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Анализа могућих мера енергетске санације једне постојеће зграде намењене образовању

Analysis of potential energy retrofit measures for an existing educational building

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У овом раду анализиране су мере енергетске санације једне предшколске установе у граду Крагујевцу, са циљем унапређења енергетске ефикасности објекта и постизања значајних уштеда енергије уз истовремено испуњавање свих потребних захтева које овај вид установе захтева. Проучавани су различити приступи, укључујући примену термичке изолације, замену столарије, увођење система подног грејања, као и уградњу вентилационих система са и без рекуперације топлоте. Напослетку, разматрана је инсталација соларног фотонапонског система као обновљивог извора енергије, у циљу подмиривања потрошње електричне енергије потребне за рад претходно наведених система и повећања енергетске ефикасности објекта. Симулације спроведене у софтверу EnergyPlus показале су значајно смањење потрошње енергије за грејање и хлађење, чак и уз примену система вентилације.

Key words:
educational building; ventilation; energy efficiency; simulation; EnergyPlus

This paper analyzes energy retrofit measures for a preschool facility in the city of Kragujevac, with the aim of improving the building's energy efficiency and achieving significant energy savings, while simultaneously meeting all necessary requirements specific to such institutions. Various approaches were studied, including the application of thermal insulation, replacement of exterior windows and doors, installation of underfloor heating systems, as well as the integration of ventilation systems with and without heat recovery. Finally, the installation of a solar photovoltaic system as a renewable energy source was considered, in order to meet the electricity consumption needs for the operation of the previously mentioned systems and further increase the building's energy efficiency. Simulations conducted using the EnergyPlus software demonstrated a significant reduction in heating and cooling energy consumption, even with the implementation of ventilation systems.

1. Introduction

Non-residential buildings in the European Union account for 25% of the total building stock and, together with residential buildings, contribute to 40% of total energy consumption and up to 36% of CO_2 emissions. Educational institutions represent 17% of all non-residential buildings [1,2]. Within the EU's energy transition framework, adopted as part of the European Green Deal, one of the key initiatives is improving the energy efficiency of buildings [3]. Although it is not an EU member state, Serbia also implements directives issued by the EU. According to the Rulebook on Energy Efficiency of Buildings [4] an energy-efficient building is defined as one that minimizes energy consumption while maintaining optimal comfort conditions. In their research, *Földváry et al.* [5] and *Jiang et al.* [6] emphasize the importance of maintaining comfort conditions during energy retrofit processes, warning about the decline in indoor air quality and comfort in buildings renovated without adequate consideration of these aspects. Additionally, *Sánka et al.* [7] point out that while energy retrofitting reduces energy consumption, it can also degrade indoor air quality if proper ventilation is not ensured, resulting in increased CO_2 and volatile organic compound (TVOC) concentrations. This issue requires particular focus in the case of preschool facilities, as non-residential buildings designed for children's education. *Cartieaux et al.* [8] emphasize that children are one of the most vulnerable groups to air pollution due to their actively growing bodies and higher air intake relative to body weight. A study conducted by *Haverinen-Shaughnessy et al.* [9] further highlights the importance of a holistic approach to energy retrofitting, indicating that higher ventilation rates and lower classroom temperatures positively impact students' academic performance, reduce the likelihood of respiratory infections among children, and limit the spread of pathogenic microorganisms.

Therefore, this study presents a detailed analysis of various energy retrofit measures applied to an existing preschool building in the city of Kragujevac, aiming to enhance its energy efficiency while maintaining comfort conditions. The proposed measures include both construction-related improvements and upgrades to heating and ventilation systems, as well as the use of renewable energy sources. These measures were evaluated through a series of energy performance simulations for this non-residential building using the EnergyPlus software. The simulations accounted for the building's actual usage conditions, including occupant presence, to ensure accurate assessment of each measure's effectiveness. These simulations enabled the creation of energy models that demonstrated potential energy savings and reductions in operational costs. The process began with the development of a 3D geometric model of the building using SketchUp software, which provided a foundation for further analysis and optimization efforts.

