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A Study Using the Hybrid Fuzzy AHP&TOPSIS Method in the Conversion of a LEED-Certified Education Building into a Nearly Zero-Energy Building in a Cold Climate

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In cold climate regions, it is essential to design and manufacture energy-efficient buildings for both economic benefits and the reduction of environmental effects by controlling energy consumption. This study aimed to increase the cost-effective energy performance and approach the nearly zero energy building (nZEB) by taking the leadership in energy and environmental design (LEED) in the cold climate region of Turkey as a model. The results of single and mixed scenarios that increase energy efficiency were determined by making energy modelling of the building. By applying single and mixed energy efficiency scenarios, a maximum saving of 85.60 % per year in terms of primary energy, an improvement of 83.6 % in terms of global costs and a reduction of 86.4 % in CO_2 emissions were obtained compared to the reference building. The payback period of the scenarios is between 3.8 years and 14.53 years. The most suitable single and mixed scenario was determined by a systematic hybrid model, in which the fuzzy analytical hierarchy process (FAHP) and technique for order of preference by similarity to ideal solution (TOPSIS) methods among multi-criteria decision-making methods are used together. The results showed that economic criteria were decisive in determining the most suitable scenario for cold climate regions. The results of this study revealed that there can be a realistic decision-support model for the creation of energy-efficient buildings for countries without the need for foreign certification.

Keywords: green building, nearly zero energy building, energy and cost-optimal analysis, fuzzy analytic hierarchy process (FAHP), TOPSIS

Highlights
- *By increasing the cost-effective energy performance, a LEED-certified educational building has been brought closer to the nZEB.*
- *Energy cost analysis of single and mixed scenarios that increase energy efficiency has been made.*
- *FAHP and TOPSIS methods from multi-criteria decision-making methods have been used together to determine the most appropriate single and mixed scenarios.*
- *With a value of 5.08 kg CO_2 m^2/year, net zero carbon emissions in buildings are approached.*

0 INTRODUCTION

The need for energy is gradually increasing due to technological developments and population density. Therefore, it has become essential to use energy efficiently and in a planned way. In many countries, a large part of the total energy is used in buildings, and energy consumption rates are often parallel to the European Union (EU) countries. It has been determined that approximately 40 % of total energy consumption [1] and 36 % of CO_2 emissions originate from buildings in many countries in Europe [2]. Therefore, energy efficiency has become an critical issue for many countries in terms of energy dependence and economic development [2]. Furthermore, it is estimated that the energy consumption of buildings will increase by 50 % until 2060, and thus carbon emissions will also increase [3]. Within the scope of the Paris Agreement, many countries have included targets for increasing energy efficiency and low-carbon economic growth in their long-term plans [4]. For example, while China aims to become carbon neutral by 2060, the United States and the United Kingdom have promised net zero greenhouse gas emissions by 2050 [5].

One of the important steps for energy efficiency in the building sector is the Energy Performance of Buildings Directive (EPBD) recast, which was published in 2002 and revised in 2010 [1]. The concepts of cost-optimal energy efficiency and nearly zero-energy building have come to the fore with this directive. Buildings should consume very little energy to approach the nearly zero energy building (nZEB), and most of it should be met by renewable energy sources [6]. Although the definition and requirements of the nZEB differ between countries, the common goal is to minimize energy consumption and greenhouse gas emissions throughout the service life of the building.

Since Turkey is dependent on foreign sources in terms of energy, it is essential to use energy effectively and efficiently. Foreign dependency on energy brings

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great risks both in terms of economy and security. In Turkey, the building sector is responsible for 30 % of the total final energy consumption as the second largest energy consuming sector due to the increasing population and technological developments [7]. It is clearly seen that the measures to be taken in this sector will contribute to the national economy. Compared to countries in Europe, studies on nZEBs in Turkey remain in their early stages. Considering all these developments, it is necessary to determine cost-optimal energy levels in buildings in Turkey. In the subsequent period, reaching the level of nearly zero-energy buildings with cost-effective improvements in buildings is expected.

There is a need for a systematic method to evaluate the scenarios used to increase the cost-effective energy performance of buildings with many conflicting criteria. The absence of such an internationally accepted method indicates a gap in the literature that needs to be explored. According to the literature review, there has been no comprehensive internationally accepted method based on national conditions in cold climate regions without the need for foreign certification until the present day. This study has determined the parameters that would guide legal regulations using multi-criteria decision-making (MCDM) methods in identifying the cost-optimum nearly zero energy level. The present study is important for constructing cost-effective energy performance buildings on university campuses.

The nZEB aims to reduce energy consumption in buildings by using energy efficient technologies and renewable energy solutions [7] and [8]. Wang and Zhao [9] investigated the effect of external walls and roofs with different heat transfer coefficients (*U*) on building energy consumption and determined that increasing energy efficiency in the building envelope affected energy saving. Zhao and Du [10] aimed to approach education buildings nZEB by optimizing national technologies in China and using four recommended technologies for the four main climate regions. They also determined that the total energy saving rate in very cold regions increased by 70.74 % compared to the current national standards and approximately 60 % of the total energy saving rate could be improved in cold regions. Sağlam et al. [11] made cost-optimal energy efficiency calculations for the existing multi-story buildings in cold climate regions. The sensitivity of the results to economic data and changes in initial investment costs was analysed. It was revealed that cost-optimal energy efficiency data varied depending on economic indicators. A new approach taking into account hourly, daily, and monthly consumption and evaluating the former energy use and renewable energy generation for all buildings of the University of Lleida (Spain) was presented [12]. This analysis constitutes a basis for energy improvements and comparisons to be made in buildings. It also enables determining the difference between actual energy data at the building and campus levels and the nZEB levels specified for non-residential buildings in the European Union. The results show that there is a wide range of energy use between campus buildings, ranging from 50 to 470 kWh/m² years. The energy use is reduced with the inclusion of renewable energy generation. This analysis revealed that the average primary energy consumption in Spain was approximately four times higher than the EU nZEB levels.

Kalaycıoğlu and Yılmaz [13] determined single or mixed measures to increase energy efficiency in accordance with the method proposed by the EPBD methodology. They also found the optimal cost and nearly zero energy levels at the settlement scale with energy and cost analyses for these measures. It was revealed that the analysis results depended on countries' economic data, the laws related to buildings, and their political and financial targets. Valancius et al. [14] proposed a methodological approach that addressed both energy and environmental factors in bringing buildings to nearly zero energy (nZEB) levels under the climatic conditions of Lithuania. With this method, several energy-efficiency increasing scenarios were applied in a case study. The results of primary energy savings and CO_2 gas emissions over a 60-year period and the most reasonable thermal insulation materials for building insulation in terms of energy and ecology were provided. A four-star hotel operating in Faro (Portugal) was taken as a reference, and technical and economic analyses were performed to determine nZEB levels in three European cities with different climates. The energy modelling of the reference building was done using the DesignBuilder/EnergyPlus software, and cost-optimal energy efficiency-increasing measures were determined. Considering the climatic and economic realities for the three cities, it was indicated that the most suitable measure to increase energy efficiency should be selected [15].

