16mm air* | *13.600* | *1.682* | *0.557* | *0.726* |
| *W14* | *Polymer* | *26.475* | *16mm air* | *26.475* | *1.617* | *0.630* | *0.438* |
| *W15* | *Low-e* | *6.000* | *16mm air* | *6.000* | *1.559* | *0.587* | *0.666* |
| *W16* | *Polymer* | *14.900* | *16mm air* | *14.900* | *1.493* | *0.500* | *0.617* |
| *W17* | *Polymer* | *2.740* | *16mm air* | *2.740* | *1.372* | *0.471* | *0.591* |
| *W18* | *Low-e* | *5.920* | *16mm air* | *5.920* | *1.366* | *0.525* | *0.683* |
| *W19* | *Polymer* | *2.740* | *16mm air* | *2.740* | *1.291* | *0.353* | *0.474* |
| *W20* | *Polymer* | *48.910* | *16mm air* | *48.910* | *1.237* | *0.511* | *0.295* |

This type is also associated with improved aesthetics of the building due to its high visual clarity (Trakya Cam ve Plastik Doğrama Sanayi ve Ticaret A.Ş, 2023). Low-e coating is a microscopically thin, nearly invisible layer of metal or metallic oxide coating as applied directly to the surface of one or more glass panels. This reduces the U-value of the window and can manage solar heat gain as well as daylight transmission through the glazing system. Different types of low-e coatings are designed to allow for high solar gain, moderate solar gain, or low solar gain, and they can also be adjusted to control the amount of transmitted visible sunlight. Low-e coated glasses have control over the heat transfer inside. Furthermore, windows produced with Low-e coatings generally cost about 10% to 15% higher compared to the regular windows, yet they can reduce energy loss by up to between 30% and 50%. The low-e coatings are often implemented during the production phase, yet they have a lifespan of 10 to 15 years without peeling (Australian Government, 2023). Polymer glass feature higher heat capacity, higher transparency, chemical resistance, and impact resistance compared to clear and coated glasses. Therefore, polymers can be preferred instead of glass. Polymer glasses are characterized by the ability to completely absorb rays in the UV region up to a wavelength of 275 nm. Furthermore, the T-vis values at the visible region above 400 nm is approximately 90% (Akkaşoğlu & Karasu, 2018).

## ANALYZING OF THE WINDOW TYPES TOWARDS THE GOALS OF 2030 SDGs

### Impacts of the Window Types on the Annual Energy Demand of the Sample Building Align with 11th Goal

A review of Figure 8 is indicative of the fact that the annual lighting and equipment electricity needs of the sample building were 670.84 kWh and 901.82 kWh, respectively, and those needs did not change in the window recommendations. As a matter of fact, the purpose of the present study was to test the effect of changing thermophysical properties of the proposed windows on the energy performance of the building by keeping all design parameters constant except the windows of the sample building. As a result of the tests, the annual heating need and cooling need of the building was 5390 kWh and 2430.79 kWh with RW use in the sample building. Considering the climatic characteristics of the 2nd degree day region in the TS825 standard, it is very important to determine the appropriate window that would help reduce the heating load of the sample residential building. As seen in Table 18, the U-value and SHGC of the selected window W01 were below those of RW. A review of the performance of W01 based on the simulation results, this option increased the heating load of the building; nevertheless, it also significantly decreased the cooling load.

This is because of the fact that W01's SHGC value was almost 0 and it could not benefit from the solar thermal gain across the year. Since the use of W01 was associated with increased annual total energy demand of the building, this option was considered not suitable for the building in question. Furthermore, as a result of the very low T-vis value of W01, indoor spaces could almost not benefit from sunlight at all. The SHGC value of the W02 option was lower compared to that of RW, which reduced the annual total cooling need of the sample building by approximately 800 kWh. Notwithstanding above, this lower value also reduced the solar radiation gain of the building and led to an increase in the heating need. This increase also contributed to an elevation in the annual total heating energy demand of the building, leading to a decreased energy performance. While the W03 option reduced the cooling need of the building, it was associated with an increase in the heating need by approximately 250 kWh. This was attributable to the fact that although its U-value was close to that of RW, its SHGC remained below RW.

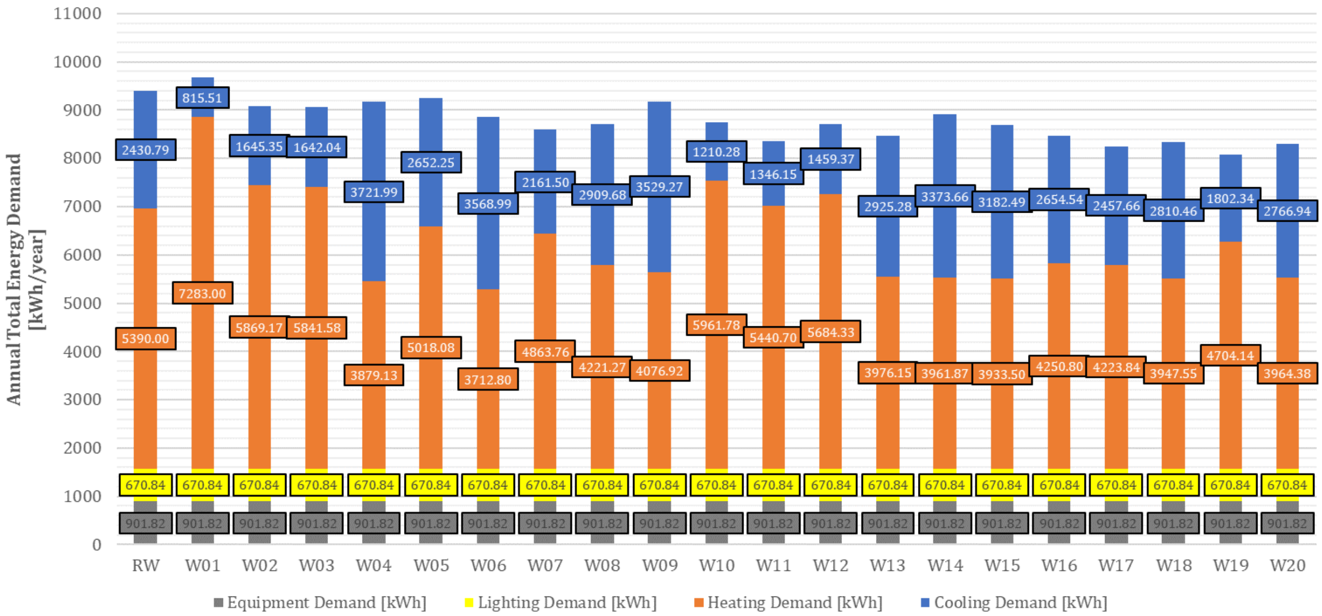



**Figure 8.** The effect of air-filled (16 mm) double-glazed window types on the annual total energy demand of the sample building.

Nevertheless, as a result, this led to a slight decrease in the annual total energy demand of the building. A review of Figure 15 indicates that W04, W06, and W08 options generally decreased the heating need of the building; yet, they also increased the cooling needs. This is because U-values were lower and SHGC was higher compared to RW. Notwithstanding above, since the T-vis of W04 and W08 options was above that of RW, those options might be preferred by the user, as they would allow the building to benefit from more sunlight. Although the U-value of W05 option was lower compared to that of RW, its SHGC was higher therefrom. This was associated with a slight increase in the heating and cooling needs of the building. Furthermore, the lower T-vis compared to RW would reduce the building performance and visual comfort as it would cause the building not to benefit from sunlight adequately. A review of the performance results of the W07 option indicated that it stood out remarkably different from other windows in reducing both the heating and cooling loads of the building. In addition, the fact that its T-vis was close to that of RW, helped interior spaces continue to benefit from sunlight at a similar rate. Although the W09 option remarkably reduced the heating loads of the building, it significantly increased the cooling loads. This was an undesirable performance for a climatic region that of Istanbul, where the heating period was long and cold, where the cooling period was short, approximately 3 months. Although the respective SHGC values of W10, W11, and W12 options were very low, causing the cooling load of the building to decrease significantly, it led to an increase in the heating load. The T-vis value of those options was also very low, significantly reducing the amount of sunlight entering the spaces. Those options reduced the annual total energy demand of the building mainly for cooling purposes, and therefore, it was considered that they would not be preferred for the Istanbul climatic zone. Although the U-values of W13, W14, W15, and W16 options were generally lower compared to RW, their SHGC values were higher. This had a positive effect on heating loads and a negative effect on cooling loads. Nevertheless, the T-vis value of W15 and W16 was close to that of RW, which affected the building's ability to benefit from sunlight in a similar way. Upon a comparison between the W17 and W19 options, and RW, the U-values of W17 and W19 were approximately 1 W/m²K lower. This increased the thermal protection of the building by significantly reducing heat losses through windows, thus remarkably reducing the heating load of the building. The SHGC value of W19 was lower compared to W17, which reduced the cooling loads of the building by approximately 600 kWh compared to W17; nevertheless, it also increased heating loads by approximately 350 kWh. As a summary, W01 increased energy demands due to its low SHGC and T-vis values; W02 reduced cooling needs compared to RW but increased heating needs with its lower SHGC. W03 decreased cooling needs but increased heating needs. W04, W06, and W08 reduced heating needs but increased cooling needs. W09 reduced heating loads but increased cooling loads. W10, W11, and W12 decreased cooling loads while increasing heating loads. W07 significantly reduced both heating and cooling loads. W17 and W19 improved thermal protection, reducing heating loads, but W19's lower SHGC increased cooling loads. A comparison between W17 and RW showed that the cooling load of the building remained almost constant with W17 and the heating load was reduced by approximately 1150 kWh. Furthermore, although the T-vis value of this option was below that of the RW, it was close, so disadvantages associated with less sunlight was limited. W18 and W20 options rendered very similar results in terms of U-value and SHGC. Especially the very low U-values remarkably decreased the heating loads of the building and slightly increased the cooling loads. This helped to significantly decrease the building's annual total energy demands. Nevertheless, the T-vis value of W20 was very low, and therefore it was concluded that the artificial lighting systems would considerably increase the electrical loads after the building was to be operational. As a result of the tests, W17 and W19 options showed the most remarkable performance among double-glazed windows with 16 mm air gap.

