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ENERGY-EFFICIENT RETROFITTING IN COMPLEX UNIVERSITY BUILDINGS: ENERGY CONSUMPTION, EXERGY LOSS, ENTROPY GENERATION AND LIFE CYCLE GREENHOUSE GAS ANALYSES

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Highlights

- Retrofitting for energy efficiency in complex university buildings was studied.
- Envelope retrofitting potential in complex university buildings was identified.
- Simulations are vital for energy analysis of different building types.
- Monthly heating, cooling, and yearly energy use in buildings were examined.
- Long-term GHG analysis in complex buildings is key for global warming studies.

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ABSTRACT: This study examines the impact of energy-efficient renovation and reinforcement of the building envelope on energy consumption and carbon dioxide emissions in the Faculty of Arts and Sciences building at Balikesir University, a complex structure constructed in 1994. Energy consumption was evaluated through EnergyPlus simulations based on the thermal transmittance values recommended in TS 825:2013, which largely reflects the characteristics of the existing building stock in Turkey. The building includes various functional spaces such as classrooms, offices, laboratories, and storage areas, with window-to-wall ratios ranging from 13.6% to 38.02%, a total external wall area of 15,986 square meters, and a window area of 4,796 square meters. Fifteen renovation scenarios were analysed, involving upgrades to external walls, floors, ceilings, and windows in line with TS 825 standards. Each scenario was assessed for its effect on heating, cooling, and annual energy consumption. In addition, the exergy loss and entropy generation associated with energy consumption were calculated for the building envelope. The building operates with a central system, employing a natural gas boiler for heating and an air-cooled chiller for cooling. Finally, a ten-year life cycle analysis of greenhouse gas emissions was carried out using natural gas and electricity to assess environmental sustainability. The maximum reduction in energy consumption and carbon dioxide emissions, amounting to 45%, was achieved when all building envelope components were upgraded. The difference in exergy loss and entropy generation between the current case and the most efficient scenario was calculated as 58% during the heating period and 52% during the cooling period.

Keywords: *Building Envelope Effect, Entropy Generation, EnergyPlus, Exergy loss, Life Cycle Greenhouse Gas Analysis (LCGA)*

1. INTRODUCTION

Energy use in buildings is a major global issue, and many countries are creating policies to save energy. In the European Union, buildings account for approximately 35% of all energy consumption, making them the largest energy-consuming sector. They also produce around 36% of CO_2 emissions. Most of this energy is used for heating and cooling, which accounts for approximately 60% of the total. As the need for heating and cooling grows, better energy systems and stronger energy policies are becoming more important [1, 2].

Energy consumption and greenhouse gas emissions in the construction sector are considered one of the most important problems in developed countries. Reducing energy consumption in the construction sector is important in combating global climate change and improving sustainability. Improving energy efficiency, i.e., strengthening building envelope elements with thermal insulation and window feature design measures, ensures efficient energy use and reduces greenhouse gas emissions and climate change [3, 4, 12, 14, 16].

Selecting appropriate building designs for effective energy management helps reduce greenhouse gas emissions throughout the building's life cycle and enables more accurate predictions to combat

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climate change globally. Building energy analysis has experienced rapid growth in recent years, using various programs and software. Such software is an important tool for determining different energy-saving strategies to reduce the impact of climate change in the future [21, 23, 30]. EnergyPlus simulation is one of them. This software is used to reveal the optimal energy-saving potential for buildings in various climatic conditions [1, 17].

A review of the literature reveals several notable studies on energy-efficient building retrofits. Jianying Hua and Xiong Yub used EnergyPlus simulations to explore the potential energy savings from adaptive building envelopes under five different climatic conditions [1]. Farshid Shadram et al. analysed the impact of multi-objective optimisation on energy use in a typical 1980s multi-family residential building in Sweden. Their study compared various retrofit strategies, such as envelope upgrades, to identify the most effective solutions for meeting Swedish energy efficiency standards [2]. A. Rogeau, R. Girard, Y. Abdelouadoud, M. Thorel, and G. Kariniotakis examined two retrofit approaches—envelope insulation and heating system replacement. Their optimisation model aimed to minimise the net present value of retrofit costs, and they proposed a linear formulation to manage the complexity of multiple retrofit combinations. Their results showed that implementing long-term strategies in the short term could reduce energy use and greenhouse gas emissions by 10% [3]. Hassan Radhi demonstrated through simulation that design measures like thermal insulation, thermal mass, window area, and glazing systems play a crucial role in responding to climate change and global warming [4]. Xiaocun Zhang and Fenglai Wang proposed a standardised method for assessing the life cycle carbon emissions of buildings, highlighting its importance for future low-carbon development [5].

Jonathan I. Levy et al. used the EnergyPlus simulation software to estimate insulation-related energy savings in 665,000 newly built homes in the United States in 2013 [6]. Christina Ismailos and Marianne F. Touchie conducted an energy modelling analysis of a typical single-family home in Ontario to evaluate potential carbon emission reductions from various mitigation strategies, including additional exterior insulation and mechanical system upgrades [7]. Fayez Aldawi et al. employed the simulation software AccuRate® to assess thermal energy performance. Their findings showed that the new home wall system offered significantly greater energy savings than the traditional brick veneer wall system [8]. Beatriz Rosselló-Batle et al. evaluated 92 sub-scenarios in a case study building to determine differences in thermal energy demand based on variations in building typology, considering ten facade types, three roof systems, and three window frame types [9]. Andrea Invidiata and Enedir Ghisi studied the impact of climate change on heating and cooling energy demand in residential buildings across three Brazilian cities. They used the EnergyPlus software to estimate indoor air temperature and annual heating and cooling energy consumption [10].

Alexandra Charles et al. developed an energy model to improve the energy efficiency of a two-storey office building constructed in the 1960s in Vancouver. The model identified key parameters for reducing energy consumption and CO_2-equivalent emissions. The study also calculated the costs of retrofit strategies, including improvements to the building envelope and the integration of renewable energy systems. The parametric analysis revealed that wall and ceiling insulation, improved air tightness, and window replacement had the greatest impact, resulting in a 45% reduction in total annual energy consumption [11]. M. Karmele Urbikain investigated heating energy savings from thermal retrofitting a multi-storey residential building using vacuum insulation panels on the opaque sections of the east, south, and west facades. Heat transfer simulations using TRNSYS, Window, and Optics software were performed to identify the optimal combination of insulation and window types for buildings located in Berlin’s cool climate and Bilbao’s warmer climate [12]. Matheus Belucio et al. presented empirical findings on building retrofits in Southern European climates. Their study showed that the most influential factors on short- and long-term eco-efficiency were roof insulation thickness, followed by the material used for external wall insulation [13]. Fayez Aldawi et al. investigated the thermal performance and energy-saving potential of a new residential wall system under various climate conditions using the AccuRate software [14]. Nader Chalfoun explored the benefits of greening university campus buildings, which are often major consumers of energy and sources of water and air pollution. His models aimed to minimise global warming emissions on campuses like the University of Arizona [15].

