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# Optimizing Energy Efficiency and Renewable Energy Integration at the Mechanical Engineering Faculty Building, Sarajevo

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**Abstract.** This study presents a methodological framework for determining the optimal combination of energy efficiency measures and renewable energy sources technologies, through a case study of the Mechanical Engineering Faculty at the University of Sarajevo. The main objective is to define a strategy for enhancing building sustainability by simultaneously addressing energy performance, environmental impact, and financial feasibility. The proposed framework enables multi-criteria decision-making in complex energy retrofit projects where conflicting objectives are often encountered. The methodology is based on the creation of six retrofit scenarios, each integrating various energy efficiency measures (e.g., building envelope insulation, high-efficiency heating, and cooling systems) and renewable energy sources technologies (e.g., solar thermal systems, photovoltaic panels). Scenario evaluation is conducted through defined criteria divided into three categories: energy (e.g. energy consumption for heating, cooling, and domestic hot water preparation), environmental (e.g. direct and indirect carbon-dioxide emissions, embodied carbon), and financial (e.g. total implementation cost). Energy simulations were performed using the KiExpert software, while the scenario ranking was conducted using the VIKOR multi-criteria decision-making method. The results indicate that Scenario S5 (ground-source heat pump combined with a natural gas condensing boiler, a mechanical ventilation system with heat recovery, graphite EPS insulation, and PVC–aluminium windows) is the most favourable from energy and investment standpoints. Conversely, Scenario S3 (biomass boiler, hemp insulation, wood–aluminium windows, and external shading devices) offers the best environmental performance while also ranking second in terms of investment. These findings suggest that the final choice depends heavily on investor preferences, underscoring the need to balance sustainability targets and economic constraints (e.g. decreasing energy consumption, increasing RES share, minimizing costs). The developed methodology is applicable to energy retrofitting of various building types, particularly in contexts of integrating EE and RES measures. A comprehensive, integrated design approach and implementation of synergistic solutions in the field of energy efficiency and renewable energy sources, are key factors in the transition to a sustainable and resilient construction sector, with the aim of reducing energy consumption and operating costs, improving the quality of the living environment and reducing the negative impact on the environment.

**Keywords:** Energy efficiency; RES; optimization; VIKOR; public buildings.


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## INTRODUCTION

The building sector, as one of the largest energy consumers globally, simultaneously represents a key area for implementing energy efficiency measures aimed at reducing dependence on fossil fuels, decreasing energy consumption, and lowering carbon dioxide emissions. Despite this importance, current building energy retrofit practices frequently rely on partial interventions [1], where individual measures are analysed and implemented in

isolation, without considering the importance of their essential interconnections and synergistic effects. An optimal and sustainable solution requires establishing a balance between energy savings, maintaining indoor environmental quality, and minimizing environmental impact, which in turn implies the need for a holistic approach in building design and renovation.

Particularly significant is the public non-residential sector, which are characterised by a heterogeneous building stock, diverse energy-use profiles, and specific technical systems. Educational institutions, in particular, have complex energy requirements due to dynamic space usage patterns, high standards of thermal and ventilation comfort, and their societal role in promoting sustainable practices [2, 3]. From the aspect of building energy savings, the interest of the education sector is deeply motivated, as these institutions have standardised energy demands and a high level of comfort that must be guaranteed [4]. In Bosnia and Herzegovina, buildings of higher education typically are characterized by the compact architecture common to public facilities, but they are also often examples of energy-inefficient structures—with outdated or insufficient thermal insulation, inefficient window systems, and insufficient ventilation. Despite their structural stability, the overall energy concept of these buildings is unsatisfactory, resulting in high operational costs and reduced indoor environmental quality. Public universities, constrained by limited budgets and rigid management frameworks, often are not able to implement comprehensive energy retrofits or implement individual measures without long-term strategic approaches. Inadequately planned or partially implemented energy efficiency measures during construction or renovation phases lead to increased costs for subsequent interventions and maintenance.

