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EXERGY ANALYSIS OF RETROFITTING MEASURES FOR ENERGY EFFICIENCY IN PRIMARY EDUCATION BUILDINGS: A CASE STUDY OF NIŠ, SERBIA

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Abstract. *This study explores the intricate relationship between exergy and key building parameters such as windows, insulation, and lighting, emphasizing their impact on energy efficiency and sustainability. Exergy indicates the quality of an energy source, representing a certain quantity of energy in a system for performing maximum amount of work. It is a critical metric for evaluating building performance. By analyzing the interaction between elements' design and performance characteristics, the research highlights how effective insulation reduces heat loss, how strategically designed windows optimize natural light while minimizing heat gain, and how advanced lighting technologies improve energy efficiency. Furthermore, the study examines the integration of heat pump systems into heating configurations. Results indicate that while using a radiator and underfloor heating systems yields nearly identical performance, the system with a heat pump and underfloor heating demonstrates superior performance, offering better exergy efficiency. These findings provide a framework for optimizing building performance, promoting sustainable energy practices, and reducing environmental impact. The case study was conducted for a school in a rural area of Niš that underwent renovation.*

Key words: *Exergy Analysis, Insulation, Demand of Energy, Sustainability Index*

1. INTRODUCTION

Global climate change and the growing energy demand, especially for commercial and residential heating and cooling, are key factors in achieving the global goal of reaching nearly zero-energy buildings (nZEB). Exergy, closely related to energy quality, is often analyzed with energy balance to achieve more efficient energy use. The construction sector

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offers significant potential for reducing exergy losses. Buildings typically require low-quality energy for their thermal needs at low temperatures, while their energy demand is often met with high-quality energy sources. The analysis of exergy in air conditioning systems based on renewable energy sources has become an important area of research, which includes various, often contradictory approaches.

Observing exergy efficiency plays a crucial role in achieving energy-efficient buildings and nZEBs, as confirmed by numerous studies. Different methodologies for defining the reference environment significantly affect the exergy analysis results, especially in air conditioning systems. The lack of consensus on the reference state or external air humidity can lead to inaccurate results, particularly in hot and humid climates. Moreover, disagreements in selecting boundaries for exergy analysis can impact the results of solar and energy systems. Therefore, a holistic approach to system optimization is recommended, along with more precise definitions of exergy efficiency and integrating exergy analysis with energy analysis for a better understanding of system performance [1].

Baniasadi's study shows that integrated systems can efficiently meet buildings' energy and water needs while optimizing cost-effectiveness and exergy efficiency [2]. The LUCIA building study in Spain shows that including exergy indicators enables more precise efficiency analysis, improving the adaptation of energy sources to the building's requirements and reducing CO_2 emissions [3]. The methodology for buildings with net zero exergy integrates various sustainability parameters and helps understand the long-term sustainability of systems, such as using PV panels in Beijing [4].

Liu's work investigates a hybrid energy system combining the gasification of torrefied biomass and solar collectors. The exergy analysis reveals the significant role of biomass gasifiers in the total exergy loss, while the economic analysis shows an investment return period of 2.89 years [5]. Fohaguo's study demonstrates that combining economic and ecological analysis based on exergy losses yields optimal results for optimizing the insulation thickness of exterior walls [6].

In his review of building retrofitting toward net zero energy consumption (NZEC), Ibrahim examines two approaches: multi-criteria analysis and optimization, as well as dynamic and quasi-static methodological modeling approaches. It was found that most researchers prefer dynamic methods due to their accuracy. Also, optimization is mainly based on dynamic methods. Analyses show that the Application of PV systems is a key part of the strategy for achieving NZEB, and passive measures, such as improving the U-value of the building, significantly reduce energy consumption, especially in warmer climates. Residential NZEB buildings have the lowest energy consumption compared to educational and commercial buildings. It is suggested that methods for optimal retrofitting choices be developed, uncertainties in input parameters and future climate change are considered, and rooftop plants are integrated [7].

Hepbasli presents LowEx systems that use lower-value energy from sustainable sources, such as heat pumps and solar collectors. Research shows that the energy efficiency of these systems ranges from 0.40% to 25.3% for buildings, while greenhouses are more efficient. The focus is on heating buildings, and a tool for exergy analysis has been developed to help optimize systems. LowEx technologies reduce exergy demand and CO_2 emissions, making them key to sustainable construction in the future. It is suggested that future buildings use lower-value energy with the development of low-temperature heating and high-temperature cooling systems and the introduction of LEExED systems for sustainability assessment [8].