Irina Baran et al. explored the potential of converting existing educational buildings into nearly Zero Energy Buildings (nZEBs) using current technologies for thermal protection [16]. S. M. Hosseini et al. examined the potential for energy savings and CO_2 emission reductions by retrofitting office buildings at Tehran University Science and Technology Park using Building Information Modelling (BIM). DesignBuilder software was employed in their study [17]. Uniben Yao Ayikoe Tettey and Leif Gustavsson analysed the energy consumption and carbon dioxide (CO_2) emissions of a multi-storey concrete residential building in Sweden, retrofitting it with various insulation, cladding, and framing materials [18]. Yasmeen Hossain and Tom Marsik investigated an energy-efficient house in rural Alaska. Using computer simulations, they compared the energy consumption of the case study house with that of a conventional house, incorporating Life Cycle Assessments (LCA) to evaluate the annual savings in greenhouse gas emissions and calculate the carbon payback period [19]. Janusz Adamczyk and Robert Dylewski used data from the Ecoinvent library within the SimaPro software for their Life Cycle Assessment (LCA) analysis, examining the thermo-modernisation of representative buildings [20].

In the studies by Marta Videras Rodríguez et al., various energy reduction strategies are proposed to mitigate the future impacts of climate change. Total building energy consumption is analysed for subtropical regions using different energy simulations [21]. Walery Jezierski, Beata Sadowska, and Krzysztof Pawłowski investigated the effects of changes in thermal insulation on building energy demand, heating costs, and emissions. Mathematical models based on the thermal transmittance coefficient were developed for the selected building [22]. Cuong N. N. Tran et al. presented a comprehensive model for valuing greenhouse gas emissions across various building envelopes, based on the energy efficiency requirements outlined in the Australian National Building Code [23]. Emeli Lalesca Aparecida da Guarda et al. examined the effects of global warming on building energy consumption due to different insulation types within the building envelope. Their study explored the impact of energy consumption in future scenarios for the years 2020, 2050, and 2080 [24]. Okan Kon et al. conducted life cycle assessments of hospitals, a complex building type, focusing on the impact of external wall insulation [25]. Lozinsky and Marianne F. Touchie demonstrated the potential carbon emission savings from various energy reduction strategies, including changes to the building envelope and mechanical systems, through an energy modelling analysis of a typical single-family home in Ontario. The most effective strategies identified were the application of external insulation and the switch to an air-source heat pump for heating and cooling [26].

Carla Rodrigues and Fausto Freire conducted a life cycle analysis to assess alternative retrofit strategies for the roofs and external walls of two residential buildings in Coimbra, Portugal, built in the early twentieth century. Their study involved a comprehensive analysis of various insulation thicknesses to identify the optimal levels that minimize life cycle (LC) environmental impacts for both a single-family house and an apartment [27]. Vidhyalakshmi Chandrasekaran et al. evaluated the environmental impact of two differently renovated multi-apartment buildings, constructed in the early 1980s and not meeting current energy efficiency standards, using life cycle assessment. The study examined the environmental impacts of various renovation measures applied to these buildings [28]. Van de Moortel et al. developed a model considering multiple factors, including the efficiency of current and future heating systems, the heating system's service life, and the building envelope's insulation level. The model aimed to determine the most effective renovation strategies for residential buildings, focusing on reducing life cycle environmental impact [29]. Sajad Abasnezhad et al. conducted an energy consumption analysis for the mechanical engineering building at Tabriz University in northwestern Iran, evaluating ten different models. The energy analysis was performed using EnergyPlus software [30].

Clayton Miller et al. conducted building energy simulations for two university campuses in Switzerland using EnergyPlus and CitySim simulation programs. The study compared measured performance data with simulated results [31]. Ayah-Allah Khalil et al. investigated the impact of residential building envelope configurations in Alexandria, Egypt, on energy consumption. They determined the most efficient envelope design for minimizing energy use in residential buildings, using the EnergyPlus simulation tool [32]. Siti Birkha Mohd Ali et al. examined the potential for energy savings in the Research and Development building at Universiti Malaya between March and May 2017 [33]. Alberto Hernandez Neto and Flávio Augusto Sanzovo Fiorelli compared a simple artificial neural network-based model for estimating building energy consumption with a model based on EnergyPlus as a prediction tool. The University of São Paulo Administration Building was used as a case study. A parametric analysis of the building's energy consumption was conducted using EnergyPlus and campus meteorological data [34]. M. Jradi et al. studied the Mærsk Building at the University of Southern Denmark’s Odense campus to reduce energy consumption, heating, and electricity use. The study developed and evaluated methodologies for major energy-efficient renovations of non-residential and public buildings [35].

Michael A. William et al. evaluated the potential energy savings in hospital buildings in Egypt, specifically focusing on the energy requirements of medical facilities. Using the DesignBuilder simulation program, they analyzed efficient retrofit applications and found that approximately 67% energy savings could be achieved in medical buildings through appropriate retrofits and renovations [36]. Christopher J. Bay et al. developed models to assess energy consumption in a Texas A&M University campus building, utilizing MATLAB and EnergyPlus for the energy consumption analysis [37]. Ryan Sharston and Scott Murray used EnergyPlus simulations to examine how the combination of thermal mass and insulation affects building energy use across eight U.S. climate zones. They analyzed building energy consumption based on annual heating and cooling energy demands and total energy use [38]. Shanbhag and Dixit evaluated the advantages and limitations of the most commonly used Life Cycle Assessment (LCA) methodologies in the literature. They also provided insights into the potential trends in this field [39]. In another study, they explored future energy scenarios to assess how embodied environmental impacts might evolve [40]. Kon and Caner, in their analysis of an airport terminal building, investigated the influence of optimal insulation thickness on both LCA and Life Cycle Savings (LCS) outcomes [41]. In a separate study, they analysed various insulation materials specific to Turkey, evaluating them in terms of life cycle saving (LCS), life cycle total cost (LCT), energy saving (ES), and payback period [42]. Greer et al. used LCA to assess the effectiveness of specific operational energy methodologies and emission factor databases in comprehensively evaluating global greenhouse gas (GHG) emissions from building operations [43]. McLaren et al. examined ways to more accurately incorporate the timing of GHG emissions and removals into building and construction product LCAs, using static and dynamic case studies focused on roofs, walls, and floors [44].

The energy performance of buildings has been investigated through different approaches, ranging from entropy generation analysis to cogeneration applications. In Spain, a study on a near-zero energy Building (nZEB) introduced entropy generation as a magnitude to evaluate efficiency. Results showed that solar irradiance was the dominant source of entropy generation, and the nZEB design produced almost half the entropy of a less efficient building. In Turkey, a micro-cogeneration system installed in a residential complex in Konya was assessed. Powered by natural gas, the system achieved an overall efficiency of 87%, reducing grid electricity use by more than 50% and providing notable economic benefits, especially in winter when its performance was at its highest [45-47].

During the winter season, the outdoor air temperature and the heat energy generated by heating systems in buildings create temperature differences around the building envelope. The generated heat energy naturally flows from regions of higher temperature to regions of lower temperature, and in accordance with the zeroth law of thermodynamics, this process continues until thermal equilibrium is established. Applying thermal insulation to the building envelope delays this flow. Chemical energy sources such as natural gas, coal, and fuel oil are converted into heat energy through heating systems within the framework of the first law of thermodynamics. The storage and utilization of the generated heat within the indoor environment, however, are related to the second law of thermodynamics. The second law is defined by the concepts of exergy and entropy [48,49].