Ferrari and Becalli [16] proposed strategies for the conversion of the building on the campus of Politecnico di Milano University, Italy into a nZEB. The aim was to achieve cost-effective energy savings and reduce greenhouse gas emissions with energy performance-increasing scenarios. Furthermore, it was determined that net energy consumption could be close to zero when on-site renewable energy sources were used. The energy and carbon payback periods of the scenarios that would increase energy performance were evaluated to bring a school building in Torino, Northern Italy closer to the nZEB [17]; it was revealed that energy efficiency scenarios for nZEB had energy and carbon paybacks that were shorter than the building's life cycle. The measurement and analysis of the two-year energy consumption values of a nearly zero-energy building in the cold regions of China are presented in this study [18]. It was emphasized that nZEBs created a more comfortable indoor environment with less energy demand and would contribute to achieving climate change targets with less carbon emissions.

In this study, the analytical hierarchy process (AHP) and multi-criteria optimization method of complex systems VIKOR (mutli-criteria optimization and compromise solution) method were employed together to determine the most suitable improvement scenarios used to increase the energy performance of old buildings [19]. Three scenarios showing the (nZEB) level were determined. They are common solution scenarios that include high energy potential on-site generation, medium energy potential mechanical/electrical system, and low energy potential building envelope components. Another study [20] presented an integrated approach requiring multi-objective optimization in the preference of passive and active design parameters that conflicted with each other instead of conventional methods in the process of designing a high-rise office building as zero energy building (ZEB) in the Mediterranean climate with hot summers in Athens, Greece. The targets set in this approach were aimed at reducing energy consumption and increasing energy generation and thermal comfort. With the implementation of this integrated approach, it was aimed to make conscious decisions in determining the design strategy to achieve ZEB.

The present study presents an approach toward constructing energy-efficient education buildings in cold climate regions in accordance with nZEB without the need for foreign certification in order to protect countries' energy resources and economic interests. Since the energy saving potential is high in cold climate regions, different nZEB scenario combinations can both reduce carbon emissions and help achieve climate change targets.

Natural gas and electricity field measurements of the reference building in 2017 to 2019 are made and the impact factors on the aim of obtaining approximately zero energy are analysed. The aim was to reach cost-optimal energy efficiency levels with the scenarios to reduce the energy demand of the leadership in energy and environmental design (LEED)-certified Faculty of Engineering and Architecture building at Erzurum Technical University, Turkey. It is obligatory to determine which criteria should be used to determine the most appropriate scenario to increase energy efficiency. Many different and contradictory factors, such as technical, economic, and environmental, make it difficult for decision makers. To overcome this difficulty, a systematic hybrid decision method that takes all factors into account has been developed. The most suitable energy efficiency scenario, which would represent the optimal cost and nearly zero energy level, was determined using the fuzzy AHP (FAHP) technique and the technique for order of preference by similarity to ideal solution (TOPSIS) methods together.

1 MATERIAL AND METHODS

The present study investigated the conversion of Erzurum Technical University Faculty of Engineering and Architecture building, located in the cold climate region and having a SILVER certificate according to the LEED criteria [21], into a nZEB.

The conversion of the reference building into a nearly zero-energy building consists of six steps, and the flow chart is presented in Fig. 1.

Step 1: Description of the characteristics of the reference building (RB) and the climatic conditions of the region where it is located.

Step 2: Calculation of primary energy consumption and emission amount of the reference building with a LEED-SILVER certificate.

Step 3: Determining single scenarios increasing energy efficiency and conducting energy and cost analyses.

Step 4: Determining mixed scenarios and making energy and cost analyses to reduce the energy consumption of the reference building.

Step 5: Calculating the carbon emission amount and payback periods of energy efficiency increasing scenarios.

Step 6: Evaluation of the results of energy efficiency scenarios by multi-criteria decision-making methods.

1.1. Characteristics and Climatic Conditions of the Reference Building

The Faculty of Engineering and Architecture building on the campus of Erzurum Technical University was taken as a reference in the study; it has a closed area of 25245 m². It has the LEED-Silver certificate, which

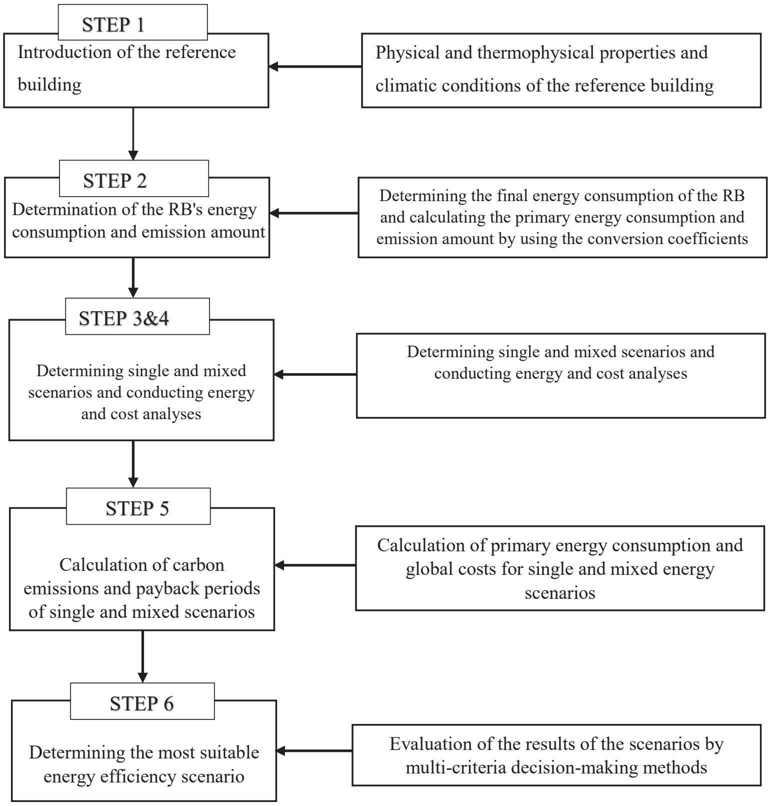

Fig. 1. *Research flow chart*

is commonly used throughout the world [22]. The reference building consists of a total of 5 blocks (Fig. 2). There are offices of faculty members in the 1st, 2nd, and 3rd blocks, classrooms in the 4th block, and dean's offices in the 5th block.