In addition to the major contribution of window selection in improving the energy performance of the building envelope, the gas to be used inside the gap between the two panes of glass play a remarkable role in terms of determining the energy performance of the building. The most important and most widely used gases for above purposes in daily life are argon and krypton. These gases are heavier and denser compared to regular air. With these features, windows filled in with argon and krypton sustain a higher effect on reducing thermal conductivity compared to air-filled windows. Therefore, argon- and krypton-filled windows can be the choice of material to help increase thermal protection in buildings. The insulation of argon gas is 2/3 of that of air and a 15% decrease in the overall U-value is possible (Umaroğulları & Kartal, 2005). Argon and krypton gases were also defined as transparent thermal insulation materials in the relevant literature, which contribute to the storage of heat in the interiors due to their ability to transmit solar radiation. Therefore, it has significant contributions compared to air-filled windows in improving the energy conservation and building performance of the building by preventing thermal bridges (Altun, 2007). A previous study tested and compared the reflectivity and absorptivity properties of air, argon gas, and krypton gas-filled windows under 10mbar pressure. As a result, the thermal protection in krypton gas-filled and air-filled windows was 75% and 50%, respectively (Yaman & Küçükkaya, 2019). For the purposes of the present study, argon and krypton gas-filled windows options were also included to test their effects on improving the energy performance of the sample building.

For the second step of the study, argon gas was used to fill in the space between the interior and exterior windows given in Table 17, and the effect of the gas on the U-value, SHGC, and T-vis of the proposed windows is shown in Table 19. Figure 9 shows the effects of argon gas-filled windows on the energy performance of the sample building. As seen in the figure, the use of Argon gas instead of air in the gap between the window panes was associated with a slight decrease in the U-values of the windows and did not sustain a significant effect on the change of SHGC. Nevertheless, the use of argon gas had no effect on the T-vis values of the windows in question. Argon gas-filled windows generally provided a remarkable decrease in the heating need of the building; yet, it is noteworthy that it had almost no effect on the change in cooling loads. This window type generally contributed to decrease in the annual total energy demand of the sample building. Among the windows in question, the WA06 option had the best heating performance. Nevertheless, the high SHGC of this option still did not give the desired performance because it was associated with an increase in the cooling loads of the building. There was no significant change in the U-values of the WA07 and WA20 options with the use of argon gas with a similar effect on the energy performance of the sample building. Even though there was a decrease in the U-value of the WA11 option by approximately 0.22 W/m$^2$ with the use of argon gas, a comparison of the performance results of this option shown in Figure 18 and Figure 19 indicated that it provided an improvement of merely 200 kWh per year in the heating load of the building. The decrease in the U-value of the WA12 option by approximately 0.1 W/m$^2$ with the use of argon gas reduced the heating load of the building by approximately 100 kWh per year. Nevertheless, the fact that this option had a very low T-vis value, sustained an adverse effect on the sunlight exposure of interior spaces. The U-values of WA15 and WA18 options decreased by approximately 0.2 W/m.$^2$ with the use of argon gas; yet the said decrease did not have the expected effect, reducing the heating load of the building by only 200 kWh per year. In the present study, the air-filled W17 and W19 options were the best performing windows with regard to the sample building. The U-values of the WA17 and WA19 options decreased by an average rate of 0.16 W/m$^2$ with the use of argon gas on average, which resulted in an average improvement of 200 kWh in the building's heating needs for both windows.

**Table 19.** Thermophysical properties of argon-filled (16 mm) double-glazed window (glass + wood frame) types proposed for the sample building.

| *Proposed Windows* | *Thickness of External Glass [mm]* | *Gap* | *Thickness of Internal Glass [mm]* | *U-value [W/m$^2$K]* | *SGHC* | *T - vis* |
|---|---|---|---|---|---|---|
| *RW* | *13.600* | *16mm air* | *13.600* | *2.390* | *0.494* | *0.659* |
| *WA01* | *6.350* | *16mm argon gas* | *13.600* | *2.229* | *0.157* | *0.100* |
| *WA02* | *3.059* | *16mm argon gas* | *3.850* | *2.057* | *0.349* | *0.395* |
| *WA03* | *3.059* | *16mm argon gas* | *7.030* | *2.031* | *0.348* | *0.414* |
| *WA04* | *2.184* | *16mm argon gas* | *2.184* | *1.918* | *0.685* | *0.713* |
| *WA05* | *12.119* | *16mm argon gas* | *12.119* | *2.056* | *0.519* | *0.255* |
| *WA06* | *3.080* | *16mm argon gas* | *3.080* | *1.712* | *0.686* | *0.645* |
| *WA07* | *3.060* | *16mm argon gas* | *3.060* | *1.808* | *0.401* | *0.608* |
| *WA08* | *5.880* | *16mm argon gas* | *5.880* | *1.774* | *0.536* | *0.802* |
| *WA09* | *19.612* | *16mm argon gas* | *19.612* | *1.772* | *0.665* | *0.528* |
| *WA10* | *6.000* | *16mm argon gas* | *6.000* | *1.74* | *0.187* | *0.192* |
| *WA11* | *11.652* | *16mm argon gas* | *11.652* | *1.583* | *0.236* | *0.319* |
| *WA12* | *6.000* | *16mm argon gas* | *6.000* | *1.746* | *0.227* | *0.233* |
| *WA13* | *5.880* | *16mm argon gas* | *13.600* | *1.423* | *0.561* | *0.726* |
| *WA14* | *26.475* | *16mm argon gas* | *26.475* | *1.573* | *0.63* | *0.438* |
| *WA15* | *6.000* | *16mm argon gas* | *6.000* | *1.394* | *0.591* | *0.666* |
| *WA16* | *14.900* | *16mm argon gas* | *14.900* | *1.338* | *0.502* | *0.617* |
| *WA17* | *2.740* | *16mm argon gas* | *2.740* | *1.215* | *0.474* | *0.591* |
| *WA18* | *5.920* | *16mm argon gas* | *5.920* | *1.193* | *0.529* | *0.683* |
| *WA19* | *2.740* | *16mm argon gas* | *2.740* | *1.130* | *0.355* | *0.474* |
| *WA20* | *48.910* | *16mm argon gas* | *48.910* | *1.208* | *0.511* | *0.295* |

For the third step of this study, krypton gas was used in the space between the glass panes of the proposed windows, and the changes in the U-value, SHGC, and T-vis of the windows with the use of krypton are shown in Table 20. A comparison of this table with Table 18 indicated that the change in the U-value of the windows was remarkable. Notwithstanding above, the SHGC values were not affected to the same extent by this change, and that T-vis was not affected at all. A comparison of the same table Table 19 showed that there was an average decrease in the U-values of the windows by 0.1 W/m$^2$. This decrease was associated with a resultant average improvement of 100 kWh per year in the building's heating loads.

The use of krypton gas in windows showed a similar trend as argon gas with regards to changes induced in the heating and cooling loads of the sample building. As with Air-filled and argon gas-filled windows, the WK17 and WK19 options had the best performance in krypton gas-filled windows. WK19 option had the lowest U-value among the options in question and it was best option with regard to increasing the thermal performance of the sample building. However, its T-vis value was lower compared to WK17. Therefore, the WK17 option with a higher T-vis value might be the window type of choice, albeit slight decrease in thermal performance, in cases where the daylight illumination requirements of interior spaces in residential buildings were prioritized.

Using argon and krypton gas instead of air-filled windows was associated with better results in many previous studies as in the example building in this study. A South Korean in 2023, added argon filling between double-layered glass panels instead of air filling in order to increase the facade insulation performance of newly constructed residential buildings. Based on the test results, it was determined that argon-filled windows increased the thermal performance of buildings by 10.9% compared to air-filled windows. Nevertheless, it was anticipated that there would be some issues, including thermal transmittance changes in the windows and gas leakage of the injected argon gas over the years

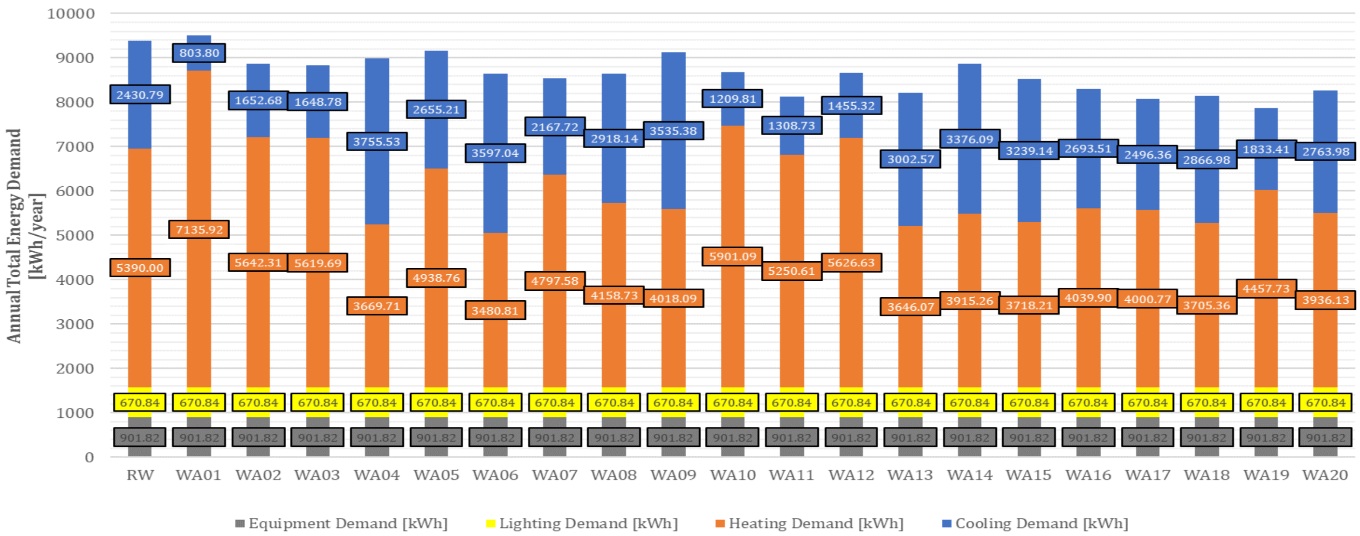



**Figure 9.** The effect of argon gas-filled (16 mm) double-glazed window types on the annual total energy demand of the sample building.