Exergy analysis is performed directly in relation to the type or thermodynamic state of the supplied energy source. The exergy loss associated with a given amount of heat energy can be calculated by multiplying the energy by its quality factor. Accordingly, exergy loss analysis is expressed as the product of the quality factor and the primary energy input. The quality factor depends on the temperatures of the system (indoor environment) and the reference dead state (outdoor environment). Thus, the further the system temperature deviates from the ambient temperature, the higher its exergy; in this sense, exergy reflects the importance of measuring the quality of energy [52,55].

The heat energy transferred from the outdoor to the indoor environment, or vice versa, at a constant rate is used to determine the temperature, entropy, and exergy values depending on the properties of a building envelope. Along the direction of heat transfer, the temperature cannot be preserved and decreases. However, since entropy generation increases, exergy loss occurs. Exergy represents the useful portion of energy, namely, the maximum amount of work that can be produced when an energy flow comes into equilibrium with the reference environment. Entropy, on the other hand, is a fundamental concept in thermodynamics. Simply stated, entropy is a measure of internal disorder that can only be transferred through heat exchange [48,49,51,53].

The distinction between reversible and irreversible processes in thermodynamics is revealed through the concept of entropy. In an adiabatic system, the entropy leaving the system is always greater than the entropy entering it, and this difference arises from the entropy produced by irreversible processes within the system. Exergy consumption is proportional to the entropy generated due to irreversibilities associated with different processes. Many engineers and scientists argue that the thermodynamic performance of a process can be most effectively evaluated by complementing conventional energy analysis with an exergy analysis. Exergy analysis is a thermodynamic method that evaluates the quality or usability of energy [50,51,53].

A different line of research investigated the impact of wall surface coatings and materials, such as white paint, brick, aluminium, marble, and porcelain, on the energy, exergy, and anergetic performance of buildings. Using Balikesir as a case study, the results showed that white-painted surfaces on northern walls yielded the highest exergy values. In contrast, dark-coated surfaces with a natural gas supply presented the lowest. Such findings highlight the importance of building envelope properties on overall thermal performance. Beyond individual building studies, broader methodological approaches have also been reviewed. One paper emphasised that traditional first-law thermodynamic analysis fails to capture the quality of energy transformations. At the same time, the second-law-based exergy approach provides a deeper insight into rational energy use. This perspective is particularly important in buildings, where high-quality energy sources are often utilised inefficiently to produce low-quality thermal energy [48-51].

Complementary research further explored the thermodynamic foundations of energy, entropy, and exergy, presenting theoretical explanations along with practical applications in engineering systems. By reviewing illustrative cases, it was shown how these concepts help evaluate the effectiveness of thermal processes in different domains. Extending this argument, another study linked thermodynamic methods to environmental sustainability. Exergy was presented as a tool to account for resource depletion, emissions, and efficiency improvements in sectors such as electricity generation and industrial processes. The analysis revealed significant improvement potential but also emphasized the limitations of applying exergy directly as a universal sustainability measure [52, 53].

Finally, within the European Union context, where buildings account for nearly 40% of total energy use, the need for new performance indicators has been addressed. Directives have promoted primary energy and CO_2-based assessments; however, their limitations have prompted the introduction of exergy-based indicators. In a case study of a hotel building in Portugal, results demonstrated a primary energy consumption of 446 kWh/(m^2·year), with exergy efficiency as low as 17%. This highlighted the discrepancy between energy and exergy performance and suggested that exergy can reveal inefficiencies hidden by conventional energy analysis [54].

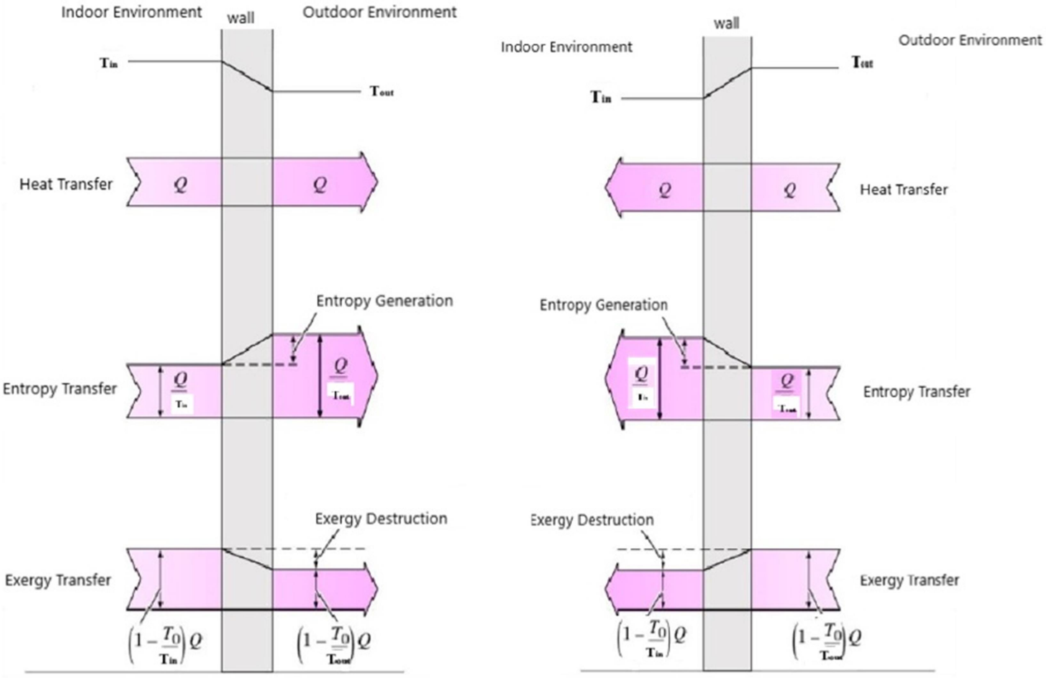
Overall, these studies collectively demonstrate that entropy, exergy, and cogeneration approaches provide valuable insights into the rational use of energy in buildings. While entropy generation offers a unified measure of degradation and efficiency, cogeneration systems ensure higher efficiency and economic benefits. Similarly, exergy-based methods capture the quality of energy flows, emphasizing areas of irrational use and guiding sustainability strategies. Together, they underline the importance of integrating thermodynamic principles into building design, material selection, system optimization, and policy development to achieve long-term energy efficiency and sustainability goals [55, 56].

This study investigates a complex university building that lacks proper insulation in its building shell, using the Balikesir University Faculty of Arts and Sciences building as a case example. The reference building, constructed in 1994, comprises various sections, including classrooms, offices, a canteen, archives, laboratories, storage areas, large common spaces, and a heating center. EnergyPlus simulation was employed to examine the changes in energy consumption, exergy loss, entropy generation and carbon dioxide emissions resulting from renovations or retrofitting, based on the heat transfer coefficients recommended in the Turkish Insulation Standard TS 825, last updated in 2013. Fifteen distinct scenarios were considered for this analysis. Additionally, electricity consumption for HVAC systems was incorporated into the energy consumption analysis during heating and cooling periods. To be used in evaluations in EnergyPlus models, buildings must be calibrated based on energy consumption over periods ranging from 1 to 3 years [57]. The study exergy loss and entropy generation resulting from energy consumption change were calculated. The study assesses the long-term impact of each proposed energy-efficient retrofitting scenario on climate change and the associated changes in life cycle greenhouse gas emissions to promote a more sustainable environment. Figure 1 illustrates different views of the Balikesir University Faculty of Arts and Sciences Building. In contrast, Figure 2 presents the schematic distribution of exergy loss and entropy generation throughout the building envelope during the heating and cooling periods. Table 1 summarises the building envelope areas of the case study building, categorised by orientation.