The building's envelope consists of external walls, floors, roofs, and glass surfaces. The facade of the reference building consists of a granite mechanical cladding system and a cladding glass system with a light transmittance of 35 % and a

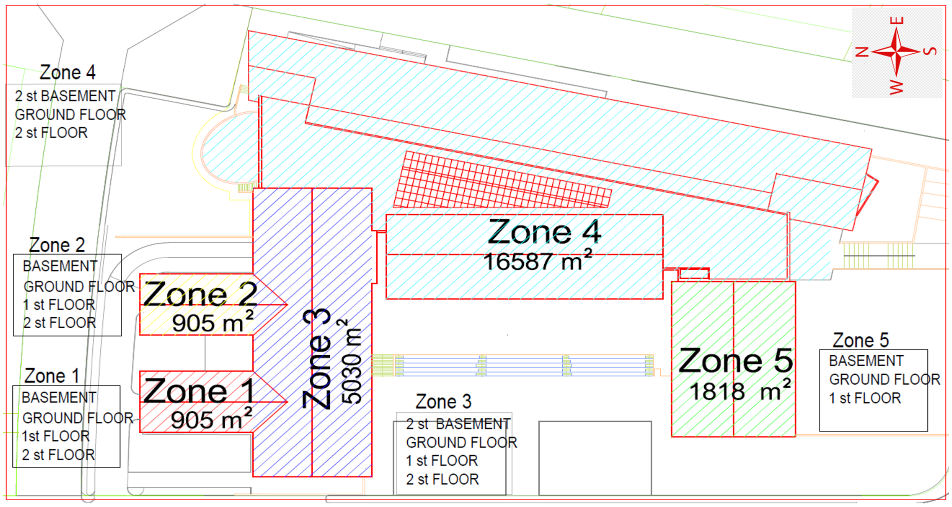

Fig. 2. *Under study building's site plan*

solar heat transmission coefficient of 0.24. The roof covering has dyed steel sheet cladding. The total heat transmission coefficients (U), [W/m²K] according to the construction materials that make up the reference building's envelope and their thickness and the recommended heat transmission coefficients according to Turkish Thermal Insulation Standard TS 825-2013 **[23]** are presented in Table 1.

Table 1. *Heat transmission coefficients of the reference building's envelope construction elements*

Building's materials	Exterior wall (Curtain)	Exterior wall (Brick)	Roof	Ground floor	Glazing system
Current U-value [W/(m²K)]	0.260	0.235	0.177	0.367	1.1
According to TS 825 U-value [W/(m²K)]	0.370	0.324	0.209	0.367	2.2

In the heating system of the reference building, four high-efficiency natural gas boilers, each with a capacity of approximately 500 kW, were used. Heating in the reference building was done with radiators, air appliances and heating, ventilation, and air conditioning (HVAC) systems. Since the heating load of the reference building is very high, the saving measures to be applied to reduce the heat energy are of great importance. To achieve the comfort temperature determined according to TS825-2013, the set temperatures in the building are between 20 °C to 22 °C on the sites **[23]**. The operating times and operating temperatures of the heating system in the reference building are programmed according to the course hours on weekdays and weekends.

Cooling is provided by an air-source variable refrigerant volume (VRV) and air handling unit on certain sites depending on the climate and usage conditions in the reference building. The requirements of the American Society of Heating and Air- Conditioning Engineers ASHRAE 90.1-2010 **[24]** standard were prioritized using efficient heating, cooling, and ventilation systems in the RB.

The amount of fresh air given to the sites was kept above the ASHRAE 62.1 **[25]** standard in order to increase indoor air quality, low-emission materials were preferred, and the conditions for thermal comfort were monitored.

Fluorescent lighting was used for lighting on all sites in the reference building. The operating hours of the lighting systems are programmed according to course hours on weekdays and weekends.

Erzurum, where the RB is located, is in the cold climate zone **[26]**. According to the results of the observations for approximately 80 years at meteorological stations, it was found that while the mean temperature of the coldest month was –8.6 °C, the mean temperature of the hottest month was 19.6 °C, and the lowest and highest temperatures were –35 °C and 35 °C, respectively. In winter, snowfall is about 50 days and the number of days covered with snow is 114 days **[27]**. Erzurum's total solar radiation (between 2011 and 2022) is between approximately 1400 kWh/m² to 1700 kWh/m² per year, and the monthly average daily radiation intensity value coming to the horizontal surface is between 1.48 kWh/m² to 6.83 kWh/m² **[28]** and **[29]**.

1.2 Calculation of the RB's Energy Consumption and Carbon Emissions

Natural gas and electricity average consumption values for 2017, 2018, and 2019 were used as references in the calculations since the pandemic started at the beginning of 2020 and education and training activities were continued remotely. Primary energy consumption and emission amounts are determined by multiplying these consumption values by conversion coefficients. With regard to primary energy conversion coefficients in Turkey, the coefficients of 2.36 for electricity and 1 for natural gas and other fuels are used. The carbon emission conversion factors are also considered to be 0.626 (kg equivalent CO_2/kWh) for electricity, 0.234 (kg equivalent CO_2/kWh) for natural gas **[30]**.

Total primary energy *(TBE)* and annual carbon emissions for the reference building were calculated with the following equations.

$$TBE = [E_{natural\ gas}] + [E_{electricity} \times 2.36], \quad (1)$$

$$E_{\mathrm{CO_2}} = (0.234 \times e_{natural\ gas}) + (0.626 \times e_{electricity}), \quad (2)$$

where TBE is total primary energy consumption, [kWh/m² year]; $E_{natural\ gas}$ is total natural gas energy consumption, [kWh/year]; $E_{electricity}$ is total electricity energy consumption, [kWh/ year]; $E_{\mathrm{CO_2}}$ is total CO_2 emission [kg m²/year].

1.3 Determination of Single and Mixed Scenarios Increasing Energy Efficiency

Since the reference building was built according to LEED-Silver green building certification standards, measures to increase energy performance are limited. As a result of evaluating the reference building's energy analysis, improvement scenarios for the use of lighting, heating systems, and renewable energy systems were determined. The average electricity consumption values of the reference building from 2017 to 2019 were taken into account for determining the capacity of the gas engine micro-cogeneration system (Table 6). The purpose of using that system is to meet a remarkable part of the electrical energy consumption of the reference building with the electrical energy (75 kW) to be produced. In addition, it is intended to support the heating system of the reference building with the heat energy (116 kW) to be produced by the micro-cogeneration system. In the design of the water source heat pump, the average natural gas consumption values of the reference building in 2017, 2018, and 2019 were taken as reference (Table 6). It is intended to support the heating system with the heat energy (2300 kW) to be produced by the water source heat pump system. The descriptions of single scenarios increasing energy efficiency are given in Table 2.