**Table 20.** Thermophysical properties of krypton-filled (16 mm) double-glazed window (glass + wood frame) types proposed for the sample building.

| *Proposed Windows* | *Thickness of External Glass [mm]* | *Gap* | *Thickness of Internal Glass [mm]* | *U-value [W/m²K]* | *SGHC* | *T - vis* |
|---|---|---|---|---|---|---|
| *RW* | *13.600* | *16mm air* | *13.600* | *2.390* | *0.494* | *0.659* |
| *WK01* | *6.350* | *16mm krypton gas* | *13.600* | *2.178* | *0.155* | *0.100* |
| *WK02* | *3.059* | *16mm krypton gas* | *3.850* | *1.982* | *0.348* | *0.395* |
| *WK03* | *3.059* | *16mm krypton gas* | *7.030* | *1.959* | *0.347* | *0.414* |
| *WK04* | *2.184* | *16mm krypton gas* | *2.184* | *1.835* | *0.686* | *0.713* |
| *WK05* | *12.119* | *16mm krypton gas* | *12.119* | *2.033* | *0.518* | *0.255* |
| *WK06* | *3.080* | *16mm krypton gas* | *3.080* | *1.617* | *0.686* | *0.645* |
| *WK07* | *3.060* | *16mm krypton gas* | *3.060* | *1.783* | *0.402* | *0.608* |
| *WK08* | *5.880* | *16mm krypton gas* | *5.880* | *1.750* | *0.537* | *0.802* |
| *WK09* | *19.612* | *16mm krypton gas* | *19.612* | *1.755* | *0.664* | *0.528* |
| *WK10* | *6.000* | *16mm krypton gas* | *6.000* | *1.717* | *0.188* | *0.192* |
| *WK11* | *11.652* | *16mm krypton gas* | *11.652* | *1.502* | *0.234* | *0.319* |
| *WK12* | *6.000* | *16mm krypton gas* | *6.000* | *1.722* | *0.227* | *0.233* |
| *WK13* | *5.880* | *16mm krypton gas* | *13.600* | *1.321* | *0.565* | *0.407* |
| *WK14* | *26.475* | *16mm krypton gas* | *26.475* | *1.560* | *0.630* | *0.438* |
| *WK15* | *6.000* | *16mm krypton gas* | *6.000* | *1.336* | *0.595* | *0.666* |
| *WK16* | *14.900* | *16mm krypton gas* | *14.900* | *1.283* | *0.506* | *0.617* |
| *WK17* | *2.740* | *16mm krypton gas* | *2.740* | *1.158* | *0.478* | *0.591* |
| *WK18* | *5.920* | *16mm krypton gas* | *5.920* | *1.129* | *0.534* | *0.683* |
| *WK19* | *2.740* | *16mm krypton gas* | *2.740* | *1.071* | *0.359* | *0.474* |
| *WK20* | *48.910* | *16mm krypton gas* | *48.910* | *1.199* | *0.511* | *0.295* |

It was also considered that there might be a likelihood of a decrease in the thermal performance of windows by approximately 4.3% after two years, given the argon gas leakage (Cho et al., 2023). Another study tested the effects of the leakage rate of argon filling used to reduce heat loss from windows on the lifetime heat transmission performance of the window. As a result, it was concluded that the effect of argon gas on both convection losses and thermal efficiency was non-linear. It was seen that a 90% argon filling between windows increased the thermal performance of the window by 6.7%. It was also reported that increasing the rate of argon gas in the window gap from 0% to 50% had almost twice the effect on the average thermal efficiency compared to increasing the rate from 50% to 90% (Summ et al., 2023). Another study on the change in the thermal insulation performance of windows depending on the volatility of argon and krypton-filled gases used in window openings over time, reported that the U values of the windows as a result of simulations were lower compared to those in environmental room tests (Cuce, 2018). An study on office buildings for heat losses originating from windows modeled a sample office building and conducted tests on the thermal performance of the building using argon and krypton gas instead of air filling in the window gaps. As a result of the tests, argon-filled and krypton-filled windows contributed 4.5% and 4.6% to the window thermal performance, respectively, compared to air-filled windows (Delarami et al., 2024). A study in the province of Isparta based on the TS 825 standards reported that the window U value of the glass sample with two-layer Solar Low-e 16 mm argon gas filling was reduced by 1.5 W/m²K. (Ogultekin & Koru, 2024) Another study by Cuce et al. (2019) reported that the window U value was reduced to 1.19 W/m²K with double-layered 16 mm argon-filled windows although the U value results obtained from classical window technologies were in the range of 2.00-2.70 W/m²K. Boyenstrasse in Germany is known for its zero-emission multi-story residences built with a 7-story wood-paneled reinforced concrete construction system. Highly insulated argon and krypton-filled windows were used in these residences as per the Passive House criteria. Mahlsdorf House in Germany is another example where krypton and argon-filled glasses were used. Argon and krypton-filled glasses with different thermal transmittance coefficients were used depending on their direction on the ground and upper floors of the house. Therefore, the potential heat losses through windows depending on the building orientation were optimized (Duran & Kartal, 2021). Argon and krypton gas-filled windows have been widely used in cold climate regions from the past to the present. However, as demonstrated in this study, these types of glazing significantly contribute to the reduction of cooling energy demands in buildings located in warm climates, particularly during the summer months. The rising temperatures due to global climate change may increasingly impact cities like Istanbul, which are situated in warm climate zones, potentially transforming these areas into hot climate regions in the coming years. Consequently, this situation further underscores the importance of argon and krypton gas-filled windows in terms of energy efficiency for buildings in these climates.

For the fourth step of the study, the effect of changes in the thickness of the gas gap in the proposed windows on both the thermophysical properties of the windows and the change in the energy performance of the building was investigated. The W17, WA17, and WK17 options and W19, WA19, and WK19 options had the highest performance by heating loads of the building during the third step of the study. Therefore, only those options were taken into account in the fourth step of the study, and the effects of the gas gap thickness in those options on the building were included.

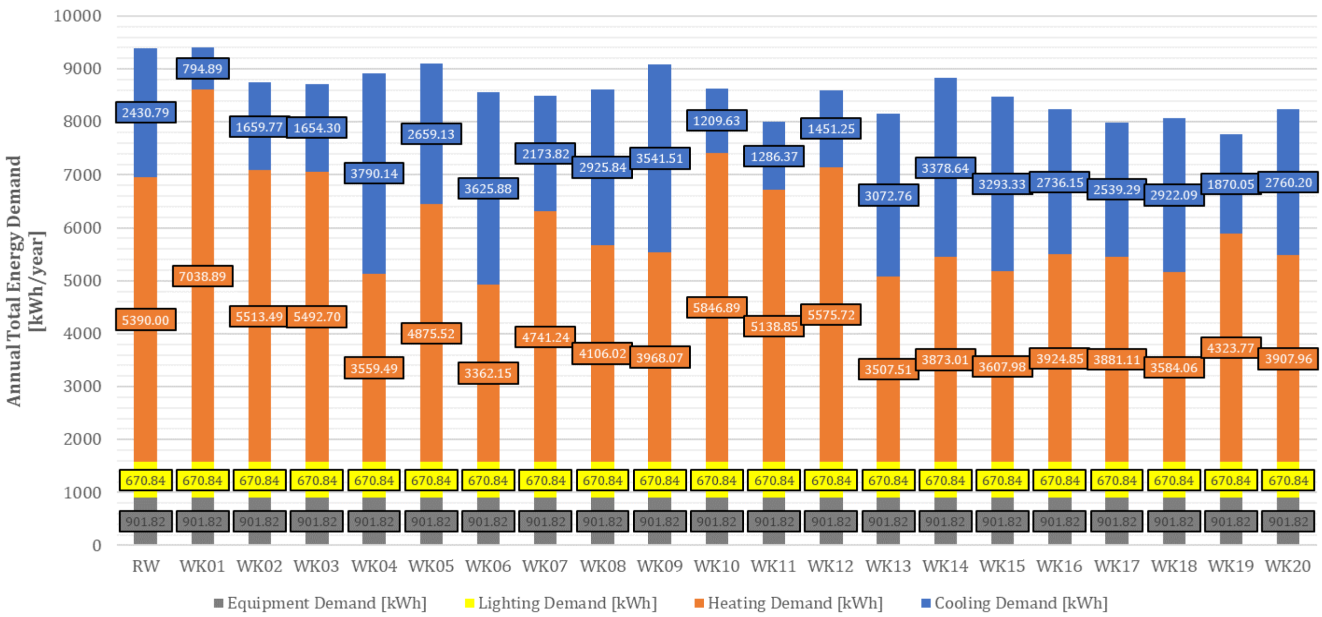



**Figure 10.** The effect of krypton gas-filled (16 mm) double-glazed window types on the annual total energy demand of the sample building.