Nevertheless, public buildings can offer considerable potential for energy savings - with estimated reductions in heating consumption by 40% to 60% through well-planned interventions [5], aligning with the broader objective of fulfilling Goal 11 of the United Nations 2030 Agenda for Sustainable Development, which aims to create inclusive, safe, resilient, and sustainable cities. The key challenge lies in integrating technical, economic, and environmental criteria into the decision-making process, applying methodologies that enable precise evaluation of existing conditions and simulation of energy performance following the implementation of measures [6]. When strategies are well-defined and validated through case studies, they can be applied to similar building types, establishing a systemic approach to energy improvement. A holistic approach, treating the building as an interconnected system of mutually dependent elements, is essential to avoid partial solutions that, in later stages lead to increased operational costs and reduced efficiency [7]. A well-designed energy concept for buildings, from a sustainability perspective, entails the design and management of facilities that balance energy efficiency (maximising the quality of the built environment), minimise environmental impact (through rational resource use), and ensure high-quality indoor conditions (health and comfort of occupants) [8]. Through the practical application of sustainable solutions, educational institutions become living examples of sustainable management, teaching future professionals how to develop, manage, and transform social institutions in line with the principles of sustainable development.

In this context, this paper analyses the Faculty of Mechanical Engineering building at the University of Sarajevo as a representative example of a public higher education facility where a pilot energy retrofit project was previously implemented but which still offers significant potential for further energy optimisation. Through systematic analysis of combinations of energy efficiency measures and the use of renewable energy sources, the objective is to define sustainable and integrated strategies (an energy concept) that balance energy efficiency, economic viability, and sustainable indoor environmental quality.

## METHODOLOGY

The applied methodology for determining optimal combination of energy efficiency measures consists of four key steps. First, six scenarios were defined, each combining various energy efficiency (EE) measures (e.g. improved thermal insulation of façade, energy-efficient windows) with renewable energy technologies (RET) (e.g., photovoltaic panels and heat pumps). Each scenario represents a unique combination of these measures. The combination of measures was determined based on the current state of the building and the proposed optimal measures to improve the building's energy performance and reduce carbon emissions.

The study defines evaluation criteria for assessing the scenarios and identifying the optimal combination of EE measures and RETs:

**1. Energy criteria**

- Annual energy demand for heating, cooling, and domestic hot water (DHW) (kWh/yr)
- Total annual primary energy consumption (kWh/yr))

- Share of renewables in primary energy (%)

**2. Environmental criteria**

- Direct and indirect carbon dioxide emissions ($tCO_2$/yr)
- Embodied carbon ($tCO_2$)

**3. Financial criteria**

- Investment amount per scenario (BAM)

Calculations for each scenario were conducted using **KiExpert Plus** software by Knauf Insulation, which enables detailed energy consumption analysis for heating and cooling in buildings. The software is developed in accordance with the latest thermal protection regulations and rational energy use, aligned with harmonized European standards. It uses real input data for energy demand calculation, such as [9]:

- Climatic data from the nearest meteorological station
- Composition and surface areas of building elements based on orientation
- Ventilation losses and air exchange rate
- Weekly operating hours for the heating system
- Weekly operating hours for the cooling system

These inputs are entered for each scenario, and the resulting output is the required energy for heating and cooling. The results also indicate the U-values of building elements and whether they meet the minimum allowed thresholds. The goal is to achieve U-values equal to or lower than permitted by using higher-quality insulation or energy-efficient windows. Based on the heating and cooling demands for each scenario, the following were calculated: primary energy consumption depending on heating system efficiency and fuel type (heating value), the share of renewables in total primary energy, direct emissions from fuel combustion, indirect emissions from electricity consumption, embodied energy in insulation materials, and investment amount per scenario.

Due to the diversity of sustainability measures and investor preferences, the scenarios can be ranked differently depending on the energy, environmental, and financial criteria. The multi-criteria optimization method **VIKOR** (*ViseKriterijumsko Optimalno Rangiranje* – Multi-Criteria Optimization Ranking) is applied as a methodological tool to analyse, evaluate, and select the optimal scenario combining EE measures and RETs. The method is applicable in decision-making situations involving complex systems with partially or fully conflicting criteria, allowing decision-makers to balance group benefits and individual risks [10].

Each evaluation criterion is assigned a weight that reflects its relative importance compared to the others and to the full set of criteria. This weighting is crucial, as it reflects investor priorities. Criteria that contribute more significantly to achievement of the defined goals are assigned higher weighting factor. The result of analysis identifies the optimal combination of measures that, depending on preferences, maximizes energy efficiency, reduces emissions, and ensures economic or investment feasibility. Due to the method's complexity, the mathematical model used is described in sources such as [10] and thus omitted here.