Table 2. *Description of single improvement scenarios*

Scenario	Description
S1	Installation of 1151 photovoltaic (PV) panel systems with a power of 425.84 kWp on the south-facing roofs
S2	Installation of 2220 PV panel systems with a power of 821.40 kWp on the south + east + west facing roofs
S3	Replacing the existing compact fluorescent lamps with light-emitting diode (LED) lamps
S4	Establishment of a gas engine micro cogeneration system with 75 kWe electricity and 116 kW heat energy power generation capacity
S5	Installation of a 2300 kW water source heat pump system in the heating system

The aim was also to reduce global costs, primary energy consumption and payback periods through mixed energy efficiency scenarios. The triple mixed energy efficiency scenarios were selected from the scenarios with low global costs. The determined mixed energy efficiency scenarios are explained in Table 3.

Two different analyses, energy analysis and cost analysis, were used to determine the nearly zero energy level of the reference building. Energy analysis was conducted according to actual energy consumption and simulation data. The measurement and calculation methods used to determine the energy performance (heating and electrical energy consumption) of the reference building comply with the ISO 52016-1(2017) standard [31]. The purpose of the energy analysis is to determine the annual total energy consumption (heat energy and electrical energy) and reveal how much energy consumption can be reduced with saving measures and renewable energy sources that will reduce consumption. Furthermore, the remaining electrical energy from consumption will be supplied to the grid. The EN 15459 Economic Evaluation Standard for Building Energy Systems, which is also guided by EU legislation, was used in the cost analysis [32].

Table 3. *Description of mixed improvement scenarios*

Scenario	Description
S1 + S3	Installation of 1151 PV panel systems with a power of 425.84 kWp on the south-facing roofs Replacing the existing compact fluorescent lamps with LED lamps
S1 + S4	Installation of 1151 PV panel systems with a power of 425.84 kWp on the south-facing roofs Establishment of a gas engine micro cogeneration system with 75 kWe electricity and 116 kW heat energy power generation capacity
S1 + S5	Installation of 1151 PV panel systems with a power of 425.84 kWp on the south-facing roofs Installation of a 2300 kW water source heat pump system in the heating system
S2+S3	Installation of 2220 PV panel systems with a power of 821.40 kWp on the south + east + west facing roofs Replacing the existing compact fluorescent lamps with LED lamps
S2+S4	Installation of 2220 PV panel systems with a power of 821.40 kWp on the south + east + west facing roofs Establishment of a gas engine micro cogeneration system with 75 kWe electricity and 116 kW heat energy power generation capacity
S5 + S3	Installation of a 2300 kW water source heat pump system in the heating system Replacing the existing compact fluorescent lamps with LED lamps
S3 + S4	Replacing the existing compact fluorescent lamps with LED lamps Establishment of a gas engine micro cogeneration system with 75 kWe electricity and 116 kW heat energy power generation capacity
S2+ S3 + S4	Installation of 2220 PV panel systems with a power of 821.40 kWp on the south + east + west facing roofs Replacing the existing compact fluorescent lamps with LED lamps Establishment of a gas engine micro cogeneration system with 75 kWe electricity and 116 kW heat energy power generation capacity
S1+ S3 + S4	Installation of 1151 PV panel systems with a power of 425.84 kWp on the south-facing roofs Replacing the existing compact fluorescent lamps with LED lamps Establishment of a gas engine micro cogeneration system with 75 kWe electricity and 116 kW heat energy power generation capacity

For the conversion of the reference building into a nearly zero-energy form, energy consumption and carbon emission amounts of the single and mixed scenarios were determined by using HAP 5.11 dynamic simulation software. It has a weather data library covering more than seven hundred cities around the world. The building model should be validated by comparing the consumption data obtained as a result of building energy modelling with the building's actual consumption data. As stated in the ASHRAE Guideline 14 **[33]**, the coefficient of variation of the root mean square error (CV_RMSE) value should be less than 15 % and the normalized mean bias error (NMBE) value should be less than 5 % for the building energy simulation data in monthly evaluations. The validation of the model after preparing the building energy model is important in terms of showing the reality of the applied energy-saving scenarios **[34]**. Next, the global cost analysis of the scenarios was performed, and the optimal cost and primary energy consumption of the scenarios were compared.

The formulae used in the global cost calculations of all scenarios were taken from EN 15459 **[35]**, stated as the most reliable cost calculation method by the European Union. The net present value method, which expresses the present value of each investment by multiplying the projected earnings and costs for the coming years with the discount factor of the current year, is used in this procedure.

In the calculations, the lifetime of the systems to increase building energy efficiency was taken as approximately 20 years **[36]**, and the scrap values were not taken into account. According to the EPBD-recast, the cost calculation period for non-residential buildings has been proposed as 20 years. The Construction and Installation Unit Prices of The Ministry of Environment, Urbanization and Climate Change, Turkey for 2021 were used in the initial investment costs to be used in global cost calculations **[37]**. Market prices for 2021 were used in the initial investment costs of energy improvement measures not defined in the unit price book (such as PV and LED lighting systems).

Cost calculations were made in Turkish lira (TL) and then the results were converted to US dollars ($). In the calculations, euro €/TL was taken as 10.40 and $/TL was taken as 8.74 **[38]** in the conversion of prices in foreign currency. The inflation rate was taken as 16.59 % **[39]** per annum in May 2021, the discount rate was taken as 1 %, and the interest rate was taken as 19 % **[40]** per annum. For Erzurum, the natural gas unit price was taken as 0.193 TL/kWh **[41]**, and electricity unit price was taken as 0.953 TL/kWh **[42]**.

1.4 Determination of Payback Periods of the Single and Mixed Scenarios Increasing Energy Efficiency

It is the period during which the sum of savings of single and mixed scenarios increasing energy efficiency reaches the initial investment cost. With the payback period, it is decided whether the investment is rational or not. The payback period is calculated with the following formula **[43]**:

$$IPP = \frac{II}{CFPP}. \tag{3}$$

In the Eq. (3), the terms of IPP, II and $CFPP$ represent investment payback period [Year], initial investment [US dollar], cash flow per period [US dollar], respectively.

Energy efficiency scenarios with a payback period of not more than 10 years as the baseline scenario and energy efficiency scenarios with a payback period of not more than 20 years as the deep renovation scenario were proposed within the scope of this study.

1.5 Multi-Criteria Decision-Making

MCDM is the process of selection, ranking, or evaluation using at least two of the evaluated criteria, in which more than one criterion or target is addressed together. One of the frequently used multi-criteria decision-making methods is the AHP, which was developed by Thomas L. Saaty in 1980 **[44]**. The AHP is a multi-criteria decision-making method based on comparing the significance levels of the criteria affecting the decision as a result of pairwise comparisons through a decision hierarchy. The FAHP method was developed by combining fuzzy logic and AHP in order to facilitate decision-making when there is incomplete and imprecise information in AHP. In pairwise comparisons in FAHP; Linguistic variables and fuzzy numbers replace the real numbers used in Saaty's AHP method. In general, trapezoidal and triangular fuzzy numbers are used in pairwise comparisons. In this method, fuzzy weight and performance values are obtained by using the geometric mean. The importance scale used in pairwise comparisons in FAHP is given in Table 4 **[45]**.