Table 21 shows the thermophysical properties of the aforementioned options for 16mm and 12mm gas gap thickness values. A review of Table 21 suggests that the U-value increased when the gas gap thickness of air-filled windows decreased from 16mm to 12mm. Nevertheless, the U-value increased when the gas gap thickness of as the argon and krypton gas-filled windows decreased.

Previous studies reported that the properties of the gas between the window panes changed with the increase in the temperature difference between them and the exterior air. This temperature difference was associated with the gas gap thickness of the window (Sehatek Enerji Verimliliği Danışmanlık Ltd. Şti., 2023). A study conducted for the Singapore climate suggested that the optimum gas gap thickness in buildings with the highest energy performance should be 12 mm. Furthermore, if the thickness of the gap was very small (e.g., 3mm), the U-value under winter conditions was high. This was because of the fact that the amount of thermal transmission was higher when heat transfer occurred by conduction in thin gas layers. This consistently continued until the gas gap thickness reached to 12 mm. As the gas gap thickness increased after 12mm, the winter condition U-value worsened. This was because of the fact that as the gas layer thickened, convective heat transfer preceded conduction heat transfer, and that the thicker gas layer allowed stronger gas flow and more convective heat transfer (OTM Solutions Pte Ltd., 2023). A study by Respondek (2018) on argon gas concluded that in cases where the temperature difference between the surfaces was high, for example under winter conditions, reducing the gas gap thickness reduced the thermal resistance as it was associated with an increase in the U-value. The graph of this change is presented in Figure 11. The above studies, which investigated the effect of the change in gas gap thickness on the U-value of the windows explain the results presented in Table 21. The U-value decreased when the gap thickness of argon and krypton gas-filled window W17 was decreased from 16mm to 12mm. A similar result was obtained for W19 filled with argon and krypton gases. A review of Figure 11 indicated that reducing the gas gap thickness of air and argon gas-filled windows to 12mm increased the annual heating need of the building.

**Table 21.** Effect of gas gap thickness on the change of thermophysical properties of windows 17 and 19.

| *Proposed Windows* | *Gap* | *U-value [W/m²K]* | *SGHC* | *T - vis* |
|---|---|---|---|---|
| *W17* | *16mm air* | *1.372* | *0.471* | *0.591* |
| *W17 / 12mm* | *12mm air* | *1.379* | *0.469* | *0.591* |
| *W17 / 8mm* | *8mm air* | *1.591* | *0.465* | *0.591* |
| *WA17* | *16mm argon* | *1.215* | *0.474* | *0.591* |
| *WA17 / 12mm* | *12mm argon* | *1.193* | *0.472* | *0.591* |
| *WA17 / 8mm* | *8mm argon* | *1.356* | *0.469* | *0.591* |
| *WK17* | *16mm krypton* | *1.158* | *0.478* | *0.591* |
| *WK17 / 12mm* | *12mm krypton* | *1.131* | *0.476* | *0.591* |
| *WK17 / 8mm* | *8mm krypton* | *1.093* | *0.474* | *0.591* |
| *W19* | *16mm air* | *1.291* | *0.353* | *0.474* |
| *W19 / 12mm* | *12mm air* | *1.297* | *0.350* | *0.474* |
| *W19 / 8mm* | *8mm air* | *1.513* | *0.347* | *0.474* |
| *WA19* | *16mm argon* | *1.130* | *0.355* | *0.474* |
| *WA19 / 12mm* | *12mm argon* | *1.107* | *0.353* | *0.474* |
| *WA19 / 8mm* | *8mm argon* | *1.273* | *0.350* | *0.474* |
| *WK19* | *16mm krypton* | *1.071* | *0.359* | *0.474* |
| *WK19 / 12mm* | *12mm krypton* | *1.044* | *0.357* | *0.474* |
| *WK19 / 8mm* | *8mm krypton* | *1.003* | *0.355* | *0.474* |

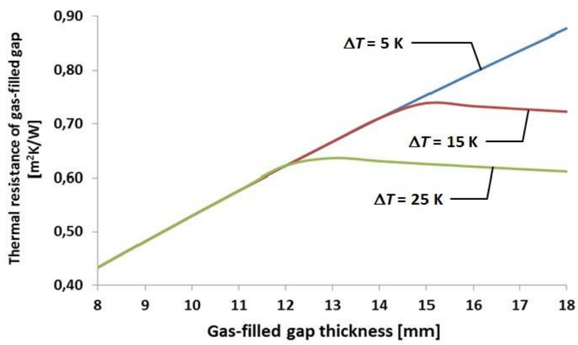



**Figure 11.** Association of the thermal resistance of an argon-filled gap on the thickness of the cavity and the temperature difference (ΔT) between the surfaces (Repondek, 2018).

This was because of the fact that decreasing the gas gap thickness reduced the thermal resistance of the window. This was associated with an increase in the thermal interaction of the building with the exterior air during winter. Reducing the gas gap thickness to 12 mm caused a smaller change in the annual cooling need of the building compared to the heating need. Table 21 provides insight into the reasons thereof. When the gas gap thickness is reduced to 12 mm, there was a slight decrease in the SHGC value of the windows. The decrease in solar thermal radiation also reduced the cooling loads of the building. Nevertheless, Table 21 indicates that this was not the case with the krypton gas-filled windows. It was seen that when the gas gap thickness of the krypton gas-filled window was reduced to 12 mm, the annual heating need of the building was improved, unlike air and argon gas-filled options. The gas gap thickness of W17 and W19 options was reduced to 8 mm and the performance of these options was retested to see up to which gas gap thickness the krypton gas would continue this improvement.

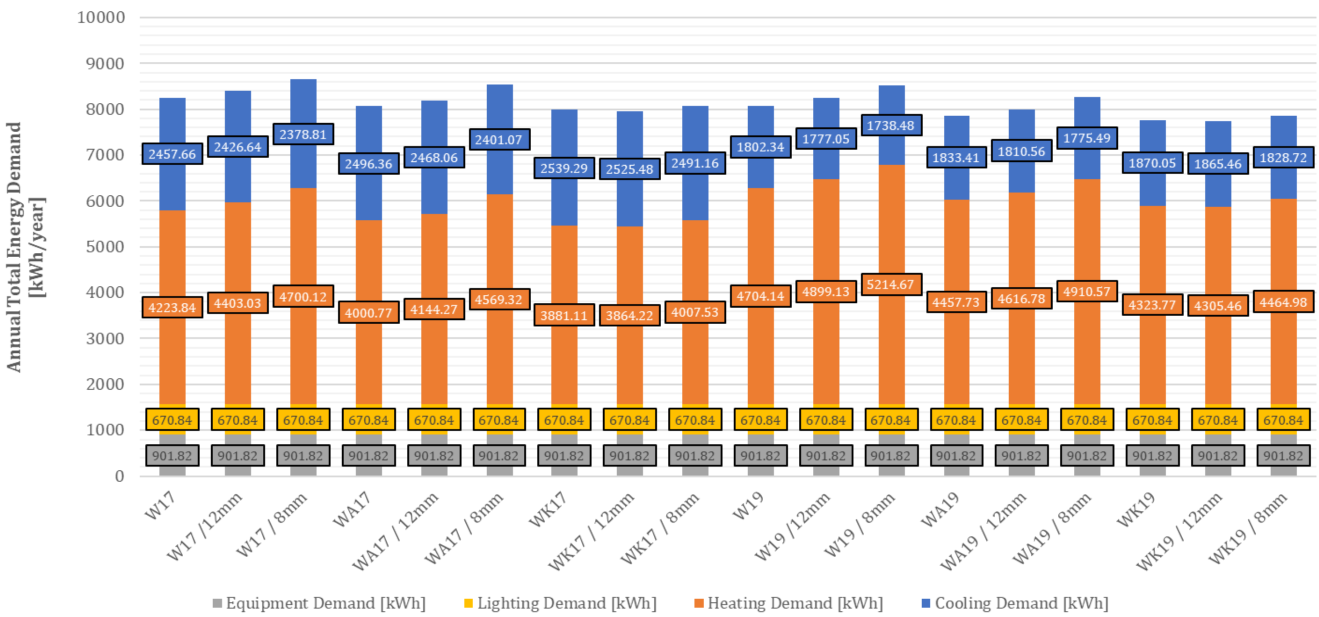



**Figure 12.** The effect of change in gas gap thickness on the energy performance of the building for W17 and W19

As a result, the 8mm gas gap thickness remarkably increased the annual heating need of the building. Accordingly, the optimum gas gap thickness to improve the annual heating need of the building was 16mm for air and argon, and 12mm for krypton for W17 and W19, for a residential building with 30% transparency in the Istanbul climatic region.