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2. Methodology

The analyzed object is a preschool facility located in the city of Kragujevac. Constructed in 1974, the building consists of three levels: basement, ground floor, and first floor. It is not surrounded by other buildings that could influence its energy performance and the building's orientation is 45° counterclockwise relative to the north. Kragujevac has a temperate continental climate, and the EnergyPlus simulations were conducted using the climatic conditions of this location, based on a weather file specific to Kragujevac. Prior to initiating the energy retrofit simulations, a 3D model of the building was created using the SketchUp software (Figure 1).

The kindergarten building consists of 37 rooms, with a total area of 2003 m^2. Of these 37 rooms, 31 are heated, and 14 are cooled. The total heated area amounts to 1569.68 m^2, while the total cooled area is 853 m^2. For the purpose of simulating the energy retrofit of this building, the actual presence of children was analyzed based on attendance records kept by kindergarten teachers. According to the real data, the total number of occupants is 356. Additional information regarding the use of the kindergarten, work schedules, building characteristics, and energy supply systems was collected during multiple field visits and interviews with teachers and kindergarten administrators. Depending on their age, the children are assigned to appropriate rooms or educational groups. There are the following types of educational groups: babies (B – 6-12 months); younger nursery group (YN – 12-18 months); middle nursery group (MN – 18-24 months); older nursery group (ON – 2-3 years); younger educational group (YE – 3-4 years); middle educational group (ME – 4-5 years); older educational group (OE – 5-6 years) and mixed group (MXE – 3-6.5 years). The layout of the children's groups within the kindergarten is shown in Figure 2.

Figure 3 provides a graphic view of the occupancy level for the rooms occupied by the children. The occupancy level represents the ratio of the number of currently present children and the maximum number of enrolled children. It has a fractional value ranging from 0 (absence) to 1 (presence). It should be emphasized that each educational group of children is in a separate and appropriate room where almost all activities take place. The situations when children leave the rooms to go to the toilet or stay outside are excluded.

In its current state, the building lacks a ventilation system, and the rooms are ventilated naturally by opening windows. This method of ventilation can significantly increase energy consumption for heating and cooling. Additionally, Nikolić et al. [10] highlighted that relying on the maximum occupancy schedule leads to the greatest error in predicting heating energy consumption (up to 11.38%), regardless of the ventilation method, and recommend using actual occupancy data instead. To address the building's ventilation issue, following the recommendation from [10], a demand-controlled ventilation (DCV) system has been proposed to ensure a consistent supply of fresh air in rooms occupied by children. The standard CEN/TR 16798-2:201 [11] provides recommended values of total ventilation requirements (q_{tot}) for kindergartens, which differ according to the category of IAQ (C1, C2, C3 and C4) and the degree of building pollution: very low-polluted buildings (VLP), low-polluted buildings (LP) and non-low-polluted buildings (NLP). For children as users of these buildings, it is recommended to maintain the highest level of IAQ (C1). In this regard, a fresh air flow rate of 12 l/(s·person) was adopted, which corresponds to the category C1 and the building pollution level LP. Since the operation of the DCV system is controlled by the presence of children (presence and counting based control), it is expected that the IAQ in all educational rooms for all developed occupancy patterns will be the highest possible throughout the year. The amount of fresh air supplied to the rooms occupied by children depends on the number of children currently present (Figure 3). The developed ventilation system model consists of a heat recovery unit (Sensible effectiveness for heating: 0.69-0.72; Latent effectiveness for heating: 0.53-0.58; Sensible effectiveness for cooling: 0.69-0.72; Latent effectiveness for cooling: 0.46-0.54) and two fans (η = 0.65) – one for supplying fresh air to the rooms and the other for extracting waste air. Ventilation with and without heat recovery was considered.