Linguistic expressions and triangular fuzzy numbers are given in Table 5 in the evaluation of alternatives to help experts make more realistic decisions.

Table 4. *Linguistic variables for importance weights*

Linguistic expression	Scale of fuzzy numbers
Absolutely strong (as)	(7.00, 9.00, 9.00)
Very strong (vs)	(5.00, 7.00, 9.00)
Fairly strong (fs)	(3.00, 5.00, 7.00)
Slightly strong (ss)	(1.00, 3.00, 5.00)
Equally (E)	(1.00, 1.00, 3.00)
Slightly weak (sw)	(0.20, 0.33, 1.00)
Fairly weak (fw)	(0.14, 0.20, 0.33)
Very weak (vw)	(0.11, 0.14, 0.20)
Absolutely weak (aw)	(0.11, 0.11, 0.14)

Table 5. *Fuzzy evaluation scores for the alternatives*

Linguistic expressions	Fuzzy score
Very poor (VP)	(0.00, 0.00, 1.00)
Poor (P)	(0.00, 1.00, 3.00)
Medium poor (MP)	(1.00, 3.00, 5.00
Fair (F)	(3.00, 5.00, 7.00)
Medium good (MG)	(5.00, 7.00, 9.00)
Good (G)	(7.00, 9.00, 10.00)
Very good (VG)	(9.00, 10.00, 10.00)

The study consists of the steps of determining the criteria by applying Buckley's approach, evaluating the significance levels of the criteria relative to each other by experts, and determining the most suitable energy efficiency scenario by using the obtained results. According to the Buckley approach, the FAHP method consists of four steps [46] and [47].

Step 1: Fuzzy pairwise comparison matrix was obtained after pairwise comparison. This pairwise comparison matrix has been created with the data from surveys answered by experts.

This matrix contains the degree of importance between the criteria. An example of a pairwise comparison matrix is as follows:

$$\tilde{A} = \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} \cdots & \tilde{d}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{d}_{m1} & \tilde{d}_{m2} \cdots & \tilde{d}_{mn} \end{bmatrix}. \qquad (4)$$

Step 2: The geometric mean of each criterion i is found with the following equation:

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{d}_{ij} \right)^{1/n} \qquad i = 1, 2, \ldots, n. \qquad (5)$$

Step 3: The fuzzy weight of the criteria is calculated.

$$\tilde{w}_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \otimes \tilde{r}_2 \otimes \ldots \otimes \tilde{r}_n \right)^{-1}, \qquad (6)$$

where lw_i, mw_i, uw_i values are determined, lw_i the lower weight of the criterion, mw_i is the middle weight of the criterion, and uw_i is the top weight of the criterion.

Step 4: Defuzzification of fuzzy numbers $\tilde{w}_i$;

$$M_i = \frac{lw_i + mw_i + uw_i}{3}, \qquad (7)$$

where M_i numbers are normalized with Eq. (7) and the weights of each criterion or alternative (N_i) are calculated.

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i}, \qquad (8)$$

TOPSIS, a method developed by Hwang and Yoon [48] in 1981, is widely used in multi-criteria decision-making problems. In the TOPSIS method, the ranking is determined according to whether the alternative chosen for the criteria is the closest to the positive ideal solution and the farthest from the negative ideal solution [49]. The algorithm of this method has been created according to the principle that the solution option is the closest to the positive-ideal solution and the farthest from the negative-ideal solution [50]. With the TOPSIS method, the distances to the positive and negative ideal solutions are calculated and ideal and non-ideal solutions are determined. The TOPSIS method consists of six steps:

Step 1: A decision matrix containing the numerical values of the alternatives according to the criteria is created.

$$A_{ij} = \begin{bmatrix} X_{11} & \cdots & X_{1j} \\ \vdots & \ddots & \vdots \\ X_{i1} & \cdots & X_{ij} \end{bmatrix}, \qquad (9)$$

where i is the number of alternatives, j is the number of criteria and X_{ij} is the numerical value of alternative i according to the j criterion.

Step 2: Obtaining the normalized decision matrix (N_{ij});

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{i} X_{ij}^2}}, \qquad (10)$$

$$N_{ij} = \begin{bmatrix} r_{11} & \cdots & r_{1j} \\ \vdots & \ddots & \vdots \\ r_{i1} & \cdots & r_{ij} \end{bmatrix}, \qquad (11)$$

Step 3: Weighted normalized decision matrix (V_{ij}) is created by multiplying the weight (w_j) of each criterion with the normalized decision matrix.

$$V_{ij} = r_{ij} x w_{ij}. \qquad (12)$$

Step 4: Constructing solutions for the positive ideal (A^*) and the negative ideal (A^-);

The maximum and minimum values are calculated for each criterion by Eqs. (13) and (14):

$$A^* = \left\{ (max_i V_{ij} \mid j \varepsilon J), \left((min_i V_{ij} \mid j \varepsilon J' \right) \right\}, \qquad (13)$$

$$A^- = \left\{ (min_i V_{ij} \mid j \varepsilon J), \left((max_i V_{ij} \mid j \varepsilon J' \right) \right\}, \qquad (14)$$

where J is the benefit (maximization) and J' is the loss (minimization).

Step 5: Calculation of separation measures: $\left(S_i^+, S_i^-\right)$;

Distances from the positive ideal solution:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, \qquad (15)$$

Distances from the negative ideal solution:

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \qquad (16)$$

are calculated.

Step 6: The relative closeness $\left(C_i^*\right)$ of the alternatives to the ideal solution is calculated:

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}, \quad 0 < C_i^* < 1. \qquad (17)$$

Evaluation of C_i^* is based on its value between 0 and 1. The relative closeness values of the alternatives to the ideal solution are ordered from the largest to the smallest.

This study determined the most suitable scenarios to increase energy efficiency by applying the FAHP and TOPSIS hybrid model, among the multi-criteria decision-making methods. The significance levels of the criteria that are effective in the selection of applied energy efficiency scenarios are analysed with Buckley's approach from fuzzy AHP methods. The weight value showing the importance of each criterion determined by Buckley's approach, one of the FAHP methods, was used in the TOPSIS method to rank the alternatives.

2 RESULTS AND DISCUSSION

2.1 Validating the Building Energy Model

The monthly measured natural gas consumption values of the building were used to validate the energy model of the reference building with the HAP 5.11 dynamic simulation software, which is widely used and accepted at the project stage, to design an energy efficient building. As a result of the calculation according to ASHRAE Guideline 14 [33], the Coefficient of Variation of the Root Mean Square Error (*CV_RMSE)* and the Normalized Mean Bias Error (*NMBE)* were calculated as 10.42 and 3.85 respectively. These values are within the limits recommended in the standard. The mentioned results show that the margins of error in the energy model are acceptable, and the building model can represent the actual building due to its accuracy.