A review of Figure 13 indicated the change in the energy performance of the building when polyvinylchloride (PVC) frame was used instead of wooden frame in W17 and W19. While all PVC framed windows improved the annual heating need of the building by approximately 4.5 kWh, there were differences in the change of the annual cooling need of the building by the type of glass and gas. PVC frame use in W17 option improved the annual cooling need of the building by approximately 2 kWh in all three gas types. Nevertheless, PVC frame use in W19 provided an improvement in the annual cooling need of the building for air, argon, and krypton gas-filled windows by 4.69 kWh, 1.75 kWh, and 10.5 kWh, respectively

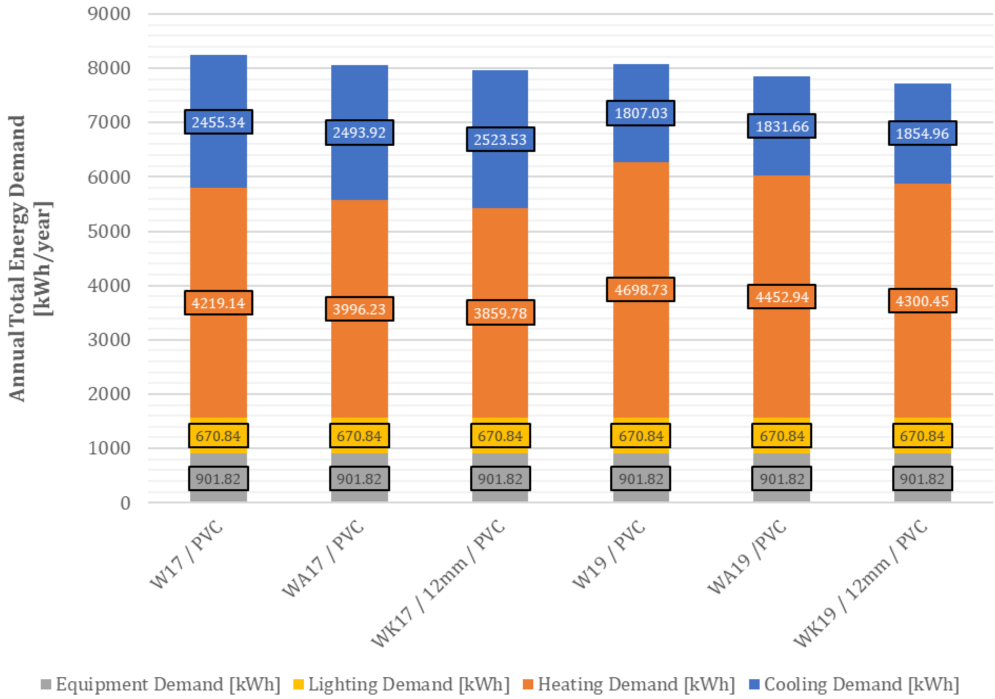



**Figure 13.** Energy performance of W17 and W19 with PVC frames.

## Impacts of the Window Types on the Annual Energy Cost of the Sample Building Align with 12th Goal

The effects of the window types selected for the sample building in the Istanbul climate region on the annual energy costs of the building were determined in this part of the study. First, the effects of all the double-glazed window types with 16 mm air gap in the W01 – W20 range on the annual electricity and natural gas costs of the building were evaluated. Table 22 shows the annual natural gas and electricity bill amounts of the sample building for all window types in the W01 – W20 range. Upon calculations, W01 window increased the heating loads by 988.81 TL in winter compared to the RW window but caused the cooling loads to decrease by 2374.46 TL in the summer period. Upon comparison of the annual total cost of the W01 window with other windows, it was less costly than many window types. Upon comparison of the selected W02 and W03 windows with the RW window, they improved the electricity cost paid for cooling although they increased the annual natural gas bill of the building. Nevertheless, it was understood that they had lower energy costs compared to the RW window, considering the annual total energy cost of both windows. This is because these two types of windows reduced the cooling needs of the building. W04 and W06 windows generally improved the natural gas cost compared to other windows; nevertheless, the use of these windows was associated with a significant increase in the monthly electricity requirement of the building, and it was understood that the average monthly electricity requirement exceeded 240 kWh. Accordingly, the electricity cost calculation of these window types was made based on the high-tariff model. As a result, the annual total energy cost of W04 and W06 windows was higher by 3863.13 TL and 3437.74 TL, respectively, compared to the RW window. Compared to the RW window, the W05 window improved the building's annual natural gas cost by 194.27 TL; yet it was associated with an increase in the electricity cost by 325.55 TL.

This caused an increase of 131.27 TL in the building's annual total energy cost. Upon comparison of the W07 with the RW window, W07 provided improvements in both natural gas and electricity costs. Furthermore, the high T-vis value of this window would allow more sunlight into the interior spaces, increasing the level of brightness. This would increase the visual comfort of users and reduce lighting electricity costs as less artificial lighting would be required. Compared to the RW window, the W08 window provided an annual improvement of 610.48 TL in the building's natural gas cost; but caused the electricity cost of cooling to increase by 2857.13 TL. This caused the total energy cost of the building to increase by 2246.64 TL. It was noticed that the W09 window created the same effect on costs as the W04 and W06 windows. The average monthly electricity need for this type of window exceeded 240 kWh, and therefore, the electricity cost calculation was made based on the high-tariff model. Although the U-value of W10, W11 and W12 window types was lower compared to that of the RW window and reduced the heat losses of the building, the very low SHGC and T-vis values caused the building not to benefit sufficiently from solar thermal radiation and light. Although this caused an improvement in the building's electricity cost, it was also associated with an increase in the cost of natural gas. It was understood that the high SHGC values of W13, W14 and W15 windows significantly increased the electricity cost required for cooling the building. Although the natural costs of these windows were low, the high electricity costs increased the total cost. The W16 window reduced the annual total cost of the building by 266.15 TL compared to the RW window. The lower U-value of the W17 window compared to the RW window increased the heat preservation of the building and significantly reduced the natural gas cost. Furthermore, the higher T-vis value of the W17 window compared to many other selected windows would help the building benefit from more natural light, thus reducing the electricity cost required for artificial lighting. The W19 window provided an improvement of approximately 1282 TL in the annual total energy cost of the building. The U-values of the W18 and W20 windows were lower compared to those of the RW, indicating an improvement in the annual gas cost of the building. Nevertheless, the SHGC values of these windows were higher compared to that of RW, which increased the electricity cost required for cooling.

**Table 22.** Annual natural gas and electricity costs of the recommended air-filled (16 mm) double-glazed window (glass+wooden frame) types for the sample building.

| ***Proposed Windows*** | ***Natural Gas Cost [TL/year]*** | ***Natural Gas Cost [Euro/year]*** | ***Electricity Cost [TL/year]*** | ***Electricity Cost [Euro/year]*** | ***Annual Total Energy Cost [TL/year]*** | ***Annual Total Energy Cost [Euro/year]*** |
|---|---|---|---|---|---|---|
| *RW* | *2815.46* | *108.29* | *3573.26* | *137.43* | *6388.73* | *245.72* |
| *W01* | *3804.27* | *146.32* | *1198.80* | *46.11* | *5003.07* | *192.43* |
| *W02* | *3065.76* | *117.91* | *2418.66* | *93.03* | *5484.42* | *210.94* |
| *W03* | *3051.35* | *117.36* | *2413.80* | *92.84* | *5465.15* | *210.20* |
| *W04* | *2026.26* | *77.93* | *8225.60* | *316.37* | *10251.86* | *394.30* |
| *W05* | *2621.19* | *100.82* | *3898.81* | *149.95* | *6520.00* | *250.77* |
| *W06* | *1939.00* | *74.58* | *7887.47* | *303.36* | *9826.47* | *377.94* |
| *W07* | *2540.58* | *97.71* | *3177.41* | *122.21* | *5717.99* | *219.92* |
| *W08* | *2204.98* | *84.81* | *6430.39* | *247.32* | *8635.37* | *332.13* |
| *W09* | *2129.58* | *81.91* | *7799.69* | *299.99* | *9929.26* | *381.89* |
| *W10* | *3114.13* | *119.77* | *1779.11* | *68.43* | *4893.25* | *188.20* |
| *W11* | *2841.95* | *109.31* | *1978.84* | *76.11* | *4820.79* | *185.42* |
| *W12* | *2969.21* | *114.20* | *2145.27* | *82.51* | *5114.48* | *196.71* |
| *W13* | *2076.94* | *79.88* | *6464.87* | *248.65* | *8541.81* | *328.53* |
| *W14* | *2069.48* | *79.60* | *7455.79* | *286.76* | *9525.27* | *366.36* |
| *W15* | *2054.66* | *79.03* | *7033.30* | *270.51* | *9087.97* | *349.54* |
| *W16* | *2220.40* | *85.40* | *3902.17* | *150.08* | *6122.58* | *235.48* |
| *W17* | *2206.32* | *84.86* | *3612.76* | *138.95* | *5819.08* | *223.81* |
| *W18* | *2062.00* | *79.31* | *4131.38* | *158.90* | *6193.38* | *238.21* |
| *W19* | *2457.21* | *94.51* | *2649.44* | *101.90* | *5106.65* | *196.41* |
| *W20* | *2070.79* | *79.65* | *4067.40* | *156.44* | *6138.19* | *236.08* |

As a result of the energy cost calculations, the W01, W10, W11 and W12 windows, among the double-glazed window types with 16 mm air gap, provided the most striking improvement in the annual total energy cost of the building. Yet, the SHGC and T-vis values of these window types were almost zero, which would largely prevent building users from benefiting from the sun. This would reduce users' visual comfort by reducing their access to daylight and also increase the electricity costs required for artificial lighting. Nevertheless, as for the W07, W17 and W19 windows, both the low annual energy costs of these windows and the high SHGC and T-vis values would significantly reduce these adverse effects suggested for other windows. In this case, it was understood that the window types W07, W17 and W19 were the most suitable windows for the TS825 2nd degree day zone in line with Article 12 of the SDGs. The choice of gas for use in the window space also has an important place in determining the energy costs of the building. In this part of the study, building energy cost calculations were made for the case where argon gas was used instead of air in the glass gaps of the recommended window types. Table 23 shows the annual total natural gas and electricity costs of the sample building for argon-filled windows. Comparing Table 22 and Table 23, the use of argon gas instead of air in the space between the windowpanes resulted in a remarkable improvement in the U-values of the windows. As a result of this improvement, argon-filled windows provided an overall improvement in the building's annual heating requirements, which also led to improvements in the building's annual natural gas costs. This improvement in U-value was associated with an increase in the thermal protection of the building, while as expected, it also led to a slight increase in the annual electricity cost.