The building is currently connected to a district heating system, with radiators serving as the primary heating elements. According to administrators, there are plans to transition to a natural gas boiler system (η = 0.8–0.89), which was incorporated into the simulation. Additionally, the installation of underfloor heating as a replacement for radiators was evaluated (temperature regime 47/42°C). For cooling, it was assumed that the building already utilizes a split air-conditioning system (COP = 3) installed in rooms occupied by children (case 0). This system operates from 07:00 to 16:00 at 26°C and remains off from 16:00 to 07:00. All HVAC systems were sized using simulation software for the analyzed scenarios. Given that the kindergarten operates from 06:00 to 17:00, the same operational period was adopted for these systems (except cooling) in the simulations. Furthermore, since children's presence impacts the operation of heating and cooling systems due to overall heat gains, the following heat gains were adopted: 38.3 W/person for children under 4 years old and 62.1 W/person for children aged 4 to 6 years [12].

The installation of a PV system to meet the electricity consumption requirements for the operation of heating, cooling, and ventilation systems was considered in four different scenarios (Table 1): Radiator heating and a ventilation system without heat recovery (case 10), radiator heating and a ventilation system with heat recovery (case 12), underfloor heating and a ventilation system without heat recovery (case 11) and underfloor

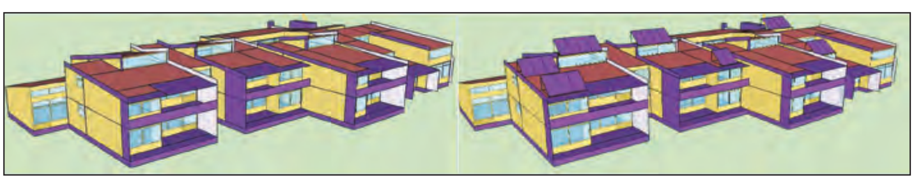

Figure 1. Isometric view of the building (left), isometric view of the building with 23 PVs installed (right)

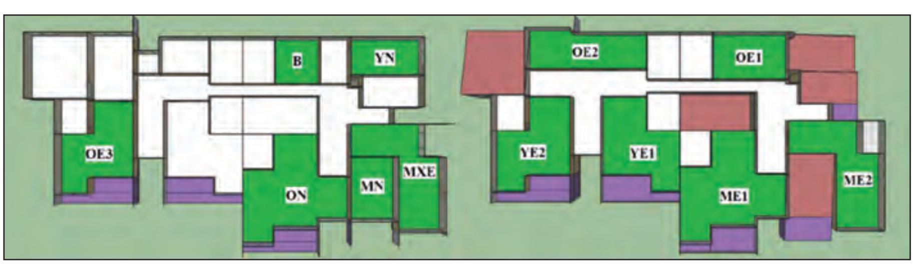

Figure 2. Arrangement of kindergarten rooms occupied by children (the ground floor (left) and the first floor (right))