## CASE STUDY – MECHANICAL ENGINEERING FACULTY SARAJEVO

The Faculty of Mechanical Engineering, University of Sarajevo, represents a typical compact architectural form of public educational buildings with a clear geometric layout. It is located in an urban part of Sarajevo and is one of the largest higher education facilities in Bosnia and Herzegovina. Established in 1958, the faculty comprises two interconnected parts: the Western (old) and Eastern (new) buildings. This study focuses on the Western building.

The building is 26 meters high, with a flat roof and a rectangular footprint of 16.2 × 57.5 meters. The structural system includes concrete columns and 26 cm thick brick walls. Initially, the building had no thermal insulation, resulting in high heat losses during winter, cold structural elements, and moisture and condensation issues due to thermal bridging. In 2011, a pilot project was implemented by UNDP, USAID 3E, and the Mechanical Engineering Faculty. It involved the façade renovation by installing 10 cm thick expanded polystyrene (EPS) thermal insulation covered with a silicate plaster finish. After insulation, the heat transfer coefficient (U-value) was 0.23 W/m²K, which is satisfactory, as the maximum allowed for this type of structure is 0.35 W/m²K. The flat roof was not included in the renovation. It was built as a typical non-walkable flat roof with insufficient insulation, causing overheating in top-floor offices during summer and heat losses in winter. The project also included the installation of new PVC windows with double glazing filled with argon and one low-emission pane (Low-E). The U-value of the window frame must not exceed 1.4 W/m²K, and glazing must not exceed 1.1 W/m²K. Solar protection consists of internal blinds and curtains. Thermomechanical measures included regulation of the heating system

**FIGURE 1.** The building of Mechanical Engineering Faculty, Sarajevo.

The building is used year-round, with high energy consumption during winter and transitional seasons. The energy balance shows significant potential for improvement in heating, ventilation, lighting, and DHW consumption.

## Definition and Calculation of Criteria for Selecting the Optimal Combination of EE Measures and RETs

The first step, as described in the methodology chapter, is defining various combinations of EE measures and RETs organized into six scenarios. The measures include architectural and construction actions (envelope insulation, window replacement, solar shading) and mechanical systems (heating, cooling, ventilation, and renewable energy systems). The current building state is used as the baseline scenario because the initial EE pilot project did not fully cover the building—roof insulation and proper cooling systems were excluded. After initial insulation, heating energy savings were approximately 46%. However, the air-tight envelope limited ventilation, causing summer discomfort in offices and impacting user productivity. Discomfort often leads users to adopt personal solutions, increasing energy use. Therefore, energy labels without accounting for indoor environmental quality are not meaningful [11]. The baseline scenario thus includes the current state with some architectural and mechanical upgrades. Scenarios with various combinations of architectural-construction measures are described below. Prices and specifications of insulation materials, windows, and shading systems are selected based on recommendations and available data from reputable global manufacturers.

**Scenario 1 (S1) – Thermal envelope insulation, installing a natural gas condensing boiler.**
**F1** (Façade) – EPS (10 cm), Finish coat: Silicate plaster.
**R1** (Roof) - Inverted roof system, Insulation: Extruded Polystyrene (XPS) (20 cm), Finish layer: Gravel ballast (≥50 mm) or stone paving slabs.
**W1** (Window) – PVC window system, Glazing: Double Low-E Insulated Glass, Gas filled, Uw = 1.4 W/m²K.
**SS1** (Solar shading) – Inner light-colored shutters with low transparency.
**H1** (Heating) - High-efficiency condensing natural gas boiler, Output: 404 kW, Efficiency (η): 106%.
**C1** (Cooling) - Split system air conditioning, Installation of 122 split AC units for educational and office spaces, Heating capacity: COP 2.5

**Scenario 2 (S2) – Thermal envelope insulation, installing a natural gas condensing boiler, ventilation system with heat recovery.**
**F2** – Graphite EPS (12 cm), Finish coat: Silicate plaster.
**R2** – Ventilated roof system, Insulation: Extruded Polystyrene (XPS) (20 cm), Ventilation layer: Air gap + Waterproofing membrane.
**W2**– Aluminum window system with triple glazing, Triple Low-E insulated glass, Gas filled, Uw = 1.1 W/m²K.
**SS2**– External aluminum shutters.
**H2** - High-efficiency condensing natural gas boiler, Output: 404 kW, Efficiency (η): 106%.
**C2** - Split system air conditioning, Installation of 122 split AC units for educational and office spaces, Heating capacity: COP 2.5.