Figure 1. Different views of the Balikesir University Faculty of Arts and Sciences Building.

Table 1. Building Envelope Areas (m²) of the Complex University Building, Categorized by Direction [58, 59]

Parameter	North	East	South	West	Total
Wall area	2286	5707	2286	5707	15986
Window area	311	2170	346	1969	4796
Window-to-wall ratio	13.60	38.02	15.14	34.50	30.00



a) Heating period b) Cooling Period

Figure 2. Exergy loss and entropy generation along the building envelope [47,56]

2. MATERIAL AND METHODS

This study investigated energy consumption changes for the current state and various energy-efficient renovation or reinforcement scenarios of the Balikesir University Faculty of Arts and Sciences building using the EnergyPlus simulation program. The complex university structure's building envelope was redesigned per the 2013 revision of Turkey's building insulation standard, TS 825, for the renovation and reinforcement scenarios [46]. Various combinations were evaluated, including upgrades to only the external walls, only the ceiling, only the floor, only the windows, combinations of two or three elements, and, finally, the complete renovation or reinforcement of the entire building envelope. Figure 3 shows the sun path diagram of the reference building, as used in the EnergyPlus simulation. Table 1 details the properties and layers of the building envelope. Table 2 summarises different scenarios involving changes to the building envelope of the reference university complex. Scenario 1 represents the current state of the building's envelope, showing existing heat transfer coefficients. The remaining scenarios illustrate energy-efficient upgrades based on the 2013 version of TS 825 [46]. The energy model of the building was calibrated based on monthly consumption data from 2022, applicable to both buildings under study. Climate-related inputs were derived from a nearby meteorological station to ensure local accuracy. The university's relevant departments gathered comprehensive physical information for both structures. Additionally, HVAC systems were modelled with a high degree of realism, informed by detailed on-site observations (Table 1) [57].

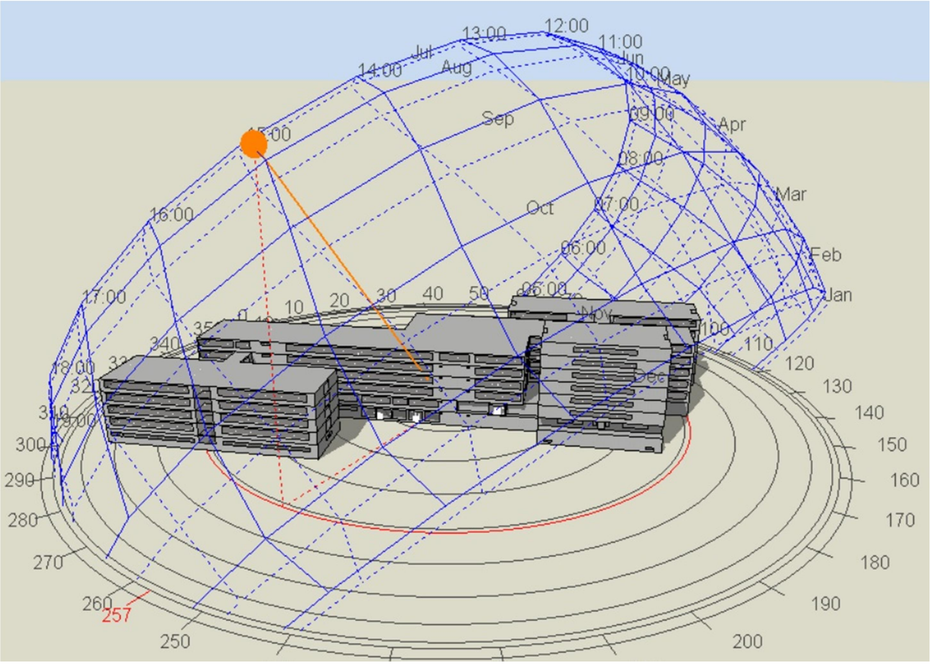


Figure 3. The reference building sunpath diagram in Design Builder

Table 1. Building envelope properties and model calibration values [58, 59]

Component	Thickness (m)
External wall (U value: 1.287 W/m^{2}K)	
Cement mortar external plaster	0.030
Vertical perforated brick	0.190
Cement mortar internal plaster	0.020
Ceiling (U value: 3.420 W/m^{2}K)	
Polymer bitumen water ceiling membrane	0.006
Primer	0.005
Slope concrete	0.050
Floor concrete	0.120
Cement mortar plaster	0.020
Floor (U value: 1.014 W/m^{2}K)	
Ceramic ceiling tile	0.015
Levelling concrete + mortar	0.060
Water ceiling membrane	0.003
Lean concrete	0.100
Sand	0.035
Blockage	0.150
Window (U value: 2.708 W/m^{2}K)	
EnergyPlus Model Properties	
Pumps efficiency	70%
Boiler Efficiency	93%
The coefficient of performance (COP)	2.5

Table 2. Scenarios related to energy-efficient retrofitting of the building envelope in the University Building Complex [60, 61]

Scenario	**External wall**	**Ceiling**	**Floor**	**Window**
1 (Current)	*1.287*	*3.420*	*1.014*	*2.708*
2	**0.570**	3.420	1.014	2.708
3	1.287	**0.380**	1.014	2.708
4	1.287	3.420	**0.570**	2.708
5	1.287	3.420	1.014	**1.800**
6	**0.570**	**0.380**	1.014	2.708
7	**0.570**	3.420	**0.570**	2.708
8	**0.570**	3.420	1.014	**1.800**
9	1.287	**0.380**	**0.570**	2.708
10	1.287	**0.380**	1.014	**1.800**
11	1.287	3.420	**0.570**	**1.800**
12	**0.570**	**0.380**	**0.570**	2.708
13	**0.570**	**0.380**	1.014	**1.800**
14	**0.570**	3.420	**0.570**	**1.800**
15	1.287	**0.380**	**0.570**	**1.800**
16	**0.570**	**0.380**	**0.570**	**1.800**

The study analysed changes in life cycle emissions associated with heating and cooling energy consumption over a 10-year period for fifteen different scenarios using the EnergyPlus simulation program. These scenarios were based on energy-efficient renovation or reinforcement options for the sample complex university building. Natural gas was considered the energy source during the heating period, while electricity was used for cooling. The Life Cycle Greenhouse Gas Assessment (LCGA) for carbon dioxide emissions over the ten years is presented in the corresponding equation,

$$LCGA=c_{fuel}\sum_{t=1}^{N}\frac{Q_{year}}{(1+i_{fuel})^{t}\,\eta} \tag{1}$$

In this study, for the example of the Balikesir University Faculty of Arts and Sciences building, Q represents the energy consumption during the heating and cooling periods. C_{fuel} denotes the unit greenhouse gas emissions, assumed to be 0.356 kg CO_2eq/kWh for electricity and 0.202 kg CO_2eq/kWh for natural gas. The parameter i_{fuel} refers to the interest rate, while i_{sg} represents the temporal valuation of greenhouse gas emissions, also known as impact inflation. The combustion efficiency of the energy sources is denoted by η, and N stands for the operational lifespan of the building, which is set at 10 years. For the life cycle greenhouse gas emissions (LCGA) assessment, the following assumptions were made for electricity consumption, a heating system efficiency of 0.99 and an energy inflation rate of 3%; and for natural gas consumption, a heating system efficiency of 0.93 and the same energy inflation rate of 3% [61-66].