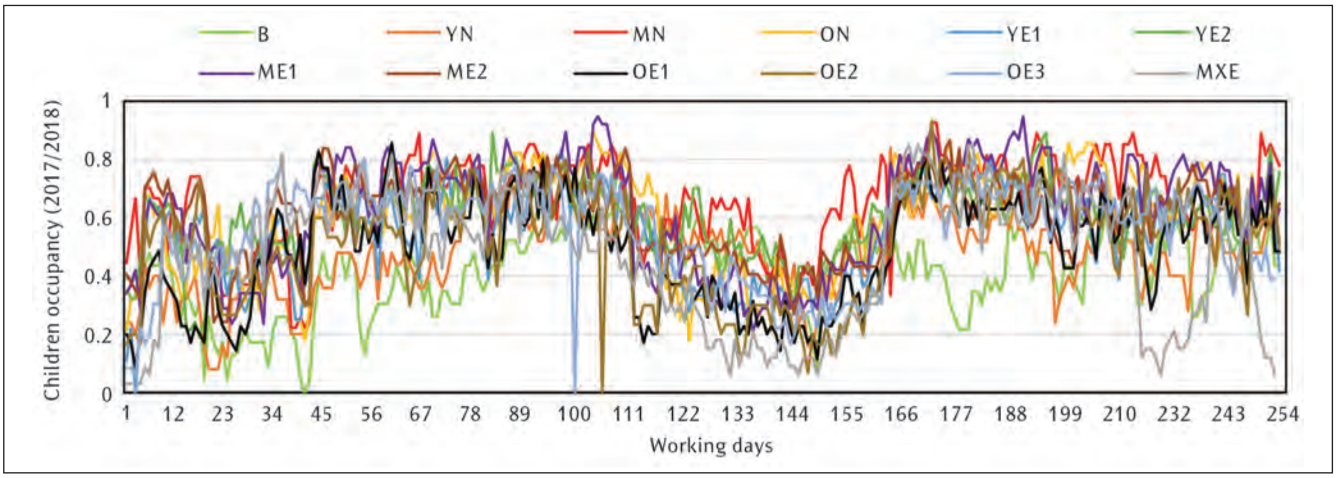

Figure 3. Graphic view of the occupancy level based on the actual presence of children during the 2017/2018 school year

heating and a ventilation system with heat recovery (case 13). The required number of PV panels was calculated as 18 (η = 22.64% [13]) for cases 10 and 12, and 23 for cases 11 and 13 (Figure 1, right). When incorporating the panels into the 3D model, the minimum spacing between panels was considered to prevent mutual shading, following the recommendations in [14].

Ultimately, a more detailed description of the current condition of the building envelope is necessary. At present, the building lacks any form of thermal insulation on its external envelope. Additionally, the outdated windows and doors in direct contact with the outside air contribute to significant heat losses due to infiltration. It is also important to note that the building is covered with an outdated metal roof. The thermal transmittance values for all the exterior construction elements of the building are as follows: roof above heated area (U_{RHTD}) = 2.319 W/m^{2}K, roof above non-heated area (U_{RNHTD}) = 2.319 W/m^{2}K, floor and ceiling above heated area (U_{FHTD}) = 3.042 W/m^{2}K, floor and ceiling above non-heated area (U_{FNHTD}) = 4.095 W/m^{2}K, floor on the ground (U_{FG}) = 1.552 W/m^{2}K, exterior wall (U_{EWALL}) = 1.564 W/m^{2}K, exterior doors (U_{ED}) = 2.689 W/m^{2}K and exterior windows (U_{EW}) = 2.770 W/m^{2}K.

The implemented energy retrofit measures can be divided into construction measures and measures of improving the heating and ventilation systems. After simulating these measures, the installation of a solar PV system was simulated to cover the electricity consumption required for the operation of the mentioned systems. Table 1 lists by the order the undertaken measures of the building's energy retrofit. In the given table, the initial case is marked as case 0, representing the existing condition of the building (radiators are dimensioned for the temperature regime 90/70°C).

The term „complete insulation“ in table 1 refers to the insulation of external walls, roof reconstruction and insulation, floor and ceiling reconstruction and insulation, and replacement of exterior doors and windows. Heating regime 1 refers to the schedule 06:00-22:00 at 20°C; 22:00-06:00 at 16°C, while regime 2 refers to the schedule 06:00-17:00 at 20°C; 17:00-06:00 at 16°C.

The first energy retrofit measure focused on optimizing the operating regime of the heating system. Since the district heating system shuts off at 10 PM, the baseline scenario assumed that the natural gas boiler operates until 10 PM. The proposed measure involved partially closing radiator valves after the kindergarten's working hours to align the heating

Table 1. List of conducted energy retrofit measures

Case	Type of insulation	Infiltration [L/h]			Mechanical ventilation	Heat recovery	Type of heating	Heating regime
		Hallways	Toilets	Remaining rooms				
0	None	0.2	0.5	0.7	No	No	Radiators	1
1	None	0.2	0.5	0.7	No	No	Radiators	2
2	EW*	0.2	0.5	0.7	No	No	Radiators	2
3	DW**	0.2	0.5	0.5	No	No	Radiators	2
4	R***	0.2	0.5	0.7	No	No	Radiators	2
5	EW+DW	0.2	0.5	0.5	No	No	Radiators	2
6	EW+R	0.2	0.5	0.7	No	No	Radiators	2
7	R+DW	0.2	0.5	0.5	No	No	Radiators	2
8	EW+R+DW	0.2	0.5	0.5	No	No	Radiators	2
9	Complete	0.2	0.5	0.5	No	No	Underfloor	2
10	EW+R+DW	0.2	0.5	0.2	Yes	No	Radiators	2
11	Complete	0.2	0.5	0.2	Yes	No	Underfloor	2
12	EW+R+DW	0.2	0.5	0.2	Yes	Yes	Radiators	2
13	Complete	0.2	0.5	0.2	Yes	Yes	Underfloor	2