**V1**(Ventilation) – Ventilation system with integrated window-mounted heat recovery unit system, Heat recovery efficiency (η): 70–90%, Integration: Directly into window frames.

**Scenario 3 (S3) – Thermal envelope insulation, installing a biomass boiler, solar collectors for the preparation of PTV on a flat roof.**
**F3** – Hemp fiber insulation (16 cm), Finish coat: Silicate plaster.
**R2** – Stone wool roofing system, Insulation: Mineral Wool (20 cm) + Waterproofing: Membrane + Protective gravel layer.
**W3** – Wood-aluminum window System, Triple Low-E insulated glass, Gas filled, Uw = 0.87 W/m²K.
**SS3** – Sunshade Systems: Vertical and Horizontal louvers for window openings.
**H3**– Biomass boiler installation - Hybrid system, capacity: 300 kW, Efficiency (η): 85%, Backup/Peak Load Boiler: Existing natural gas boiler, Capacity: 814 kW, Efficiency (η): 85%
**C3**- Split system air conditioning, Installation of 122 split AC units for educational and office spaces, Heating capacity: COP 2.5
**RET1** (Renewable energy technology) – Installation of solar thermal collectors for Domestic Hot Water (DHW) preparation on a flat roof.

**Scenario 4 (S4) – Thermal envelope insulation, installing a ground-water heat pump.**
**F4**– Ventilated façade system, Insulation: Stone wool with black glass veil facing (12 cm), Air gap: 4 cm,
Cladding: Cement-gypsum composite panels with silicate finishing coat.
**R4**– Extensive green roof system, Thermal Insulation: Stone wool (20 cm). The recommendation of the manufacturer of materials for a green roof is to insulate a flat roof with stone wool, with the fact that then the investment increases compared to the application of XPS thermal insulation.
**W4** – High-performance aluminum window system, Triple Low-E insulated glass, Gas filled, Uw: 0.96 W/m²K.
**S4** – External aluminum shutters.
**H6C6** - Hybrid Heating System: High efficiency heat pump groundwater, performance coefficient COP 5 and natural gas condensing boiler, efficiency 106% and power 404 kW. The heat pump will be used for both heating and cooling of the building.

**Scenario 5 (S5) – Thermal envelope insulation, installing a ground-water heat pump, ventilation system with a heat recuperator.**
**F5** – Graphite EPS (12 cm), Finish coat: Silicate plaster.
**R5** – XPS Insulation System, Material: Extruded Polystyrene (XPS) (20 cm) + Waterproof membrane + gravel ballast (≥50 mm) or Waterproof membrane + stone paving slabs.
**W5**– PVC-Aluminum window system, Triple Low-E insulated glass, Gas filled, Uw: 0.86 W/m²K.
**SS5** – Sunshade systems: Vertical and horizontal louvers for window openings.
**H5C5** - Hybrid heating system: High efficiency heat pump groundwater, performance coefficient COP 5 and natural gas condensing boiler, efficiency 106% and power 404 kW. The heat pump will be used for both heating and cooling of the building.
**V5** – Ventilation System with integrated window-mounted heat recovery, Heat recovery efficiency (η): 70–90%
Integration: Directly into window frames.

**Scenario6 (S6) – Thermal envelope insulation, installing a ground-water heat pump, photovoltaic power plant on the flat roof, ventilation system with a heat recuperator.**
**F6** – Stone wool (12 cm), Finish coat: Silicate plaster.
**R6** – Stone wool roofing system, Insulation: Mineral Wool (20 cm) + Waterproofing: Membrane + Protective gravel layer.
**W6**– Wood-Aluminum window system, Triple Low-E insulated glass, Gas-filled, Uw = 0.87 W/m²K.
**SS6** – Sunshade Systems: Vertical and horizontal louvers for window openings.
**H6C6** - Hybrid Heating System: High efficiency heat pump groundwater, performance coefficient COP 5 and natural gas condensing boiler, efficiency 106% and power 404 kW. The heat pump will be used for both heating and cooling of the building.
**RET2** – 20 kW Photovoltaic power plant, Panel efficiency: 17%.
**V6** – Ventilation System with integrated window-mounted heat recovery, Heat recovery efficiency (η): 70–90%.