2.2 Energy Analysis of the Reference Building

The energy consumption distribution of Erzurum Technical University Faculty of Engineering and Architecture, Turkey showing the average natural gas and electricity consumption for 2017 to 2019 is presented in Table 6. According to these data, the annual total energy consumption of the reference building is 2,857,723.23 kWh. This consumption consists of 76 % natural gas and 24 % electricity.

Table 6. *Energy consumption distribution of the reference building*

Average natural gas and electricity consumption (2017 to 2019)				
Electricity [kWh/year]	Ratio	Natural gas [kWh/year]	Ratio	Annual total energy consumption [kWh]
693,002.50	24 %	2,164,720.73	76 %	2,857,723.23

After converting the actual consumption values into primary energy consumption, the energy consumption data calculated per unit area will be used as a reference in the comparison. The annual total primary energy consumption of the reference building is 3,800,206.63 kWh/year. The share of total primary energy consumption per unit area is 150.54 kWh/m² per year. It is observed that this value is much lower than the recommended 450 kWh/m² year for education buildings specified in Appendix 4A [23] of the Thermal Insulation Rules in Buildings in force in Turkey and more efficient by 66.6 %.

The type of fuel used in the generation of energy has a significant effect on the quantity of carbon emissions. The total carbon emission calculated according to the energy consumption amounts of the reference building is 940,364.22 kg CO_2/year, and the carbon emission per unit area is 37.25 kg CO_2/m²year.

2.3 Analyses of Single Energy Efficiency Scenarios

The primary energy consumption and global costs of the scenarios of energy efficiency measures and the reference building are presented in Table 7. While the total primary energy consumption of the reference building was 150.54 kWh/(m² year), the primary energy consumption in the lowest S2 scenario achieved with improvements was calculated as 64.83 kWh/(m² year) (Table 7). With this scenario, it was possible to save 57 % of primary energy compared to the reference building. Upon evaluating the global costs of the energy efficiency scenarios, the primary energy consumption of scenario S2 was the lowest, although its global cost was the highest. It was observed that the lowest global cost was in scenario S3 (Table 7). The improvement of this scenario compared to the reference building's global cost was 83.6 %.

Global costs and primary energy consumption should be compared simultaneously to determine the cost-optimal energy efficiency scenario. With this analysis, the optimal cost solution and nearly zero-energy solution are determined among the energy efficiency scenarios. Scenarios S3 and S2 represent the optimal cost and the nearly zero energy level, respectively (Fig. 3). With scenario S3, 11.4 % savings in primary energy and 83.5 % savings in global costs were achieved. Scenario S2, which shows nearly zero energy, was efficient by 57.3% in terms of primary energy and by 37 % in terms of global cost.

Table 7. *Primary energy consumptions and global costs for energy efficiency scenarios*

Scenario	Global cost [$/m²]	Primary energy consumption [kWh/(m² year)]
Reference Building	658.66	150.54
S1	256.35	102.40
S2	414.86	64.83
S3	108.12	133.40
S4	114.57	129.65
S5	317.30	85.37

While the total CO_2 emission of the reference building was 37.25 kg CO_2 m²/year, the total CO_2 emission of scenario S2 with the lowest primary energy consumption was calculated as 15.17 kg CO_2 m²/year (Fig. 4). It was observed that this scenario emitted 59.3 % less CO_2 than the reference building.

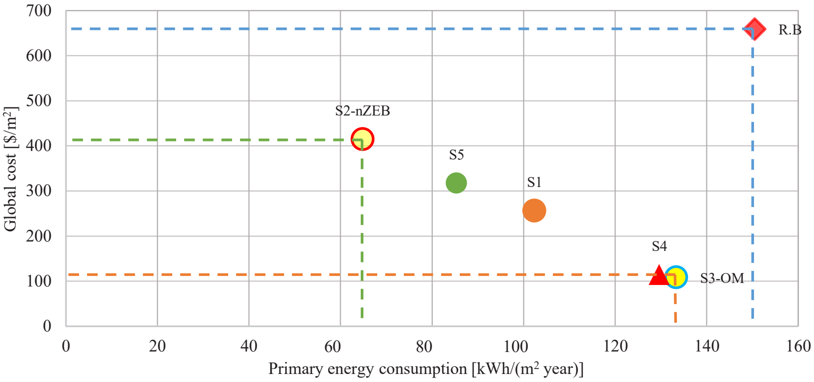

Fig. 3. *Optimal cost and nearly zero energy levels for single energy efficiency scenarios*

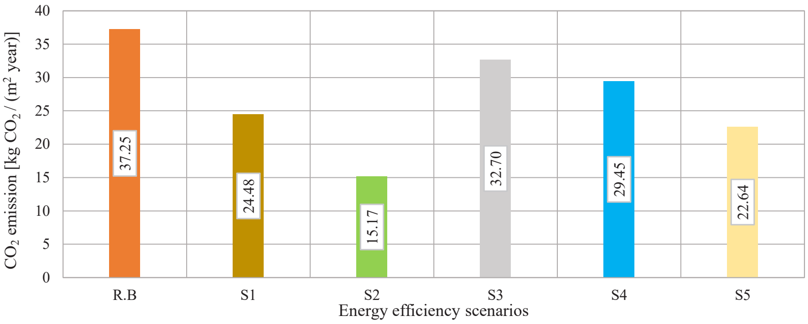

Fig. 4. *CO_2 emission amounts for single energy efficiency scenarios*

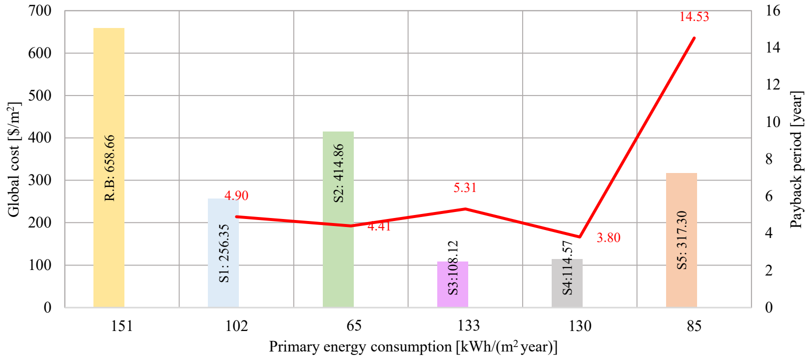

Fig. 5. *Primary energy consumption and global costs and payback periods of the single scenarios*

It was found that while the payback period of the optimal cost scenario S3 was 5.31 years, the payback period of scenario S2 showing nearly zero energy was 4.41 years (Fig. 5). According to these results, although scenario S3 resulted in the lowest cost, it had the highest primary energy consumption and CO_2 emissions. Although scenario S4 was advantageous in terms of payback period, it was not advantageous in terms of global cost, primary energy consumption, and CO_2 emissions (Fig. 5). When the global costs were analysed, the global costs of optimal cost and nearly zero energy levels all remained below the reference building levels, which indicated that the investments were economically beneficial in addition to energy consumption in the long run.