** External wall; ** Replacement of exterior doors and windows; *** Roof reconstruction* system's operation with the building's usage schedule. Following this optimization, simulations of construction retrofit measures were conducted. Initially, individual measures were implemented (cases 2–4), starting with external wall insulation, then replacement of exterior doors and windows, and finally roof reconstruction and insulation. The thickness of the insulation layer for external walls was set at 10 cm (U_{EWALL} = 0.293 W/m^{2}K), while the replacement of exterior doors and windows included substituting double-glazed windows with triple-glazed ones (U_{EW} = 1.525 W/m^{2}K) and replacing entrance doors (U_{ED} = 1.875 W/m^{2}K). The building's roof was divided into two groups: the roof above heated spaces, insulated with a 12 cm layer (U_{RHTD} = 0.249 W/m^{2}K), and the roof above unheated spaces, insulated with a 10 cm layer (U_{RNHTD} = 0.292 W/m^{2}K). The next step involved simulating various combinations of these measures (cases 5–8). Reconstruction and insulation of floors and ceilings were not considered within previous measures due to their significantly higher investment costs compared to the earlier proposed measures. However, this measure was included in cases where the installation of an underfloor heating system was planned, representing the next step in the simulation process. Within this measure, the underfloor heating system was introduced. The floors were categorized into three types: floors on the ground, floors (and ceilings) above heated spaces, and floors (and ceilings) above unheated spaces. The insulation thickness for all three cases was set at 12 cm (U_{FG} = 0.146 W/m^{2}K, U_{FHTD} = 0.290 W/m^{2}K and U_{FNHTD} = 0.290 W/m^{2}K). Ventilation system improvement measures were implemented in the final phase. The simulation included installing a ventilation system in both scenarios: with underfloor heating and with radiator heating. Additionally, the simulation considered the installation of a ventilation system with heat recovery in both scenarios.

3. Results

The first step in the building's energy retrofit involved aligning the model with the actual state based on the annual energy consumption for heating, which amounts to 157.25 kWh/m^2. This calibration also enabled the estimation of electricity consumption for air conditioning system operation (during the cooling season) which amounted to 7.25 kWh/m^2. These values, reflecting the building's existing state, were used as a reference to evaluate the efficiency of the implemented measures. According to the Rulebook on Terms, Content, and the Process of Issuing Certificates of Building Energy Performance [15], the building in its original state corresponds to energy class F. The results achieved during the heating season will be further analyzed based on the energy class the building attains after the implemented measures. All results are presented in Table 2.

For the heating season, the results in table 2 refer to the amount of natural gas used for heating the building per unit of heated area. For the cooling season, the results refer to the amount of electricity used to operate the building's air conditioning system per unit of cooled area.

3.1. Heating season

By changing the operating mode of the heating devices, an annual savings of 8.27% is achieved compared to the initial case. Implementing this measure allows the building to meet the requirements for transitioning to a higher energy class, E. Among individual measures, the greatest savings (compared to the initial case) are achieved with measure 4 (33.07%), followed by measure 2 (22.55%), and then measure 3 (20.16%). Implementing measure 4 meets the requirements for energy class D. Regarding grouped measures, the greatest savings are achieved with measure 6 (49.07%), followed by measure 7 (45%), while measure 5 achieves savings of 34.69%. Implementing these measures does not result in a transition to a higher energy class. By implementing measure 8, savings of 61.20% are achieved, meeting the requirements for energy class C. However, since there is no mechanical ventilation system in this case, the minimal hygienic conditions for children's occupancy are not met. Case 10 describes a scenario where a ventilation system is added. Analyzing the results achieved after the simulation of construction measures, it can be concluded that, among individual measures, roof reconstruction and insulation provides the highest savings. It achieves savings comparable to those obtained through insulating external walls and replacement of the building's exterior doors and windows. When it comes to upgrading heating and ventilation systems, it is important to emphasize that, regardless of the potential savings that may or may not be achieved, these measures directly impact the comfort and well-being of the children and should therefore be considered essential. Measure 9 achieves savings of 77.65% and meets the requirements for energy class B. However, this scenario also lacks a ventilation system, requiring the simulation of scenario 11. During