For the purpose of calculations in the KiExpert software, input data based on an analysis of the building's current condition are required. The data were collected by reviewing the existing technical documentation and include the following basic input information:

- Floors: Basement + Ground Floor + 5 Floors
- Average floor height: 3.0 m
- Building occupancy rate: 95%
- Energy usage profile: Educational institution
- Heating system: Natural gas boiler
- Heated envelope area A ($m^2$): 5,457
- Heated building volume Ve ($m^3$): 22,000
- Useful building area Ak ($m^2$): 5,559
- Climatic data: Typical Meteorological Year (TRY) for Sarajevo

For each building envelope element, the heat transfer coefficient was calculated by entering the surface area of each component depending on orientation, as well as the thickness and material of each layer into KI Expert.

The annual heating and cooling energy demand was calculated in KiExpert for the meteorological conditions of Zone 1 (Sarajevo). The city of Sarajevo belongs to the Northern climatic zone according to the Rulebook on Energy Certification of Buildings for reference climate data in the Federation of Bosnia and Herzegovina. The coldest month is January with an average air temperature of 0.5°C, while the warmest month is July with an average air temperature of 20.6°C. According to statistics, August is the sunniest month in Sarajevo with 270 sunshine hours, while December has the fewest sunny days. During the week, the building is heated for 53 hours out of 168 weekly hours, with an indoor temperature set at 20°C. For cooling calculations, it is assumed that the building is cooled for 25 hours weekly out of 168, with an indoor temperature of 24°C.

For the criterion "**Total Primary Energy**", in scenarios S4, S5, and S6, 60% of heating demand is covered by a ground-water source heat pump, and 40% by a natural gas condensing boiler. In scenario S3, heat from solar collectors is used for domestic hot water (DHW) heating. The total annual thermal energy produced by solar collectors is 22,306 kWh/year. In June, all DHW needs are met by solar collectors. Based on solar insolation in June, the absorber surface area of the solar collectors was dimensioned. July and August were not included in the calculation because the building is either not used due to summer holidays or is used less intensively. In other months, DHW needs are met using electric boilers.

In scenario S6, a 20 kW photovoltaic plant for the Sarajevo region produces 22,000 kWh of electricity annually. The data were obtained from the European Commission's Joint Research Centre. The photovoltaic system is grid-connected, so all generated electricity is fed into the grid, and the building's electricity needs are covered from the grid. According to the calculations, the electricity consumption for operating the heat pump (heating, DHW, and cooling) amounts to 26,061 kWh.

According to the criterion "**Share of RES in total primary energy**", electricity generated from the photovoltaic system and fed into the power grid is treated as renewable energy in the building's energy consumption. Heat produced by solar collectors for DHW is also treated as renewable energy in the building's energy consumption.

Regarding **carbon dioxide emissions**, in scenario S3, where a biomass boiler is used, direct carbon dioxide emissions are zero because biomass is considered carbon neutral. In scenarios using natural gas, direct carbon dioxide emissions are calculated as the product of primary energy consumption from fossil fuels for heating and the emission factor for natural gas, k = 0.2 $kgCO_2/kWh$. Indirect carbon dioxide emissions are calculated as the product of electricity consumption for S1 and the emission factor for electricity. **Embodied energy data** for the materials used were obtained based on recommended and available manufacturer data. By summing the individual emission values for different materials, the total embodied energy for each scenario is calculated.

## Optimal Selection of Energy Efficiency Measures and Renewable Technologies for the Faculty of Mechanical Engineering in Sarajevo Using the VIKOR Method

Based on the applied methodology, the values of the defined criteria for the Faculty of Mechanical Engineering in Sarajevo were calculated, which serve as the basis for further analysis aimed at identifying the optimal solution in relation to all criteria. The values of all criterion functions are presented in **Table 1**