For the case study building, the Balikesir University Faculty of Arts and Sciences, equations (2)–(5) were employed in calculating the exergy loss and entropy generation under different building envelope configurations. In this study, the analyses of exergy loss and entropy generation were conducted for both the heating and cooling periods. The outdoor temperature data used in these calculations are presented in Figure 4 [47–56].

$$Ex_{win}=Q.\left(1-\frac{T_{out}}{T_{in}}\right) \tag{2}$$

$$Ex_{sum}=Q.\left(\frac{T_{out}}{T_{in}}-1\right) \tag{3}$$

$$S_{gen,\ win}=\frac{Q}{T_{out}}-\frac{Q}{T_{in}} \tag{4}$$

$$S_{gen,\ sum}=\frac{Q}{T_{in}}-\frac{Q}{T_{out}} \tag{5}$$

Here, Q denotes the heat transfer through the building envelope. T_{in} and T_{out} represent the indoor and outdoor air temperatures, respectively. Ex_{win} and Ex_{sum} denote the exergy loss during the winter and summer periods, while Sgen,win and Sgen,sum correspond to the entropy generation in the winter and summer periods, respectively. Figure 4 presents the outdoor temperature data for the entire year. The maximum outdoor temperature during the summer was recorded in August at 30.3 °C, while the minimum was observed in January at 5.6 °C [67]. In the present study, for the calculation of exergy loss and entropy generation associated with the building envelope of the case study university building, the average indoor air temperature was assumed to be 23 °C for both the heating and cooling periods. The heating period covers the months in which the outdoor temperature is below 23 °C, based on the indoor temperature of 23 °C. These months are January, February, March, April, May, November, and December. The cooling period, on the other hand, includes the months in which the outdoor temperature is above 23 °C, based on the indoor temperature of 23 °C. These months are May, June, July, and August. In May, both heating and cooling can be required. Since the indoor and outdoor temperatures are both 23 °C in September and October, neither heating nor cooling is performed. Therefore, exergy loss and entropy generation calculations for the building envelope were not carried out for these two months.

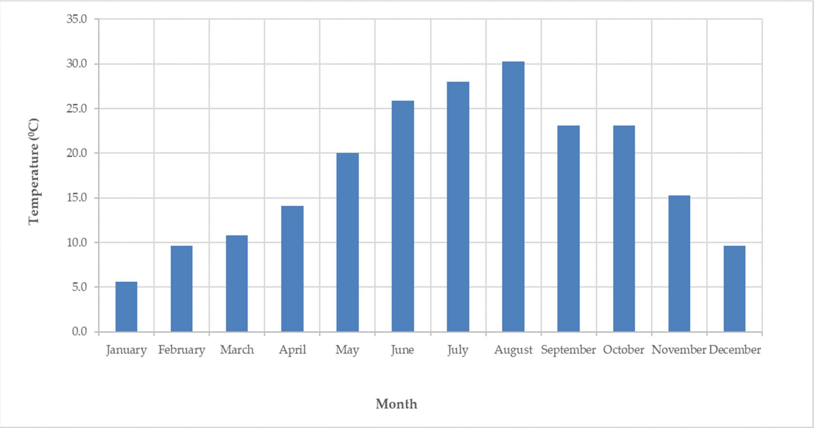


Figure 4. Monthly outdoor temperatures [67]

3. RESULTS AND DISCUSSION

In the study, the heat transfer coefficients of the existing building envelope elements of the Balikesir University Faculty of Arts and Sciences complex building were determined as follows: 1.287 W/m²·K for external walls, 3.420 W/m²·K for the ceiling, 1.014 W/m²·K for the floor, and 2.708 W/m²·K for windows. According to the 2013 revision of Turkey's TS 825 insulation standard, which applies to Balikesir province located in the second climate zone, the recommended values are 0.570 W/m²·K for external walls, 0.380 W/m²·K for ceilings, 0.570 W/m²·K for floors, and 1.800 W/m²·K for windows [58].

Based on simulations conducted with EnergyPlus for the existing building envelope, energy consumption was calculated as 219,931 kWh for cooling, 3,197,789 kWh for heating, and 3,147,720 kWh in total for the year. Corresponding CO_2 emissions were determined as 78,295 kg for cooling, 645,953 kg for heating, and 724,249 kg for the entire year. For the Life Cycle Greenhouse Gas Assessment (LCGA) over a ten-year period, emissions were calculated as 104,116 kg for cooling, 820,980 kg for heating, and a total of 925,096 kg.

Figure 3 shows monthly heating energy consumption across fifteen different renovation or reinforcement scenarios, while Figure 4 presents monthly cooling energy consumption. It was observed that there is a transitional period during September and October, when neither heating nor cooling is typically required. The highest heating energy consumption (combined electricity for natural gas and HVAC) occurred in January, followed by December. For cooling, the highest consumption was recorded in July, followed by August.

This pattern aligns with the climatic characteristics of Balikesir province, where January and December are the coldest months, and July and August are the hottest. These climatic extremes are key factors influencing energy consumption.

CO_2 emissions associated with energy consumption for both the existing state and the fifteen renovation scenarios are shown in Figures 5 and 6. Figure 5 illustrates monthly CO_2 emissions during heating, while Figure 6 shows emissions during cooling. Figures 7 and 8 also display the Life Cycle Greenhouse Gas Assessment (LCGA) based on monthly energy consumption, with Figure 7 focusing on heating and Figure 8 on cooling.

The study observed that the highest cooling energy consumption was 206,183 kWh, while the lowest was 112,472 kWh. The highest energy consumption for heating reached 3,131,559 kWh, and the lowest was 1,889,969 kWh. Total annual energy consumption ranged from a maximum of 3,337,742 kWh to a minimum of 2,002,441 kWh.

Regarding CO_2 emissions, the highest cooling-related emission was 73,401 kg, and the lowest was 40,040 kg. Heating-related emissions ranged from 632,575 kg to 381,774 kg. The total annual CO_2 emissions ranged from a high of 705,976 kg to a low of 421,814 kg.

For the Life Cycle Greenhouse Gas Assessment (LCGA) over ten years, the highest cooling-related CO_2 emission was calculated as 97,608 kg and the lowest as 53,245 kg. For heating, the LCGA ranged from a maximum of 801,573 kg to a minimum of 477,217 kg. The total annual LCGA emissions ranged from 899,181 kg at the highest to 530,462 kg at the lowest.

Energy consumption and emission analyses were conducted using the EnergyPlus simulation program based on TS 825, considering various renovation or reinforcement scenarios of the building envelope of the sample complex university building. The scenarios included individual upgrades to external walls, ceiling, floor (base), and windows; binary combinations (external wall + ceiling, external wall + floor, external wall + window, ceiling + floor, ceiling + window, floor + window); triple combinations (external wall + ceiling + floor, external wall + ceiling + window, external wall + floor + window, ceiling + floor + window); and a full upgrade including all four elements.