Ranđelović's paper provides an overview of possible renovations and cost-effectiveness specifically for primary education buildings in Serbia, where some of the criteria for improving the envelope and reducing environmental impact will also appear in this research. This paper reviews energy efficiency, carbon dioxide emissions, and ROI [9].

2. MODEL

2.1 Description

This paper focuses on a primary education building in Belotince, near Niš, representing a structure in a rural area. The basic model was created in Google SketchUp and is presented in Fig. 1, which illustrates the layout and dimensions of the building. Energy needs were obtained from simulations in EnergyPlus, where the design day for the winter period was analyzed, precisely when energy is used for heating. The reason for focusing on the heating period is that most educational buildings in Serbia still only use heating systems, especially in rural areas, so the study does not focus on the cooling period. The total area of the building is 774.07 m². The net total conditioned area is 688.71 m².

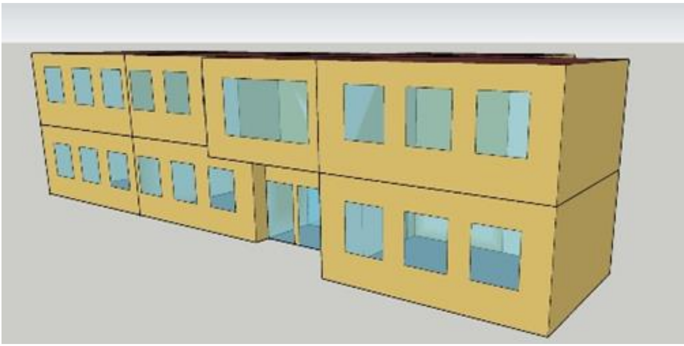

Fig. 1 Model in Google SketchUp

The simulation was conducted for climate conditions characteristic of the Niš area, a moderately continental climate region, which includes winter climate conditions with a minimum temperature of -14.5°C and a barometric pressure of 0.9892 bar. Summer climate conditions are less relevant to this study since the school does not have cooling systems.
The calculation for combinations of multiple retrofitting measures includes the base model, which has 10 cm of insulation on the building envelope and glazing (B1, A1), lighting (C1) with a 40 W lighting load per unit area of the building, radiator heating system (D1), and (E1) with boiler-biomass as heat source. This is the most common case in many retrofitted buildings in Serbia, as most buildings before retrofitting were without insulation and used coal boilers.

2.2 Exergy analysis

Initially, simulations were performed for the combinations of retrofitting measures, and the results for energy demand in the building were obtained. In the following section, the equations for the exergy load rate and exergy demand rate, which relate to energy systems both from the perspective of energy production and energy distribution, will be discussed. Both parameters – exergy load rate and exergy demand rate – provide a detailed insight into the energy dynamics of the system, considering not only the amount of energy required for operation but also the quality of energy used in production and distribution.

For the energy source in the primary energy transformation, the given parameters are F_P and Fq,s, representing the energy source's primary energy and quality factors, respectively. While F_R is the fraction factor for the environment.

In the following, the used calculation approach (Eq. 1-32) is based on the method developed by Schmidt [10].

The thermal efficiency of the distribution system is calculated by:

$$\eta_{dis} = 0.98 \cdot f_{HPP} \cdot f_{ins} \cdot f_{dt} \cdot f_{td} \tag{1}$$

The auxiliary energy factor $p_{aux,dis}$ can be obtained from:

$$p_{aux,dis} = \frac{\Delta p \cdot \dot{v}}{\eta_{circ}} \tag{2}$$

The pressure drop Δp, in the distribution system, is calculated from:

$$\Delta p = (1 + N) \cdot R \cdot I_{max} \cdot A_N + p_{ex} \tag{3}$$

Based on the temperature difference in the distribution system ΔT_{dis}, the average volumetric flow $\dot{v}$, at design conditions, is calculated:

$$\dot{v} = \frac{1}{1.163 \cdot \Delta T_{dis} \cdot 0.0036} \tag{4}$$

For the quality factor of the indoor air $F_{q,air}$ is calculated by:

$$F_{q,air} = 1 - \frac{T_0}{T_i} \tag{5}$$

The exergy load rate can be given by:

$$\dot{E}x_{air} = F_{q,air} \cdot \dot{Q}_h \tag{6}$$

The surface temperature of the radiator, T_{heat} is estimated using the logarithmic mean temperature of the carrier medium with the inlet, T_{in}, and return temperature, T_{ret} of the heating system:

$$T_{heat} = \frac{T_{in} - T_{ret}}{\ln((T_{in} - T_i) - (T_{ret} - T_i))} \cdot \frac{1}{2} + T_i \tag{7}$$