**TABLE 1.** Calculated values for the established criteria for all six scenarios.

| Scenario / Criteria | C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| **S1** | $f_{11}$ =185,782 | $f_{21}$ = 250,115 | $f_{31}$=24 | $f_{41}$ =69.24 | $f_{51}$ =26.33 | $f_{61}$= 761,813 |
| **S2** | $f_{12}$= 162,225 | $f_{22}$ =228,578 | $f_{32}$ =24 | $f_{42}$ =63.69 | $f_{52}$ =23.22 | $f_{62}$= 2,126,828 |
| **S3** | $f_{13}$= 160,356 | $f_{23}$ =222,198 | $f_{33}$ =76 | $f_{43}$ =29.17 | $f_{53}$ =35.90 | $f_{63}$= 2,001,547 |
| **S4** | $f_{14}$= 166,638 | $f_{24}$ =93,613 | $f_{34}$ =24 | $f_{44}$ =25.95 | $f_{54}$ =34.10 | $f_{64}$ =2,432,053 |
| **S5** | $f_{15}$= 148,404 | $f_{25}$ =81,607 | $f_{35}$ =25 | $f_{45}$ =22.96 | $f_{55}$ =23.23 | $f_{65}$= 2,450,920 |
| **S6** | $f_{16}$=173,496 | $f_{26}$ =98,080 | $f_{36}$ =46 | $f_{46}$ =27.1 | $f_{56}$ =52.9 | $f_{66}$= 3,018,643 |

The starting point for applying the VIKOR method is the initial decision matrix F, i.e., the matrix of criterion functions for all alternatives, where:

j = m – the total number of scenarios and i = n = 6 – the total number of criterion functions for the six defined and adjusted criteria used to analyse the optimal combination of measures and populate the matrix F.

Requirements for maximization and minimization were defined, and weight values were assigned to the criteria depending on three aspects: financial, environmental, and energy related. For all criteria, except for the share of RES (1) in energy demand, a requirement for minimization (-1) was defined. For all considered aspects, the requirements for minimization and maximization remained the same.

**TABLE 2.** Weighting Values for Criteria – Investment, Energy and Environmental Aspect.

| Considered aspect | | Energy demands | Primary energy consumption | RES share in total primary energy | $CO_2$ emissions | Embodied energy | Investment | Sum of weighting factors |
|---|---|---|---|---|---|---|---|---|
| | | min | min | max | min | min | min | |
| | min/max | -1 | -1 | 1 | -1 | -1 | -1 | |
| **Investment** | Weighting values | 2 | 2 | 1 | 1 | 1 | 3 | 10 |
| **Energy** | Weighting values | 2 | 3 | 2 | 1 | 1 | 3 | 10 |
| **Environmental** | Weighting values | 1 | 1 | 3 | 2 | 2 | 1 | 10 |

The next step presents an example of the calculation of values for the investment aspect: the values Sj – the pessimistic solution, and Rj – the expected solution, and based on them, Qj – the compromise solution (**Table 3**).

**TABLE 3.** Investment Aspect: Values for Pessimistic, Expected, and Compromise Solutions.

| Scenario | Sj | Rj | QSj | QRj | Qj |
|---|---|---|---|---|---|
| **S1** | 0,6105 | 0,200 | 0,9669 | 0,2489 | 0,608 |
| **S2** | 0,6168 | 0,1815 | 0,9881 | 0,1096 | 0,549 |
| **S3** | 0,4518 | 0,1669 | 0,4350 | 0,0000 | 0,218 |
| **S4** | 0,4768 | 0,2220 | 0,5188 | 0,4143 | 0,467 |
| **S5** | 0,3219 | 0,2245 | 0,0000 | 0,4332 | 0,217 |
| **S6** | 0,6204 | 0,3000 | 1,0000 | 1,0000 | 1,000 |

The ranking is performed by sorting the alternatives according to the value of the Qj measure (Table 4). As the result, a ranking list of the alternatives is obtained. After that, the Q matrix is formed in ascending order, i.e., from the best to the worst scenario.

**TABLE 4.** Final Ranking List (Best to Worse Investment Value)

| Scenario | Qj | Rank |
|---|---|---|
| **S5** | 0.217 | 1 |
| **S3** | 0.218 | 2 |
| **S4** | 0.467 | 3 |
| **S2** | 0.549 | 4 |
| **S1** | 0.608 | 5 |
| **S6** | 1.000 | 6 |

The top-ranked scenario is **Scenario S5**, which is considered the compromise solution. To ensure that the obtained optimal solution based on the previously defined criteria is indeed the "best" scenario, the VIKOR method requires an additional stability check and verification of its advantage over other scenarios. According to the mathematical calculation from (10), Condition U1 is not satisfied because the top-ranked scenario S5 does not have a sufficient advantage over the second-ranked scenario S3. Regarding Condition U2, due to the insufficient advantage, a set of compromise solutions is formed up to the scenario that satisfies Condition U1, i.e., the one over which the top scenario has a "sufficient advantage," as follows:

$$S3 - S5 = Q(q'') - Q(q') = 0.218 - 0.217 = 0.001 \geq DQ = 0.2 \quad \text{insufficient advantage} \tag{1}$$
$$S4 - S5 = Q(q'') - Q(q') = 0.467 - 0.217 = 0.250 \geq DQ = 0.2 \quad \text{sufficient advantage}$$

The proposed set of compromise solutions includes **Scenarios S5** and **S3**.