As a result of the calculations, argon-filled glass types reduced the annual total energy cost of the building compared to air filled glass types for the TS 825 2nd degree day region. As a result of the calculations in the scope of Article 12 of the SDGs, it was understood that, as in air-filled windows, WA01, WA10, WA11, WA12, WA07, WA17 and WA19 windows in argon-filled window types had the most striking performance in terms of reducing the annual total energy costs of the sample building. Similar to air-filled windows, the low SHGC and T-vis values of WA01, WA10, WA11, and WA12 windows would not benefit from the sun, a natural heat and light source, although these windows provided the lowest energy costs, as much as WA07, WA17 and WA19 windows. This would reduce the visual comfort in indoor spaces and increase the electricity costs required for artificial lighting.

**Table 23.** Annual natural gas and electricity bill amounts of the argon-filled (16 mm) double-glazed window (glass+wooden frame) types recommended for the sample building.

| *Proposed Windows* | *Natural Gas Cost [TL/year]* | *Natural Gas Cost [Euro/year]* | *Electricity Cost [TL/year]* | *Electricity Cost [Euro/year]* | *Annual Total Energy Cost [TL/year]* | *Annual Total Energy Cost [Euro/year]* |
|---|---|---|---|---|---|---|
| *RW* | *2815.46* | *108.29* | *3573.26* | *137.43* | *6388.73* | *245.72* |
| *WA01* | *3727.45* | *143.36* | *1181.59* | *45.45* | *4909.03* | *188.81* |
| *WA02* | *2947.26* | *113.36* | *2429.44* | *93.44* | *5376.7* | *206.80* |
| *WA03* | *2935.44* | *112.90* | *2423.71* | *93.22* | *5359.15* | *206.12* |
| *WA04* | *1916.87* | *73.73* | *8299.72* | *319.22* | *10216.59* | *392.95* |
| *WA05* | *2579.76* | *99.22* | *3903.16* | *150.12* | *6482.92* | *249.34* |
| *WA06* | *1818.20* | *69.93* | *7949.46* | *305.75* | *9767.66* | *375.68* |
| *WA07* | *2506.01* | *96.39* | *3186.55* | *122.56* | *5692.56* | *218.94* |
| *WA08* | *2172.31* | *83.55* | *6449.09* | *248.04* | *8621.40* | *331.59* |
| *WA09* | *2098.85* | *80.73* | *7813.19* | *300.51* | *9912.04* | *381.23* |
| *WA10* | *3082.43* | *118.56* | *1778.42* | *68.40* | *4860.85* | *186.96* |
| *WA11* | *2742.65* | *105.49* | *1923.83* | *73.99* | *4666.49* | *179.48* |
| *WA12* | *2939.07* | *113.04* | *2139.32* | *82.28* | *5078.39* | *195.32* |
| *WA13* | *1904.52* | *73.25* | *6635.68* | *255.22* | *8540.2* | *328.47* |
| *WA14* | *2045.13* | *78.66* | *7461.16* | *286.97* | *9506.29* | *365.63* |
| *WA15* | *1942.21* | *74.70* | *7158.5* | *275.33* | *9100.70* | *350.03* |
| *WA16* | *2110.24* | *81.16* | *3959.46* | *152.29* | *6069.70* | *233.45* |
| *WA17* | *2089.80* | *80.38* | *3669.65* | *141.14* | *5759.45* | *221.52* |
| *WA18* | *1935.49* | *74.44* | *4214.46* | *162.09* | *6149.95* | *236.54* |
| *WA19* | *2328.49* | *89.56* | *2695.11* | *103.66* | *5023.61* | *193.22* |
| *WA20* | *2056.04* | *79.08* | *4063.05* | *156.27* | *6119.09* | *235.35* |

In this part of the study, the annual energy cost of the sample building was calculated for the case where krypton gas was used in the glass gaps of the suggested window types. Krypton gas had a similar performance to argon gas. Upon comparison of krypton-filled windows with argon-filled windows, all windows except WK04 and WK17 window types provided improvements in the annual energy cost of the sample building. This was because of the fact that the use of krypton gas provided a slight improvement in the U-values of WK04 and WK17 windows compared to WA04 and WA17. Nevertheless, the use of krypton was associated with an increase in the SHGC values of the windows and the electricity cost paid for cooling. As a result, the calculations indicated that the WK01, WK10, WK11 and WK12 windows had the most striking performance in terms of the annual total energy cost of the building in krypton-filled window types, as in air-filled and argon-filled windows, especially with the improvements they provided in heating loads. As with air- and argon-filled windows, the low SHGC and T-vis values of these window types would cause the interior spaces to not benefit from natural light as much as WK07, WK17 and W19 windows. It was considered that this would have an adverse effect on the visual comfort of the user. In addition, the user would need to use artificial lighting devices more frequently, which would increase the building's electricity costs. Upon review of the building energy costs and the visual comfort of the building users in combination, WK07, WK17 and WK19 windows stood out among the selected window types.

**Table 24.** Annual natural gas and electricity bill amounts of the recommended krypton-filled (16 mm) double-glazed window (glass+wooden frame) types for the sample building.

| *Proposed Windows* | *Natural Gas Cost [TL/year]* | *Natural Gas Cost [Euro/year]* | *Electricity Cost [TL/year]* | *Electricity Cost [Euro/year]* | *Annual Total Energy Cost [TL/year]* | *Annual Total Energy Cost [Euro/year]* |
|---|---|---|---|---|---|---|
| *RW* | *2815.46* | *108.29* | *3573.26* | *137.43* | *6388.73* | *245.72* |
| *WK01* | *3676.76* | *141.41* | *1168.49* | *44.94* | *4845.25* | *186.36* |
| *WK02* | *2879.97* | *110.77* | *2439.86* | *93.84* | *5319.83* | *204.61* |
| *WK03* | *2869.11* | *110.35* | *2431.82* | *93.53* | *5300.93* | *203.88* |
| *WK04* | *1859.3* | *71.51* | *8376.21* | *322.16* | *10235.51* | *393.67* |
| *WK05* | *2546.73* | *97.95* | *3908.92* | *150.34* | *6455.65* | *248.29* |
| *WK06* | *1756.22* | *67.55* | *8019.82* | *308.45* | *9776.04* | *376.00* |
| *WK07* | *2476.58* | *95.25* | *3195.52* | *122.90* | *5672.1* | *218.16* |
| *WK08* | *2144.78* | *82.49* | *6466.11* | *248.70* | *8610.88* | *331.19* |
| *WK09* | *2072.72* | *79.72* | *7826.74* | *301.03* | *9899.46* | *380.75* |
| *WK10* | *3054.12* | *117.47* | *1778.16* | *68.39* | *4832.28* | *185.86* |
| *WK11* | *2684.28* | *103.24* | *1890.96* | *72.73* | *4575.24* | *175.97* |
| *WK12* | *2912.48* | *112.02* | *2133.34* | *82.05* | *5045.81* | *194.07* |
| *WK13* | *1832.15* | *70.47* | *6790.8* | *261.18* | *8622.95* | *331.65* |
| *WK14* | *2023.07* | *77.81* | *7466.79* | *287.18* | *9489.86* | *364.99* |
| *WK15* | *1884.63* | *72.49* | *7278.26* | *279.93* | *9162.89* | *352.42* |
| *WK16* | *2050.14* | *78.85* | *3875.14* | *149.04* | *5925.28* | *227.90* |
| *WK17* | *2027.3* | *77.97* | *3732.76* | *143.57* | *5760.05* | *221.54* |
| *WK18* | *1872.13* | *72.01* | *6457.82* | *248.38* | *8329.95* | *320.38* |
| *WK19* | *2258.52* | *86.87* | *2748.97* | *105.73* | *5007.49* | *192.60* |
| *WK20* | *2041.32* | *78.51* | *4057.49* | *156.06* | *6098.82* | *234.57* |

As seen in the energy cost calculations in the scope of Article 12 of the SHK, it was understood that the use of krypton gas caused a decrease in the heating and cooling loads of the sample building and showed a similar trend as argon gas in reducing the annual total energy costs. As with air- and argon-filled windows, Windows No. 07, 17, and 19 had the best performance in krypton-filled windows.

### Impacts of the Window Types on the Greenhouse Gas Emission of the Sample Building Align with 13th Goal

Krypton gas provided the highest improvement in building energy performance and annual total energy cost compared to the use of air and argon gas in the glass gaps of the window types recommended for Istanbul. Therefore, in this part of the study Within the scope of Article 13 of the SDGs, greenhouse gas emission calculations of the building were made for the WK01 to WK20 window types and the optimum window types that would reduce greenhouse gas emissions were determined among these windows.

The annual electricity and natural gas $CO_2$ emission calculations depending on the window type selection of the sample building were made within the scope of the 13th Climate Action Article of the SDGs based on the data from the Ministry of Energy and Natural Resources of the Republic of Türkiye for the year 2024 as seen in Table 25. The WK01, WK02 and WK03 window types provided a remarkable reduction in the building's greenhouse gas emissions compared to the RW window type. Nevertheless, the poor performance of these window types in terms of the building's annual energy requirements and total energy costs prevented them from being among the optimum window types for the Istanbul climate zone. The WK10, WK11 and WK12 window types were among the windows with the best performance in reducing annual total greenhouse gas emissions. Yet, the SHGC and T-vis values of these windows were quite low, causing the interior spaces of the building to benefit from sunlight at a lower rate compared to the RW window. This would have an adverse effect on the visual comfort of the user, preventing these window types from being among the optimum window types for the Istanbul climate zone. The WK07, WK17 and WK19 window types were the windows with the highest performance in reducing the annual total greenhouse gas emissions of the building within the scope of Article 13 of the SDGs, as well as Article 12.