The results indicated that by renewing or reinforcing only the external wall, energy and emissions savings reached 17% during the heating season, 11% during the cooling season, and 13% for the entire year. For the ceiling alone, savings were significantly higher—36% for heating, 26% for cooling, and 29% annually, highlighting it as the most effective individual element, given the high original heat transfer coefficient compared to TS 825 standards.

In contrast, upgrading only the floor (base) resulted in relatively low savings: 6% for heating, nearly 0% for cooling, and 3% annually. For the windows alone, savings were 9% in heating, 2% in cooling, and 5% over the year.

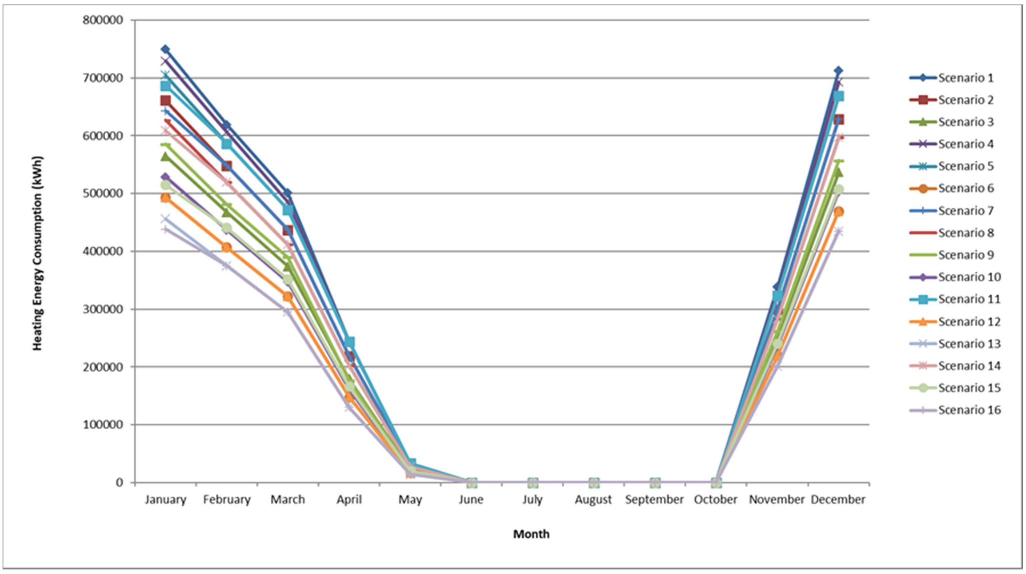


Figure 5. Monthly Energy Consumption in Heating Period for Different Scenarios

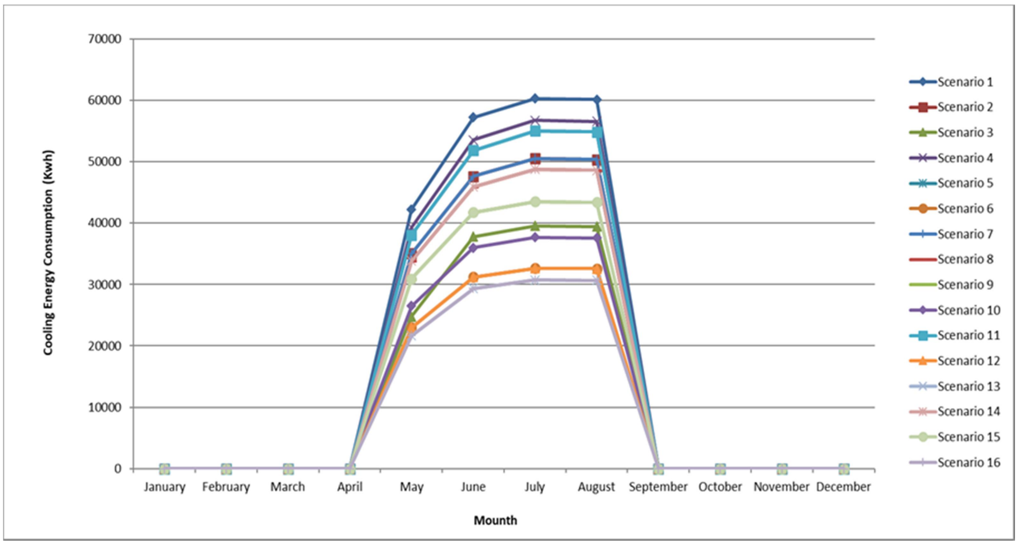


Figure 6. Monthly Energy Consumption in Cooling Period for Different Scenarios

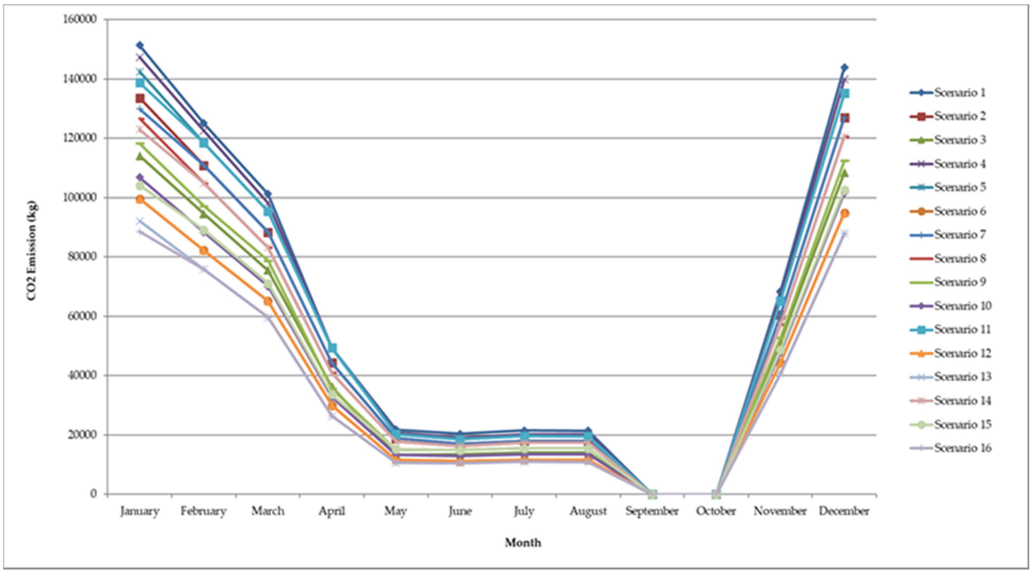


Figure 7. CO_2 emissions depending on monthly energy consumption in the heating and cooling systems for different scenarios