2.4 Analyses of Mixed Energy Efficiency Scenarios

Among the mixed energy efficiency scenarios, the scenario with the lowest primary energy consumption of 21.69 kWh/m² years and the highest global cost of 610.67 $/m² was S2+S3+S4 (Table 8). This scenario shows the nearly zero energy level (Fig. 6) and saves primary energy by 85.60 % and global cost by 7.3 %. Although this scenario provided minimum energy consumption, it was observed that its cost did not result in minimum cost by moving away from the optimum point, which was due to the higher initial investment cost of the relevant scenario compared to the others.

The lowest global cost was 208.51 $/m² in scenario S3+S4 (Table 7). The improvement of this scenario compared to the reference building's global cost was 68.4 %, indicating the optimal cost solution level (Fig. 6). However, this scenario had the highest primary energy consumption and saved primary energy consumption by 31.7 %.

Among the mixed energy efficiency scenarios, scenario S2+S3+S4 provided the lowest CO_2 emission by 5.08 kg CO_2 m²/year (Fig. 7). This mixed energy efficiency scenario had 86.40 % less CO_2 emissions compared to the reference building. It was observed that the amount of carbon emissions decreased in the

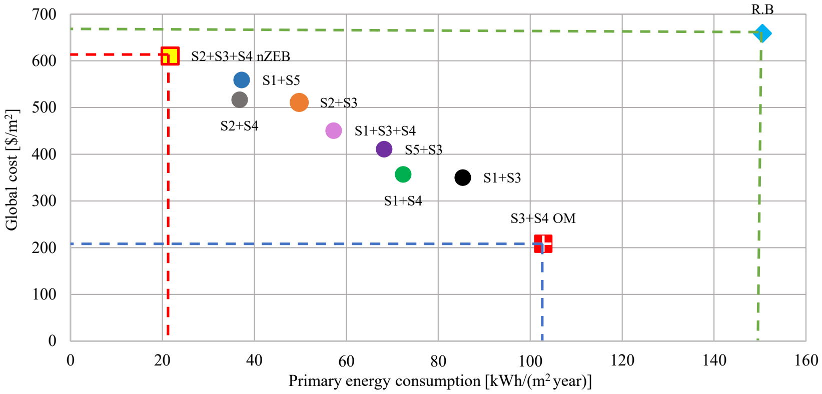

Fig. 6. *Optimal cost and nearly zero energy levels for mixed energy efficiency scenarios*

reference building at the rate of effective measures to reduce energy consumption.

Table 8. *Primary energy consumptions and global costs for energy efficiency scenarios*

Scenario	Global cost [$/m²]	Primary energy consumption [kWh/(m² year)]
R. B	658.65	150.54
S1+S3	350.28	85.32
S1+S4	356.74	72.36
S2+S3	511.12	49.74
S2+S4	516.93	36.79
S1+S5	559.14	37.22
S5+S3	410.91	68.23
S3+S4	208.51	102.86
S2+S3+S4	610.67	21.69
S1+S3+S4	450.68	57.27

Among the mixed energy efficiency scenarios, the payback period of the scenarios showing the optimal cost solution (S3+S4) and the nearly zero energy level (S2+S3+S4) was the same and determined as 4.41 years (Table 9). The payback period varies depending on annual savings. The ratios of the initial investment costs to the annual savings of scenario S3+S4 and scenario S2+S3+S4 were equal.

Table 9. *Payback periods of the mixed energy efficiency scenarios*

Scenarios	S1+S3	S1+S4	S2+S3	S2+S4	S1+S5
Payback periods (year)	5.01	4.52	4.55	4.27	7.75

Scenarios	S5+S3	S3+S4	S2+S3+S4	S1+S3+S4
Payback periods (year)	10.30	4.41	4.41	4.67

2.5 Evaluation of Energy Efficiency Scenarios by the FAHP & TOPSIS Hybrid Method

The determination of the significance level of main criteria and sub-criteria that are effective in the selection of applied energy efficiency scenarios is analysed with Buckley's approach among FAHP methods. The criteria effective in the preference of energy efficiency increasing scenarios in buildings were determined based on the experiences of experts in the field of energy efficiency and quantitative information based on studies in the literature, rather than subjective and imprecise opinions.

The criteria consist of three main criteria: technical, economic, and environmental. Each main criterion consists of sub-criteria (Table 10).

Table 10. *Order of sub-criteria*

Main criteria	Sub criteria codes	Sub-criteria
Economic (C1)	C11	Global cost
	C12	Return on investment
	C13	Initial investment cost
	C14	Energy unit price
	C15	Economic life of investment
	C16	Real interest reduction
Technical (C2)	C21	Primary energy consumption
	C22	Energy efficiency
Environmental (C3)	C31	Carbon emission

A questionnaire study including the pairwise comparison of sub-criteria was conducted with engineers and academics who were experts in the field of energy efficiency in buildings, and consistency analysis was also performed for the results. Defuzzification was performed for determining the importance weights of the experts in the decisions and

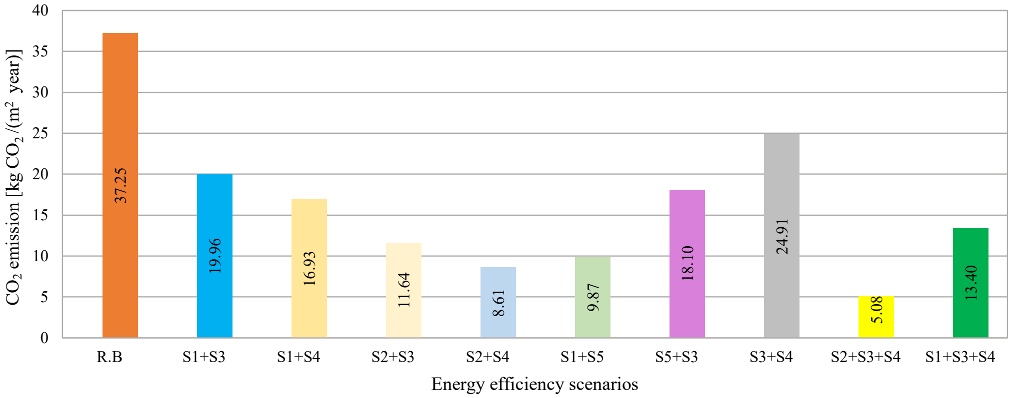

Fig. 7. *CO$_2$ emission amounts for mixed energy efficiency scenarios*

Table 11. *Weight values (W) of sub-criteria, best real number value (BNP), and ranking*

Main criteria	Sub criteria codes	W			BNP	Ranking
Economic (C1)	C11	0.167	0.163	0.154	0.162	2
	C12	0.105	0.114	0.117	0.112	4
	C13	0.099	0.105	0.113	0.106	5
	C14	0.120	0.118	0.121	0.120	3
	C15	0.088	0.081	0.080	0.083	7
	C16	0.083	0.072	0.073	0.076	9
Technical (C2)	C21	0.174	0.190	0.180	0.181	1
	C22	0.085	0.080	0.086	0.084	6
Environmental (C3)	C31	0.078	0.076	0.076	0.077	8

for the combined decision matrix to yield meaningful results. To this end, the Best Non-fuzzy Performance (BNP) defuzzification method was employed. In the study, the weight of each criterion was calculated using the FAHP method, and the weights obtained were added to the TOPSIS method to determine the best alternative. Also, the hierarchical structure of the defined MCDM problem is given in Fig. 8.