Table 2. Results of energy retrofit measures

Case	Type of insulation	Infiltration [L/h]			Mechanical ventilation	Heat recovery	Type of heating	Heating regime	Results – heating [kWh/m^2]	Results – cooling [kWh/m^2]	Primary energy [kWh/m^2]
		Hallways	Toilets	Remaining rooms							
0	None	0.2	0.5	0.7	No	No	Radiators	1	157.25	7.25	191.1
1	None	0.2	0.5	0.7	No	No	Radiators	2	144.25	7.25	176.8
2	EW*	0.2	0.5	0.7	No	No	Radiators	2	121.79	7.23	152.04
3	DW**	0.2	0.5	0.5	No	No	Radiators	2	125.55	7.08	155.81
4	R***	0.2	0.5	0.7	No	No	Radiators	2	105.24	4.53	127.09
5	EW+DW	0.2	0.5	0.5	No	No	Radiators	2	102.71	7.08	130.68
6	EW+R	0.2	0.5	0.7	No	No	Radiators	2	80.08	4.39	99.06
7	R+DW	0.2	0.5	0.5	No	No	Radiators	2	86.49	4.33	105.96
8	EW+R+DW	0.2	0.5	0.5	No	No	Radiators	2	61.01	4.23	77.69
9	Complete	0.2	0.5	0.5	No	No	Underfloor	2	35.14	11.07	66.33
10	EW+R+DW	0.2	0.5	0.2	Yes	No	Radiators	2	79.5	3.7	96.7
11	Complete	0.2	0.5	0.2	Yes	No	Underfloor	2	42.8	8.38	68.03
12	EW+R+DW	0.2	0.5	0.2	Yes	Yes	Radiators	2	58.23	3.27	72.23
13	Complete	0.2	0.5	0.2	Yes	Yes	Underfloor	2	24.84	9.02	49.87

the simulation process for installing underfloor heating, in addition to the flooring, it is necessary to increase the thickness of the thermal insulation in ceiling structures. Furthermore, underfloor heating uses a condensing boiler, while conventional non-condensing boilers are used for radiator heating. The use of a condensing boiler allows for the utilization of latent heat from the condensation of water vapor in natural gas combustion products, further increasing heating efficiency and reducing natural gas consumption. These measures directly influence heating-related natural gas consumption by reducing it. As a result, later cases demonstrate varying changes in gas consumption between radiator and underfloor heating when the same measures are applied. Measures 10 and 11 result in savings of 49.44% and 72.78%, respectively, while the building transitions to a lower energy class: in case 10, from class C to D, and in case 11, from class B to C. Comparing the results of measures 8 and 10, as well as 9 and 11, it is concluded that natural gas consumption increases by 30.3% and 21.8%, respectively. This increase is due to the higher air exchange rate and the need for constant heating of larger volumes of fresh air. Measure 12 achieves total savings of 62.97%, meeting the requirements for energy class C, while case 13 achieves savings of 84.20%, meeting the requirements for energy class B. The savings achieved by comparing cases 10 and 12 amount to 26.75%, while the savings from comparing cases 8 and 12 amount to 4.56%. Savings from comparing cases 11 and 13 amount to 41.96%, while the savings from comparing cases 9 and 13 amount to 29.31%.