**Table 25.** Annual greenhouse gas emissions of the type of krypton-filled (16 mm) double-glazed windows (glass+wooden frame) recommended for the sample building.

| *Proposed Windows* | *Electricity [kg$CO_2$/year]* | *Natural Gas [kg$CO_2$/year]* | *Total [kg$CO_2$/year]* |
|---|---|---|---|
| *RW* | *1169.21* | *1078.00* | *2247.21* |
| *WK01* | *382.34* | *1407.78* | *1790.12* |
| *WK02* | *798.35* | *1102.70* | *1901.05* |
| *WK03* | *795.72* | *1098.54* | *1894.26* |
| *WK04* | *1823.06* | *711.90* | *2534.96* |
| *WK05* | *1279.04* | *975.10* | *2254.15* |
| *WK06* | *1744.05* | *672.43* | *2416.48* |
| *WK07* | *1045.61* | *948.25* | *1993.86* |
| *WK08* | *1407.33* | *821.20* | *2228.53* |
| *WK09* | *1703.47* | *793.61* | *2497.08* |
| *WK10* | *581.83* | *1169.38* | *1751.21* |
| *WK11* | *618.74* | *1027.77* | *1646.51* |
| *WK12* | *698.05* | *1115.14* | *1813.20* |
| *WK13* | *1478.00* | *701.50* | *2179.50* |
| *WK14* | *1625.13* | *774.60* | *2399.73* |
| *WK15* | *1584.09* | *721.60* | *2305.69* |
| *WK16* | *1316.09* | *784.97* | *2101.06* |
| *WK17* | *1221.40* | *776.22* | *1997.62* |
| *WK18* | *1405.53* | *716.81* | *2122.34* |
| *WK19* | *899.49* | *864.75* | *1764.25* |
| *WK20* | *1327.66* | *781.59* | *2109.25* |

### Determination of the Optimum Window Type for the 2nd Degree Day Region of TS825 Standard within the Framework of 11th, 12th, and 13th Goals

In this part of the study, the effects of the proposed krypton-filled window types on the annual total energy requirement of the building within the scope of Article 11 of the SDGs, on the annual total energy costs of the building within the scope of Article 12 and on the annual total greenhouse gas emissions within the scope of Article 13 were evaluated and the TS825 was determined as the optimum window type for the 2nd degree day zone was these windows. Table 26 shows the total energy requirement, total energy costs, and total greenhouse gas emission results for the case where these window types were used in the building. Figure 14 shows the graphical results of the data from Table 26. As seen in Figure 14, it is remarkable that the WK07, WK17 and WK19 window types provided higher performance compared to the RW window. Considering the thermal protection of the building due to the improvement in U-values, the WK17 and WK19 window types stood out compared to WK07 window type. Considering the SHGC and T-vis values, the WK17 window type was a more advantageous window type for Istanbul compared to the WK19 window type, in order for interior spaces to benefit more from natural lighting. In the light of above discussion, the effects on the building's annual total energy requirement, energy cost, and greenhouse gas emissions within the scope of 11th, 12th and 13th goals of the SDGs were tested again for the gas gap thickness of krypton-filled windows reduced to 12 mm and PVC selected for the window frames.

Upon review of Figure 15, the WK19 window type had the highest performance compared to the WK07 and WK17 window types. Daylight can meet some or all of the light needs required in indoor spaces as prescribed in the EN 12464-1 "Light and lighting - Lighting of workplaces - Part 1: Indoor workplaces" standard, which was accepted and published by the European Union (EU) on 09.05.2021. This provides potential energy savings for buildings. Furthermore, the amount of daylight in the interior space is directly proportional to the climatic conditions in which the building is located, the building's surroundings, and the thermophysical properties of the selected window type (British Standards Institution, 2021). EN 17037 "Daylight in buildings" is another standard accepted and published by the EU on 29.07.2018. In this standard, daylight is considered an important source of illumination for all spaces with daylight opening(s) and that daylight is strongly preferred by building occupants as a way to adequately illuminate interior surfaces and save energy for electric lighting (British Standards Institution, 2018). Accordingly, the lower SHGC and T-vis value of the WK19 window compared to the WK07 and WK17 window types would cause the sample building to benefit less from sunlight throughout the year, thus allowing less light to enter the interior spaces, which would have an adverse effect on user comfort.

The results of this study offer a comprehensive overview of how different window types and gas infill options can influence the overall energy performance of residential buildings. While these findings provide valuable insights into the technical aspects of building energy efficiency, simulation-based analyses alone may not be sufficient to fully capture the complexities of real-world implementation. It is crucial to critically assess the assumptions, constraints, and broader implications of the data to translate simulation results into actionable strategies for designers, policymakers, and building practitioners.

Accordingly, the subsequent discussion aims to reflect upon the technical findings by a review of the strengths and limitations of EnergyPlus and DesignBuilder simulation tool in the context of their usability, accuracy, and data input requirements. Furthermore, the performance of various window configurations was analyzed not only in terms of energy savings but also from an economic standpoint, considering potential investment and maintenance costs. The discussion also outlines directions for future research, including the integration of statistical validation techniques and cost-effectiveness analyses to enhance the robustness and applicability of the results. Through this multifaceted review, the study aims to make a robust contribution into the existing literature and offer a solid foundation for future investigations into high-performance building envelope solutions

**Table 26.** Effects of krypton-filled (16 mm) double-glazed window (glass+wooden frame) types on the annual annual total energy requirement, energy cost, and greenhouse gas emission of the sample building.

| *Proposed Windows* | *Total Energy Demand [kWh/year]* | *Total Energy Cost [TL/year]* | *Total Energy Cost [Euro/year]* | *Total Greenhouse Gas Emissions [kgCO₂/year]* |
|---|---|---|---|---|
| *RW* | *7820.79* | *6388.73* | *245.72* | *2247.21* |
| *WK01* | *7833.78* | *4845.25* | *186.36* | *1790.12* |
| *WK02* | *7173.26* | *5319.83* | *204.61* | *1901.05* |
| *WK03* | *7147.00* | *5300.93* | *203.88* | *1894.26* |
| *WK04* | *7349.63* | *10235.51* | *393.67* | *2534.96* |
| *WK05* | *7534.65* | *6455.65* | *248.29* | *2254.15* |
| *WK06* | *6988.03* | *9776.04* | *376.00* | *2416.48* |
| *WK07* | *6915.06* | *5672.1* | *218.16* | *1993.86* |
| *WK08* | *7031.86* | *8610.88* | *331.19* | *2228.53* |
| *WK09* | *7509.58* | *9899.46* | *380.75* | *2497.08* |
| *WK10* | *7056.52* | *4832.28* | *185.86* | *1751.21* |
| *WK11* | *6425.22* | *4575.24* | *175.97* | *1646.51* |
| *WK12* | *7026.97* | *5045.81* | *194.07* | *1813.20* |
| *WK13* | *6580.27* | *8622.95* | *331.65* | *2179.50* |
| *WK14* | *7251.65* | *9489.86* | *364.99* | *2399.73* |
| *WK15* | *6901.31* | *9162.89* | *352.42* | *2305.69* |
| *WK16* | *6661.00* | *5925.28* | *227.90* | *2101.06* |
| *WK17* | *6420.40* | *5760.05* | *221.54* | *1997.62* |
| *WK18* | *6506.15* | *8329.95* | *320.38* | *2122.34* |
| *WK19* | *6193.82* | *5007.49* | *192.60* | *1764.25* |
| *WK20* | *6668.16* | *6098.82* | *234.57* | *2109.25* |