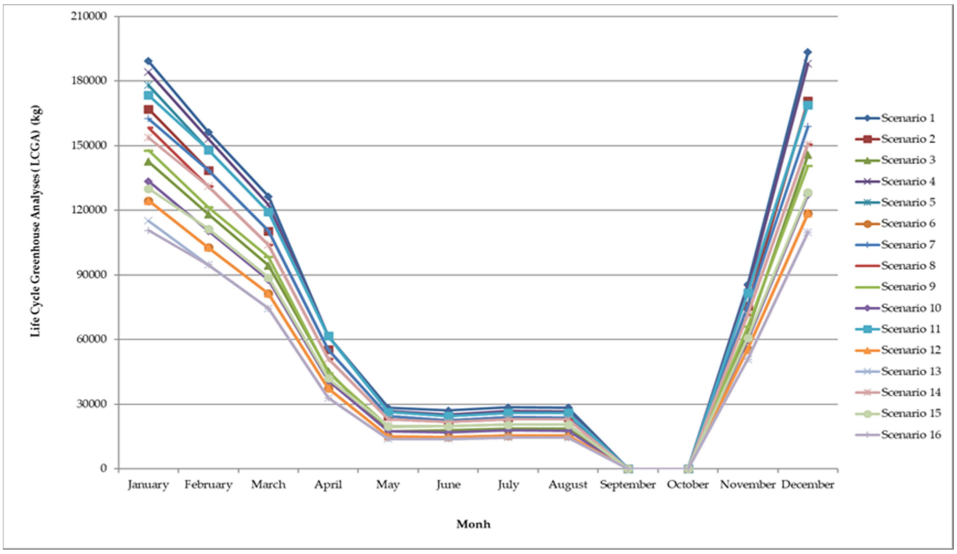
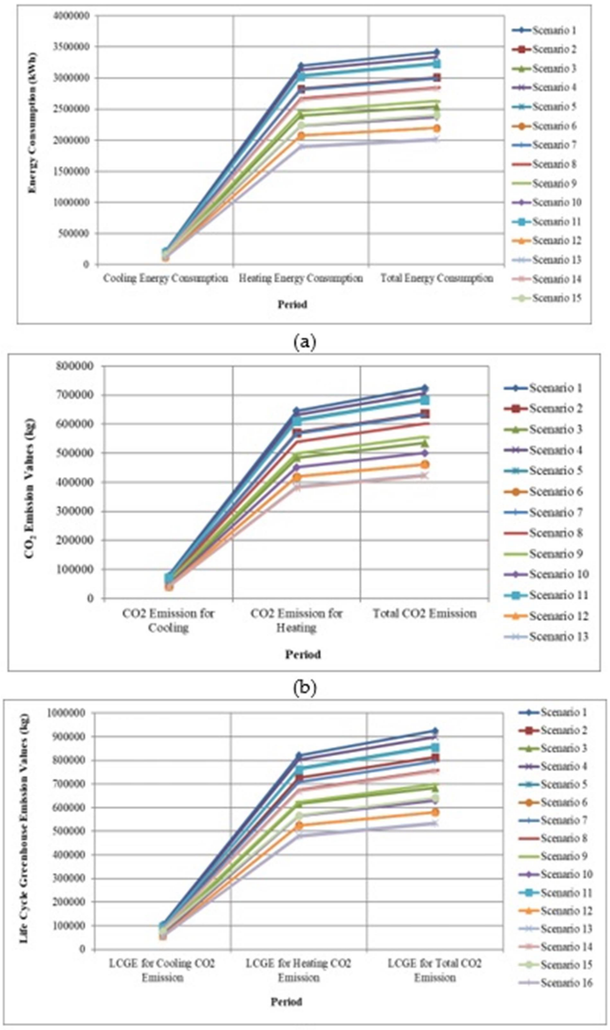


Figure 8. Life Cycle Emission Assessment (LCGA) based on monthly energy consumption in the heating and cooling systems for different scenarios



(a)

(b)

(c)

Figure 9. Cooling, heating and the whole year for different scenarios, a) total energy consumption, b) total CO_2 emissions, c) total life cycle greenhouse gas emission values

The greatest reduction in energy consumption and emissions was achieved through the full renovation or reinforcement of the entire building envelope, resulting in 49% savings in heating, 44% in cooling, and 45% across the year. These findings are consistent with results reported in the literature. Table 3 summarises percentage changes in energy consumption, emission outputs, and LCGA values for all energy-efficient renovation or reinforcement scenarios applied to the building envelope of the Balikesir University Faculty of Arts and Sciences complex.

Table 3. Cooling, heating and total energy consumption change percentage (%) for different scenarios, depending on the energy-efficient building envelope change of the reference Complex University Building compared to the current situation.

Cooling Energy Consumption	Heating Energy Consumption	Total Energy Consumption
1.Scenario (Current Situation)	**1.Scenario (Current Situation)**	**1.Scenario (Current Situation)**
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2.Scenario	**2.Scenario**	**2.Scenario**
17	11	13
3.Scenario	**3.Scenario**	**3.Scenario**
36	26	29
4.Scenario	**4.Scenario**	**4.Scenario**
6	0	3
5.Scenario	**5.Scenario**	**5.Scenario**
9	2	5
6.Scenario	**6.Scenario**	**6.Scenario**
46	37	40
7.Scenario	**7.Scenario**	**7.Scenario**
17	11	13
8.Scenario	**8.Scenario**	**8.Scenario**
19	16	18
9.Scenario	**9.Scenario**	**9.Scenario**
27	25	25
10.Scenario	**10.Scenario**	**10.Scenario**
37	32	33
11.Scenario	**11.Scenario**	**11.Scenario**
9	2	6
12.Scenario	**12.Scenario**	**12.Scenario**
46	37	40
13.Scenario	**13.Scenario**	**13.Scenario**
49	43	44
14.Scenario	**14.Scenario**	**14.Scenario**
19	17	18
15.Scenario	**15.Scenario**	**15.Scenario**
27	31	29
16.Scenario	**16.Scenario**	**16.Scenario**
49	44	45

In the case study building, the Faculty of Arts and Sciences at Balikesir University, the maximum exergy loss through the building envelope in the current state was calculated as 5139.4 kW in January during the heating period and 451.1 kW in August during the cooling period. The minimum values were found to be 38.5 kW for the heating period and 132.1 kW for the cooling period in May. For other scenarios of energy-efficient retrofitting, the maximum exergy loss during the heating period was obtained in Scenario 4, with 5001.5 kW in January, while during the cooling period, it was 424.4 kW in August. The minimum exergy loss in the heating period was determined in Scenario 15 to be 16.6 kW in January, and in the cooling period, it was 67.8 kW in May. The second-highest exergy loss was calculated in Scenario 5, with 4835.7 kW in January for the heating period and 411.7 kW in August for the cooling period. It should be noted that both heating and cooling are possible in May. Exergy loss depends on energy consumption as well as indoor and outdoor temperatures. These and all other values of heating and cooling period scenarios related to the energy-efficient retrofitting of the building envelope are presented in Figure 10.

Currently, the maximum entropy generation was calculated as 18.5 kW/K in January during the heating period and 1.5 kW/K in August during the cooling period. The minimum values were found to be 0.1 kW/K during the heating period and 0.5 kW/K during the cooling period in May. For other scenarios of energy-efficient retrofitting of the building envelope, the maximum entropy generation during the heating period was obtained in Scenario 4, with 18.0 kW/K in January, while during the cooling period it was 1.4 kW/K in August. The minimum entropy generation in the heating period was determined in Scenario 15 as 10.8 kW/K in January, and in the cooling period as 0.8 kW/K in May. The second-highest entropy generation was calculated in Scenario 5, with 17.4 kW/K in January for the heating period and 1.4 kW/K in August for the cooling period. As in the case of exergy loss, both heating and cooling may occur in May. Entropy generation is dependent on indoor and outdoor temperatures as well as energy consumption. These and other related values for the heating and cooling period scenarios are presented in Figure 11.