In **Table 5**, when priority is given to the energy aspect, the Q matrix is arranged in ascending order, i.e., from the best to the worst scenario.

**TABLE 5.** Final Ranking List (Best to Worse) – Energy aspect.

| Scenario | Qj | Rank |
|---|---|---|
| **S5** | 0.182 | 1 |
| **S6** | 0.202 | 2 |
| **S4** | 0.351 | 3 |
| **S3** | 0.494 | 4 |
| **S2** | 0.766 | 5 |
| **S1** | 1.000 | 6 |

The top-ranked scenario is **Scenario S5;** however, an additional stability check of the solution is required. The first scenario in the compromise ranking list, S5, does not satisfy Condition U1, but under Condition U2 it has a "sufficiently stable" position, as it meets one of the conditions—being ranked first according to both QS and QR when v = 0.75. After verification, the proposed set of solutions includes **Scenarios S5, S6,** and **S4.**

In Table 6, the Q matrix, when the environmental aspect is given the highest priority, is arranged in descending order—from the best to the worst ranked scenario.

**TABLE 6.** Final Ranking List (Best to Worse) – Environmental aspect.

| Scenario | Qj | Rank |
|---|---|---|
| **S3** | 0.000 | 1 |
| **S5** | 0.578 | 2 |
| **S6** | 0.592 | 3 |
| **S4** | 0.764 | 4 |
| **S2** | 0.920 | 5 |
| **S1** | 1.000 | 6 |

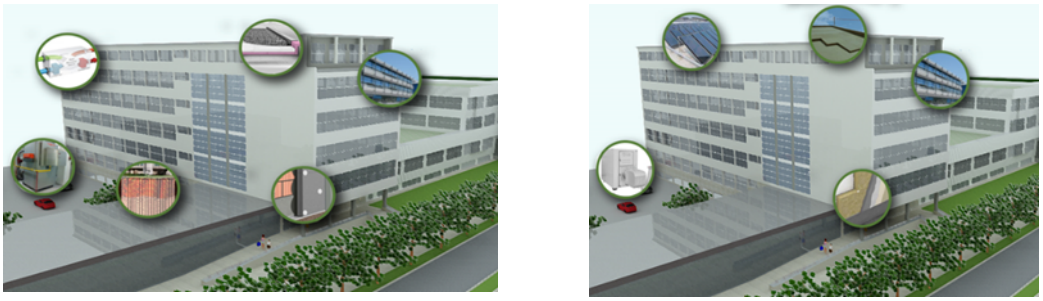
The top-ranked scenario is Scenario S3, but an additional stability check of the solution is required. Condition U1 is satisfied, meaning that Scenario S3 has sufficient advantage over the second-ranked Scenario S5. The first scenario in the compromise ranking list, S3, meets Condition U1 and has a "sufficiently stable" position under Condition U2, as it satisfies all the criteria. The proposed "best" solution is **Scenario S3**.

## RESULTS AND DISCUSSION

Depending on the aspect given higher priority (investment, energy, or environmental), the scenarios were ranked from best to worst based on the results obtained by applying the methodology described in the previous chapter.

According to the **investment cost criterion**, which was assigned the highest weight, **Scenario S5** involves about 25% higher investment than Scenario S3, due to more expensive mechanical measures: a ground-source heat pump (COP 5), a condensing natural gas boiler, and a ventilation system with heat recovery. Scenario S3 uses a biomass boiler, split systems, and solar collectors. S5 has lower **annual heating energy** demand compared to S3. In S3, heating is provided by a biomass boiler, cooling by split systems (COP 2.5), and domestic hot water (DHW) is supplied by a combination of solar collectors and electricity. In S5, 60% of the heating is provided by a heat pump and 40% by a condensing boiler, while cooling and DHW are entirely supplied by the ground-source heat pump. Scenario S3 consumes almost three times more **primary energy** than S5. Although S5 has higher fossil fuel consumption due to the condensing boiler, S3 uses fossil fuels only partially for cooling and DHW. At the same time, S3 has a higher share of energy from renewable sources due to the biomass boiler and solar collectors. S3 has no **direct carbon dioxide emissions** because it uses biomass, while S5 emits 6.11 $tCO_2$/year. However, S3 has 3.5 times higher **indirect carbon emissions** due to increased electricity usage for cooling and DHW. Despite the higher investment, S5 justifies the cost through significantly lower annual energy demand and lower overall primary energy consumption. Due to the combination of highly efficient mechanical systems, electricity consumption in S5 is about 50% lower than in S3.