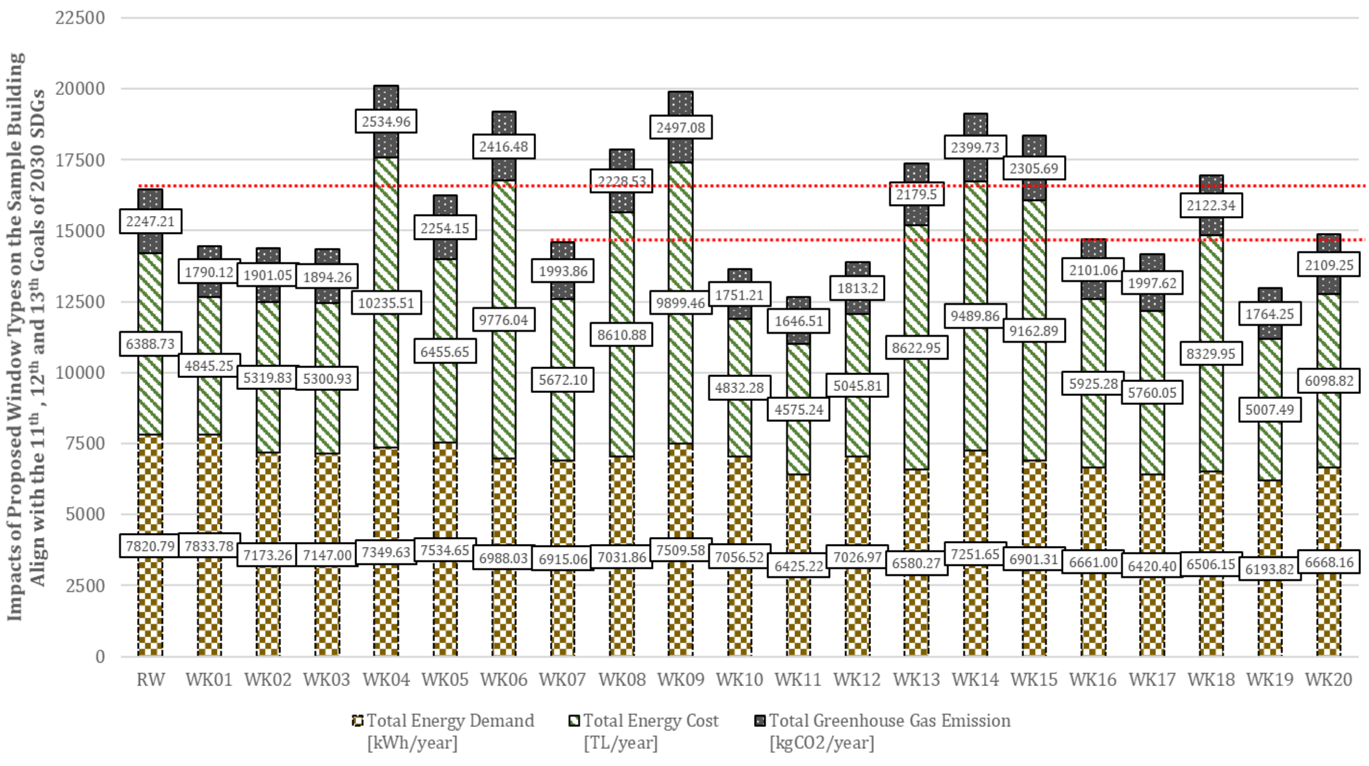



**Figure 14.** Annual total energy demand, energy cost, and greenhouse gas emission of the types of krypton-filled (16 mm) double-glazed windows (glass+wooden frame) recommended for the sample building.

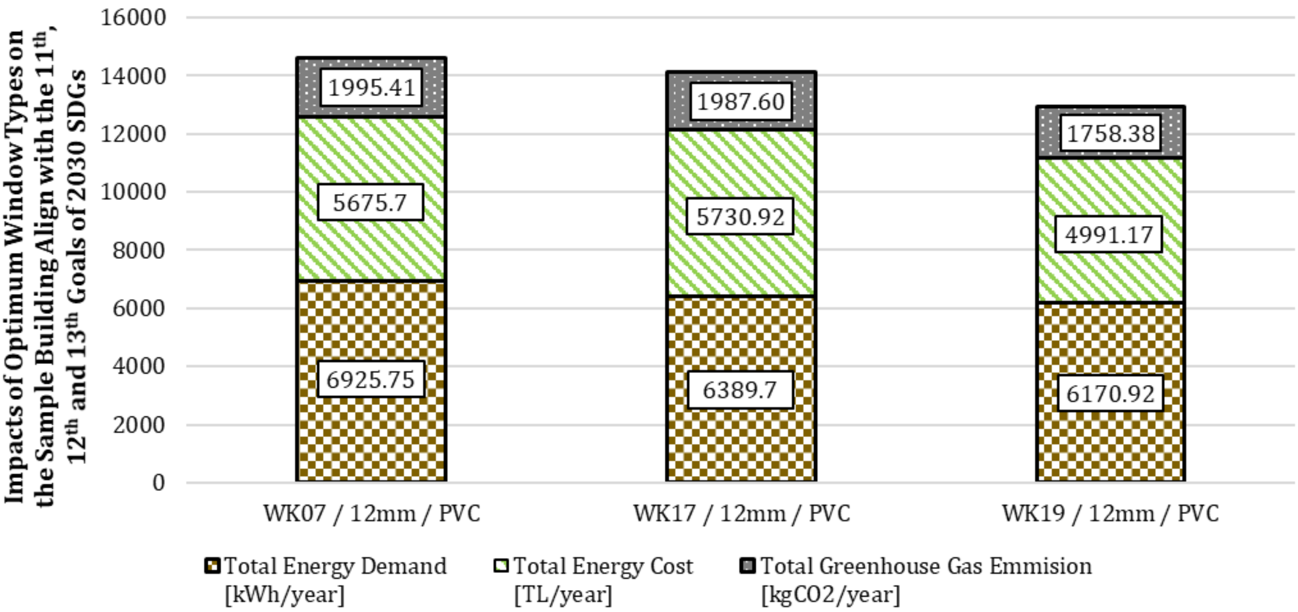



**Figure 15**. Annual total energy demand, energy cost, and greenhouse gas emission of PVC-framed WK07, WK17, and WK19 windows.

## DISCUSSION

In the present study, EnergyPlus and DesignBuilder were used for building performance simulations, each offering distinct advantages and challenges. While EnergyPlus is a highly accurate and powerful tool for building energy calculations, its lack of a user-friendly interface can prove to be a significant barrier for users. In contrast, DesignBuilder provides a more intuitive user interface, making it easier to use, but it still relies on EnergyPlus for the baseline calculations such as building loads, HVAC system consumption, thermal comfort, and more (Akgüç & Yilmaz, 2024). Despite its ease of use, DesignBuilder requires less detailed input compared to EnergyPlus, which can be a limitation for users who need more precision. These shortcomings in both programs can be time-consuming, especially for users attempting to create a comprehensive energy model. Therefore, addressing these issues and improving the interface and data input processes could significantly enhance the efficiency of building energy modeling, enabling faster and more accurate results with a single, streamlined tool.

Looking ahead, the future direction of this research will involve integrating statistical validation methods to further enhance the reliability and generalizability of the simulation results. Specifically, applying statistical tools such as variance analysis and confidence intervals will provide a more objective assessment of the impact of different window types and gas fillings on energy efficiency. This will not only reinforce the scientific contribution of the study but also offer valuable insights for similar future studies. Therefore, the integration of statistical analyses into subsequent research will further broaden the scope and strengthen the conclusions drawn from these findings. In addition to these analytical improvements, future studies should also include an economic analysis to assess the cost-effectiveness of the proposed window types.

While this study primarily focuses on energy savings, evaluating the initial investment costs alongside long-term economic returns from energy savings will provide a more comprehensive view of the practical implications of these systems. Such economic assessments will not only enhance the applicability of the findings but will also help facilitate the wider adoption of energy-efficient strategies. Furthermore, although the simulation results and other examples showed that argon- and krypton-filled windows contribute to improved energy performance compared to air-filled windows, building users should carefully evaluate the initial investment and ongoing maintenance costs associated with these windows. Given the volatility of argon and krypton gases, these window types require regular maintenance to prevent performance degradation due to gas leaks, which should be factored into the overall assessment of their viability.

## CONCLUSION

The present study investigated the thermophysical properties of the reference window, which was considered constant for all degree day regions by the TS825 standard, i.e., the building standard in Türkiye for the 2nd degree day region. Study selected the city of Istanbul as the pilot region, a sample building model was created using the DesignBuilder building simulation tool, and the thermophysical properties of the window for this sample building were categorized as U-value, SHGC, and T-vis. Based on the study results, recommendations were made for the optimum glass and frame type that would improve the performance of the building towards 11th, 12th and 13th goals of 2030 SDG. In the first phase of the study, significant improvements in heating efficiency were observed with argon- and krypton-filled windows compared to air-filled windows. Specifically, windows No. 17 and 19, which featured a 16 mm gas gap and wooden frames, demonstrated the best performance in reducing heating energy consumption. Notably, the use of krypton gas showed higher energy performance than air- or argon-filled windows, especially in maintaining consistent heating efficiency even when the gas gap thickness was reduced to 12 mm. The analysis also highlighted that reducing the gas gap thickness further to 8 mm resulted in decreased performance across all window types, with krypton-filled windows still performing the best due to their superior thermal resistance. The reduction in gas gap thickness caused an increase in annual heating requirements, but krypton-filled windows exhibited the least increase in heating load, showcasing the benefit of selecting optimal gas types and gap thickness for achieving energy savings. In the second phase, the study assessed the impact of different window types on the building's energy costs. While argon and krypton windows offered thermal benefits, they also contributed to increased cooling costs due to reduced thermal losses and subsequent interior heat accumulation. Among the tested windows, No. 7, 17, and 19 showed the best overall performance in minimizing energy costs, with window No. 7 standing out due to its higher transmittance of visible light, which allowed the building to benefit from natural sunlight more effectively, thereby reducing overall energy consumption. In the third phase, the impact of these windows on the building's greenhouse gas emissions was examined. $CO_2$ emission calculations confirmed that windows No. 7, 17, and 19 were the most effective in reducing the building's carbon footprint, with krypton-filled windows performing the best in terms of reducing emissions. These results underline the importance of selecting not only energy-efficient materials but also optimizing the gas type and window configuration to minimize environmental impact. In the final analysis, the effect of replacing the wooden frame with PVC and reducing the gas gap thickness to 12 mm was tested. This change led to significant improvements in both the building's energy costs and $CO_2$ emissions. While the PVC frames did not dramatically affect the heating or cooling performance as much as the glass type and gas choice, they still provided a noticeable benefit in overall energy efficiency, demonstrating the importance of material selection beyond just glazing and gas types.

Achieving the targets set forth in the 2030 SDGs, particularly within the housing sector, necessitates the strategic implementation of targeted investment incentives and robust economic policies in Türkiye. These measures are crucial for facilitating the widespread adoption of energy-efficient technologies, such as the advanced window systems evaluated in this study, while addressing the financial challenges that often impede their deployment. By integrating energy efficiency optimization strategies into national policy frameworks, Türkiye can not only accelerate its progress towards sustainable building practices but also stimulate economic growth within the construction industry, positioning itself as a leader in environmentally conscious development.

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