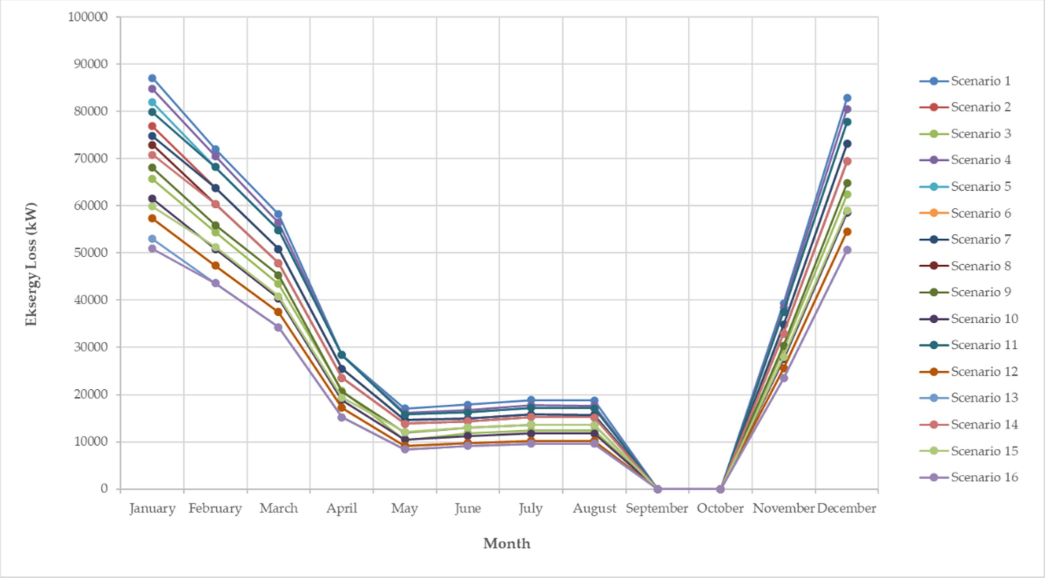

Figure 10. Exergy loss in heating and cooling period scenarios for energy-efficient retrofitting of the building envelope

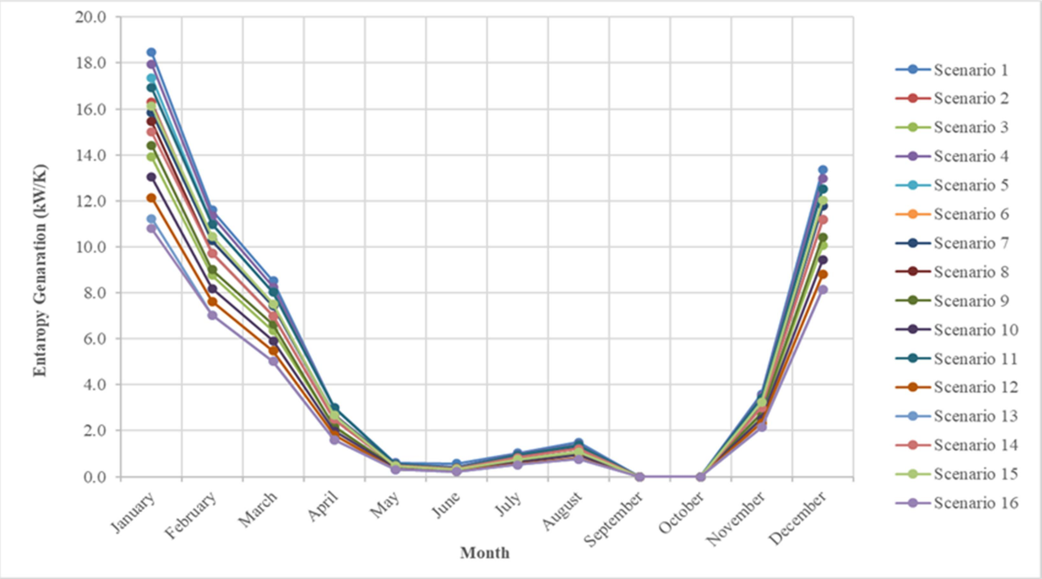

Figure 11. Entropy generation in heating and cooling period scenarios for energy-efficient retrofitting of the building envelope

4. CONCLUSIONS

This study investigated changes in energy consumption, carbon dioxide emissions, and life cycle greenhouse gas emissions (LCGA) over ten years using the EnergyPlus simulation program. The analysis focused on the Faculty of Arts and Sciences building at Balikesir University—a complex structure—based on the heat transfer coefficients recommended in the 2013 version of Turkey's insulation standard, TS 825, for energy-efficient renovation or reinforcement of the building envelope.

The study involved analyses and calculations across fifteen scenarios based on natural gas and electricity consumption. Results showed that the ceiling was the most impactful building envelope element in reducing energy consumption and CO_2 emissions. Currently, renewing or reinforcing the ceiling alone results in a 29% annual energy savings. The lowest improvement was achieved by renewing or reinforcing the floor, resulting in only a 3% annual savings.

Up to 45% of the overall savings were achieved by upgrading the entire building envelope, including external walls, ceiling, floor, and windows. On average, a 25% energy saving was observed across the scenarios. Among partial upgrades, the combination of external walls, ceiling, and windows yielded the highest savings, with an annual reduction of 44%. Similarly, a 40% saving was observed when the external walls, ceiling, and floor were renewed or reinforced. According to Life Cycle Greenhouse Analyses (LCGA), in the current state, annual CO_2 emissions range between 27,090–193,402 kg. In the best scenario, Scenario 15, which involves energy-efficient retrofitting of the entire building envelope, the emissions decrease to 13,880–109,861 kg CO_2.

A reduction in exergy loss and entropy generation of 42–58% during the heating period and 49–52% during the cooling period was calculated between the current state and Scenario 15, which provides the highest energy savings.

For the case study building, the Faculty of Arts and Sciences at Balikesir University, exergy loss associated with the building envelope was found to be 38.5–5139.4 kW annually under current conditions. In Scenario 15, which represents the most energy-efficient retrofitting, annual exergy loss decreases to 16.6–3004.7 kW.

The maximum exergy loss and entropy generation were observed in January during the heating period and in August during the cooling period. In the current state, entropy generation associated with the building envelope is between 0.5–18.5 kW/K annually. With energy-efficient retrofitting of the entire building envelope (walls, ceiling, floor, and windows) in Scenario 15, entropy generation decreases to 0.2–10.8 kW/K.

Declaration of Ethical Standards

The authors declare that all ethical guidelines, including authorship, citation, data reporting, and Publishing original research is followed.

Credit Authorship Contribution Statement

İsmail CANER: Investigation, Modeling, Analyses, Supervision, Writing.
Okan KON: Investigation, Supervision, Review, Editing.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence

Generative artificial intelligence (AI) tools were used solely for typesetting purposes. These tools were not used to generate scientific content, research data, interpretations, or analyses. AI tools were not listed as authors. The authors remain fully responsible for the accuracy, originality, integrity, and ethical compliance of the manuscript. The use of AI tools is transparently disclosed in accordance with applicable ethical and legal standards.

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