3.2. Cooling season

By changing the operating mode of heating devices, no savings are achieved regarding cooling. Among the individual measures, measure 4 achieves the highest savings (37.52%), followed by measure 3 (2.34%) and measure 2 (0.28%). Measure 5 achieves savings of 2.34%, measure 6 achieves 39.45%, and measure 7 achieves 40.26%. Implementing measure 8 achieves savings of 41.65%. As in the previous case, the greatest savings are achieved through measures involving the reconstruction and insulation of the roof. On the other hand, small savings are observed when implementing other measures. This phenomenon can be explained by the fact that, in cases where there is no thermal insulation on the building elements of the cooled rooms, the space can be further cooled during the night; however, this is no longer possible. On the other hand, roof reconstruction involves replacing the metal structure, which spans over a large area of the building, and adding an insulation layer to effectively minimize heat gains through this construction element. Measure 9 does not result in savings but rather an increase in consumption by 52.69% compared to the initial scenario. In case 10, consumption decreases by 48.97% compared to the initial scenario and by 12.53% compared to case 8. On the other hand, in case 11, energy consumption increases by 15.59% compared to the initial scenario but decreases by 24.30% compared to case 9. The increase in electricity consumption for operating air conditioning systems in the case of underfloor heating arises due to the complete insulation of the building. With the insulation of floors and ceilings, the building becomes entirely thermally insulated, causing the heat generated by the presence of children to remain trapped in the space. On the other hand, introducing a mechanical ventilation system removes this generated heat and replaces it with fresh air. This not only reduces the amount of electricity consumed by the cooling system but also ensures minimal hygienic conditions for children's stay and enhances air comfort. In case 12, a consumption reduction of 54.90% is achieved, while case 13 results in a 24.41% increase. Comparing cases 10 and 12 shows a reduction in consumption of 11.62%, while comparing cases 11 and 13 reveals an increase of 7.64%. On the other hand, comparing cases 8 and 12 achieves savings of 22.70%, while comparing cases 9 and 13 shows savings of 18.52%. The increase in electricity consumption observed when using a heat recovery system compared to a mechanical ventilation system without heat recovery in the case of underfloor heating occurs due to higher achieved indoor air temperatures in occupied spaces. Namely, in systems without heat recovery, the incoming fresh air has a lower temperature than fresh air treated through a heat recovery system. Its lower temperature results in cooler indoor air in cooled spaces compared to when a heat recovery system is active. This leads to shorter and less frequent operation of air conditioning systems. This phenomenon does not affect electricity consumption in radiator heating systems due to significantly different and lower heating demands compared to buildings with underfloor heating systems.

4. Conclusion

Mechanical ventilation, particularly with heat recovery, ensures comfort conditions and a healthy environment in educational institutions, improves students' academic performance, and reduces the risk of respiratory illnesses. On the other hand, panel heating systems contribute to optimal thermal comfort at lower temperatures, which positively affects children's health. Construction retrofit measures, with reducing the heat losses and improving the energy efficiency of the building, ensure the effective use of ventilation and underfloor heating systems. The results achieved through the implementation of construction measures show that, for both the heating and cooling seasons, the most significant results are obtained with measures involving roof reconstruction. Additionally, for the heating season, maximum savings are achieved through the use of underfloor heating combined with a ventilation system integrating heat recovery, which includes complete building insulation, corresponding to savings of 84.20%, or a consumption of 24.84 kWh/m^2 and an energy class of B. In terms of the cooling season, the application of underfloor heating leads to increased consumption. Mechanical ventilation reduces consumption, while the additional implementation of a heat recovery system results in increased consumption with underfloor heating and decreased consumption with radiator heating. The measure that achieves the highest savings during the heating season leads to a 24.41% increase in consumption during the cooling season, while the maximum savings for the cooling season are achieved with measure 12 (54.90%). Based on primary energy consumption (Table 2), determined using Serbia's conversion factors (2.5 for electricity and 1.1 for natural gas), Measure 13 proves to be the most favorable option [4]. Finally, based on the electricity consumption for the operation of the analyzed systems, the dimensioning of the PV system was carried out for four different scenarios (Measures 10–13). The system size is 18 PV panels for cases with radiator heating and 23 PV panels for cases with underfloor heating.

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