According to the total **primary energy consumption criterion**, Scenario S5 is ranked as the best. It has the lowest primary energy consumption from both fossil fuels and renewable sources compared to S4 and S6, due to lower annual energy demands. S5 also has the lowest heating energy requirement, ahead of second-ranked S6 and third-ranked S4. All three scenarios use the same heating system: a ground-source heat pump (COP 5) and a condensing boiler for peak loads. The **share of renewable energy in** primary energy is highest in S6 (46%), followed by S5 (25%) and S4 (24%). Additionally, S6 generates 22,000 kWh/year of its own electricity through a PV system. S5 has the **lowest direct carbon dioxide emissions** because the condensing boiler is used minimally, and the lowest **indirect carbon emissions** due to minimal electricity consumption. Although the investment criterion carries the least weight, S5 has approximately the same investment cost as S4, while the investment in S6 is about 25% higher due to more expensive architectural and mechanical measures (ventilation with heat recovery and the PV system). From an **energy perspective**, S5 is the leading scenario across the criteria of total annual energy demand, total primary energy consumption, carbon dioxide emissions (direct and indirect), and investment level.



(a) (b)

**FIGURE 2.** (a) The highest-ranked Scenario S5 for the Mechanical Engineering Faculty in Sarajevo - investment and energy aspects, (b) The highest-ranked Scenario S3 – environmental aspect.

From the **environmental perspective**, Scenario S3 is ranked first among all six scenarios. Hemp is used as thermal insulation for the façade and stone wool for the roof. The windows are wood aluminium with triple glazing ($U=0.86$ W/m²K), and sun protection is provided through vertical and horizontal louvers. Heating is provided by a biomass boiler (efficiency 85%), and domestic hot water (DHW) is heated using rooftop solar collectors. Scenario S3 has the highest share of renewable energy in primary energy (76%), thanks to the use of biomass and solar collectors. Hemp, as an insulation material, has the lowest embodied carbon dioxide emissions (0.345 $kgCO_2$/kg). Although it generates more total emissions due to higher density, it is more environmentally friendly than EPS and similar materials. In terms of total primary energy consumption from renewable sources, S3 is the leader due to the dominant use of renewables.

## CONCLUSION

The methodology developed in this study is based on the creation of scenarios with different combinations of energy efficiency measures and renewable energy technologies for the building of the Faculty of Mechanical Engineering, University of Sarajevo. The objective was to achieve a sustainable energy concept through an integrated approach that combines building envelope insulation, the application of renewable energy technologies, and modern energy-efficient systems while maintaining indoor environmental quality. The defined evaluation criteria were categorized into three groups—energy, environmental, and financial. Their calculated values, derived from energy simulations using the KiExpert Plus software for each scenario, served as the foundation for further analysis and model development. The application of multi-criteria optimization proved essential in addressing conflicting investor objectives. The results of the analysis highlight optimal combinations of energy efficiency measures and renewable energy technologies for the faculty building, depending on the dominant decision-making aspect:

- Scenario S5 (ground-source heat pump with natural gas condensing boiler, heat recovery ventilation, graphite EPS insulation, PVC-aluminium windows) demonstrated the most favourable performance in terms of investment and energy efficiency, offering the best ratio of energy savings to investment return.
- Scenario S3 (biomass boiler, hemp insulation, wood-aluminium windows) outperformed others environmentally, with significantly lower $CO_2$ emissions and acceptable investment feasibility.

Given the small difference in investment cost, Scenario S3 can be considered as an optimal choice from a combined investment and environmental standpoint. The final selection between S3 and S5 depends on the investor's preferences—whether the priority lies in environmental sustainability or energy savings. This methodological framework, based on an integrated approach to energy sustainability planning, is essential for ensuring sustainable construction, rational energy consumption, and extended building lifespans, thereby contributing to the broader goal of decarbonizing the construction sector. Future research may focus on adapting this methodology to other building types and assessing the long-term performance of the implemented solutions.

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