Using the above-given temperature, a new quality factor at the heater surface can be calculated from:

$$F_{q,heat} = 1 - \frac{T_{ref}}{T`_{heat}} \tag{8}$$

$$T`_{heat} = T_{heat} + 273.15\ K \tag{9}$$

The exergy load rate at the heater is:

$$\dot{E}x_{heat} = F_{q,heat} \cdot \dot{Q}_h \tag{10}$$

Since the energy efficiency of the distribution system (η_E) is not 100%, an energy load calculation first must be performed, and the heat loss rates have to be calculated as follows:

$$\dot{Q}_{loss,HS} = \dot{Q}_h \cdot \left(\frac{1}{\eta_{HS}} - 1\right) \quad (11)$$

The heating system is a subsystem of the distribution system. By keeping the derivation of the exergy demand rate of the heating system as calculated from [10]:

$$\Delta\dot{E}x_{HS} = \frac{\dot{Q}_h + \dot{Q}_{loss,HS}}{T_{in} - T_{ret}} \cdot \left\{(T_{in} - T_{ret}) - T_{ref} \ln\left(\frac{T_{in}}{T_{ret}}\right)\right\} \quad (12)$$

Thus, the exergy load rate of the heating system results in:

$$\dot{E}x_{HS} = \dot{E}x_{heat} + \Delta\dot{E}x_{HS} \quad (13)$$

The heat loss rate of the distribution system becomes:

$$\dot{Q}_{loss,HS} = \left(\dot{Q}_h + \dot{Q}_{loss,HS}\right)\left(\frac{1}{\eta_{dis}} - 1\right) \quad (14)$$

The demand for auxiliary energy or electricity in the distribution system is calculated:

$$P_{aux,dis} = p_{aux,dis}\left(\dot{Q}_h + \dot{Q}_{loss,HS}\right) \quad (15)$$

The exergy demand rate of the distribution system is given:

$$\Delta\dot{E}x_{dis} = \frac{\dot{Q}_{loss,dis}}{\Delta T_{dis}}\left\{T_{dis} - T_{ref} \ln\left(\frac{T_{dis}}{T_{dis} - \Delta T_{dis}}\right)\right\} \quad (16)$$

Thus, the exergy load rate of the distribution system results in:

$$\dot{E}x_{dis} = \dot{E}x_{HS} + \Delta\dot{E}x_{dis} \quad (17)$$

The required energy to be covered by the heat production is:

$$\dot{Q}_{HP} = \left(\dot{Q}_h + \dot{Q}_{loss,HS} + \dot{Q}_{loss,dis}\right)(1 - F_S)\frac{1}{\eta_{HP}} \quad (18)$$

The demand rate on auxiliary energy of the heat production system to drive pumps and fans can be calculated by:

$$P_{aux,HP} = p_{aux,HP}\left(\dot{Q}_h + \dot{Q}_{loss,HS} + \dot{Q}_{loss,dis}\right) \quad (19)$$

The exergy load rate of the heat production is calculated by:

$$\dot{E}x_{HP} = F_{q,S} \cdot \dot{Q}_{HP} \quad (20)$$

The production of domestic hot water (DHW) is calculated in a similar way as the heat production system for heating. The DHW energy demand is estimated according to the considered system and the number of occupants:

$$P_W = \frac{V_W \cdot \rho C_p \cdot \Delta T_{DHW} \cdot no_0}{\eta_{DHW}} \quad (21)$$

As the second step, the exergy load rate of other building service appliances, such as lighting and ventilation, are taken into consideration and, in this case, named plant:

$$\dot{E}x_{plant} = F_{q,el} \cdot (P_l + P_V) \quad (22)$$

The building's overall energy and exergy load rates are expressed in the required primary energy and exergy input rates. For the fossil or non-renewable part of the primary energy, the result becomes:

$$\dot{E}_{p,tot} = \dot{Q}_{HP} \cdot F_p \cdot \left(P_l + P_V + P_{aux,HP} + P_{aux,dis} + P_{aux,HS}\right) \cdot F_{p,el} + P_W \cdot F_{DHW} \quad (23)$$

Suppose the heat production system utilizes a renewable energy source or extracts heat from the environment, as heat pumps or solar collectors do. In that case, the additional renewable energy load rate is estimated by:

$$\dot{E}_R = \dot{Q}_{HP} \cdot F_R + \dot{E}_{env} \quad (24)$$

The total exergy load rate of the building becomes:

$$\dot{E}x_{tot} = \dot{Q}_{HP} \cdot F_p \cdot F_{q,s} + \left(P_l + P_V + P_{aux,HP} + P_{aux,dis} + P_{aux,HS}\right) \cdot F_{p,el} + \dot{E}_R \cdot F_{q,R} + P_W \cdot F_{DHW} \cdot F_{q,s,DHW} \quad (25)$$