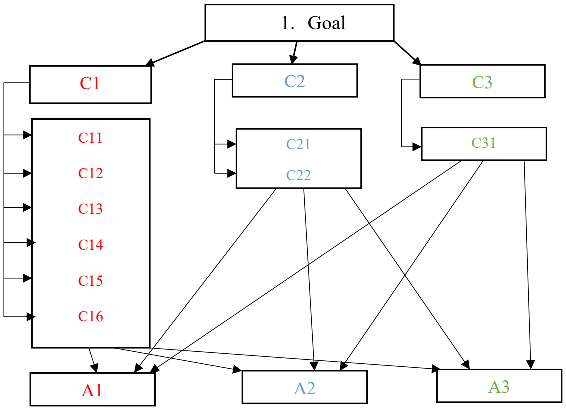

Fig. 8. *Hierarchical structure of the study*

According to the FAHP method, the criteria effective in choosing scenarios were determined in line with the experts' opinions. Considering Table 11, it was observed that criterion C21 (Primary Energy Consumption) was the most effective criterion. Criterion C11 (Global Cost) and criterion C14 (Energy Unit Price) were the second and third effective criteria, respectively. The order of importance of all criteria was obtained as C21> C11> C14> C12> C13> C22> C15> C31> C16.

Alternative scenarios were ranked using the weight value showing the importance of each criterion, which was determined by the FAHP method, in the TOPSIS method. In the ranking of the scenarios implemented to increase the energy efficiency of the reference building, the distance values from the positive ideal solution and negative ideal solution of each scenario were calculated by creating positive ideal (S^+) and negative ideal (S^-) solution sets. The relative closeness of single and mixed scenarios to the ideal solution is shown in Table 12.

Table 12. *Ideal solution values*

Scenarios		C (The degree of proximity)	Ranking
Single scenarios	S1	0.6156	3
	S2	0.4553	4
	S3	0.7178	2
	S4	0.7480	1
	S5	0.2981	5
Mixed scenarios	S1+S3	0.4981	7
	S1+S4	0.5658	4
	S2+S3	0.4628	8
	S2+S4	0.5950	1
	S1+S5	0.5667	3
	S5+S3	0.3788	9
	S3+S4	0.5202	6
	S2+S3+S4	0.5693	2
	S1+S3+S4	0.5642	5

As a result of using the FAHP-TOPSIS hybrid method, S4 was found to be the most suitable single energy efficiency scenario with a high *C* value and the closest to the ideal solution by ordering the closeness degrees from the largest to the smallest (Table 12). The scenario that must be in the last place was S5. It was revealed that the most suitable scenario was S2+S4 by ordering the closeness degrees of the mixed energy efficiency scenarios from the largest to the smallest. According to the FAHP-TOPSIS method, while the preference order of single scenarios was calculated as S4>S3>S1>S2>S5, the preference order of the mixed scenarios was calculated as S2+S4>S2+S3+S4>S1+S5>S1+S4>S1+S3+S4>S3+S4>S1+S3>S2+S3>S5+S3

(Table 12). Scenario S3, which provided the optimal cost solution among single scenarios, was the second most suitable scenario. Scenario S2, which showed the nearly zero energy level, was in the last place. In the mixed energy efficiency scenarios, scenario S2+S3+S4, which showed the nearly zero energy level, was the second most suitable scenario. Scenario S3+S4, which provided the optimal cost solution, was among the less suitable scenarios.

3 CONCLUSION

This study determined the most advantageous method in obtaining high-performance nZEB-compliant buildings in terms of energy, economy, and carbon emissions at universities located in cold climate regions. To this end, the criteria were prioritized in order to achieve high energy savings in education buildings with intense energy use in cold climate regions. Concerning its results, this study can guide both those who determine the energy policies of countries and those who conduct scientific studies. The results constitute a realistic decision support model in the selection of energy efficiency increasing scenarios in buildings in Turkey.

It was found that an improvement of 57 % to 75.3 % was achieved in the total energy consumption per unit area through the scenarios used to increase the cost-effective energy performance of the green building-certified education building. These results show that there is an energy saving potential even in certified buildings with criteria that prioritize energy efficiency. The use of this potential will contribute to achieving both energy efficiency and economic savings. It was determined that carbon emissions decreased by 59.3 % and 73.6 % by increasing the energy performance of the buildings compared to the reference building. It was lower than the predicted value of the EU, which aims to reduce greenhouse gas emissions by 55 % by 2030. In the EPBD recast, only energy-related costs are considered in the global cost in the definition of energy efficient cost. The life cycle cost and carbon emissions should also be taken into account for a full life cycle assessment of buildings. The results showed that the mixed application of energy efficiency increasing scenarios was more effective in terms of energy efficiency, CO_2 emissions, and payback period.

The most suitable scenarios showing the optimal cost and nearly zero energy levels that brought the buildings closer to nZEB were not the same. It was also revealed that these scenarios differed in terms of both CO_2 emission and payback period. Many criteria are effective in determining the most suitable energy efficiency scenario according to both national and global developments. It was found that the use of multi-criteria decision-making methods in determining the most suitable energy efficiency increasing scenarios was more effective in terms of the results. According to the opinions of experts with the FAHP & TOPSIS methodology employed in the study, the most important criterion in the selection of scenarios was primary energy consumption. The global cost ranked second, followed by the energy unit price. The experts observed that the rates of increase in interest, inflation, and energy unit prices in the country were effective in determining the effective criteria in the scenario. The findings also demonstrated that the results determined by a hybrid method were consistent and reliable.

The results of this study showed that the use of renewable energy was effective in achieving high savings at nearly zero energy levels. In fact, net energy consumption may be close to zero in some scenarios using renewable energy sources. Thus, it was determined that the use of renewable energy systems was complementary in achieving the European Commission’s energy efficiency and carbon emission targets. However, in nearly zero-energy scenarios, global costs may be higher than in other scenarios depending on the renewable energy investment. It should not be forgotten that costs are an important parameter in the decision-making phase when realizing investments.

This study revealed that countries should make a clear definition of country-specific nearly zero-energy building, which prioritizes countries’ geographical, cultural, ecological, and economic characteristics without the need for foreign certifications.

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