2.3 Key parameters

These key parameters can be used to rank specific values, compare buildings and their efficiency and quality of exergy utilization, and evaluate the success of exergy optimization [10], as given below.
The total energy input rate per area:

$$\dot{E}"_{tot,pa} = \frac{\dot{E}_{tot}}{A_N} \left(\frac{W}{m^2}\right) \quad (26)$$

The total energy input rate per volume:

$$\dot{E}"_{tot,pv} = \frac{\dot{E}_{tot}}{V_N} \left(\frac{W}{m^3}\right) \quad (27)$$

The total exergy input rate per area:

$$\dot{E}x"_{tot,pa} = \frac{\dot{E}x_{tot}}{A_N} \left(\frac{W}{m^2}\right) \quad (28)$$

The total exergy input rate per volume:

$$\dot{E}x"_{tot,pv} = \frac{\dot{E}x_{tot}}{V_N} \left(\frac{W}{m^3}\right) \quad (29)$$

The total energy efficiency of the system, η_{sys} (%), is expressed as follows:

$$\eta_{sys} = \frac{\dot{E}_{building}}{\dot{E}_{tot}} \quad (30)$$

The total exergy efficiency of the system, ψ_{sys} (%), is expressed as follows:

$$\psi_{sys} = \frac{\dot{E}x_{building}}{\dot{E}x_{tot}} \quad (31)$$

The exergy flexibility factor, F_{flex} it is calculated by:

$$F_{flex} = \frac{\dot{E}x_{HS}}{\dot{E}x_{tot}} \quad (32)$$

In addition to the energy and exergy efficiencies given above, other parameters can be used for comparison purposes, namely the sustainability index, energetic renewability ratio, and exegetic renewability ratio. Exergy efficiency may be a more important indicator than energy efficiency, as it typically provides a deeper understanding of performance [11]. Higher exergy efficiency indicates better energy quality within a system, which enhances sustainability. Conversely, lower exergy efficiencies signify energy losses and irreversible internal reactions, therefore lower energy quality and a reduced sustainability score. Sustainability index (SI) shows how sustainability is affected by changing the exergy efficiency of a process [12]:

$$SI = \frac{1}{1-\psi} \tag{33}$$

3. VALUES OF PARAMETERS

Table 1. Building envelope

	1		2		3		
A	U (W/m^2K)	SHGC	U (W/m^2K)	SHGC	U (W/m^2K)	SHGC	**Windows**
	1.5	0.61	1.3	0.61	1.3	0.36	
B	1		2		3		**External wall and roof**
	U (W/m^2K)		U (W/m^2K)		U (W/m^2K)		
	0.3		0.217		0.17		

Table 1 provides an overview of the combinations of envelope retrofitting applied to the building, in terms of glazing (A), where U represents the heat transfer coefficient, SHGC refers to the solar heat gain coefficient, and the heat transfer coefficient for the exterior walls and roof (B), listed by the combinations of retrofitting.

Table 2. The light

	1	2	3	4	
C	P (W/m^2)	P (W/m^2)	P (W/m^2)	P (W/m^2)	**Light**
	40	25	12	6	

Table 2 presents an overview of the lighting used by combinations, including the minimum allowed illumination for classrooms of 500 lm/m^2. The types of lighting are listed as follows: classic light bulb, halogen, fluorescent, and LED. Table 3 presents systems for heat energy distribution, where the combinations most commonly applied in buildings in Serbia are considered. Table 4 presents the values of f parameters. The heat loss values for various building parameters are depicted in Fig. 2.

Table 3. The heating

	1	2	**The heating system in the building**
D	Radiators	Floor heating	
E	1	2	

	Boiler-Biomass	Heat pump	**The heating energy source for the system**

Table 4. Values of f parameters [10]

	Criteria	Parameter f
Position of the heat production system f_{HPP}	Inside envelope	1
	Outside envelope	0.9
Insulation f_{ins}	No insulation	0.7
	Bad insulation	0.9
	Good insulation	1
Mean design temperature f_{dt}	Low (<35°C)	1
	Middle (35°C <f_{dt}<50°C)	0.95
	High (>50°C)	0.9
Design temperature drop f_{td}	Low (<5K)	0.98
	Middle (5K<f_{td}<10K)	0.99
	High (>10K)	1

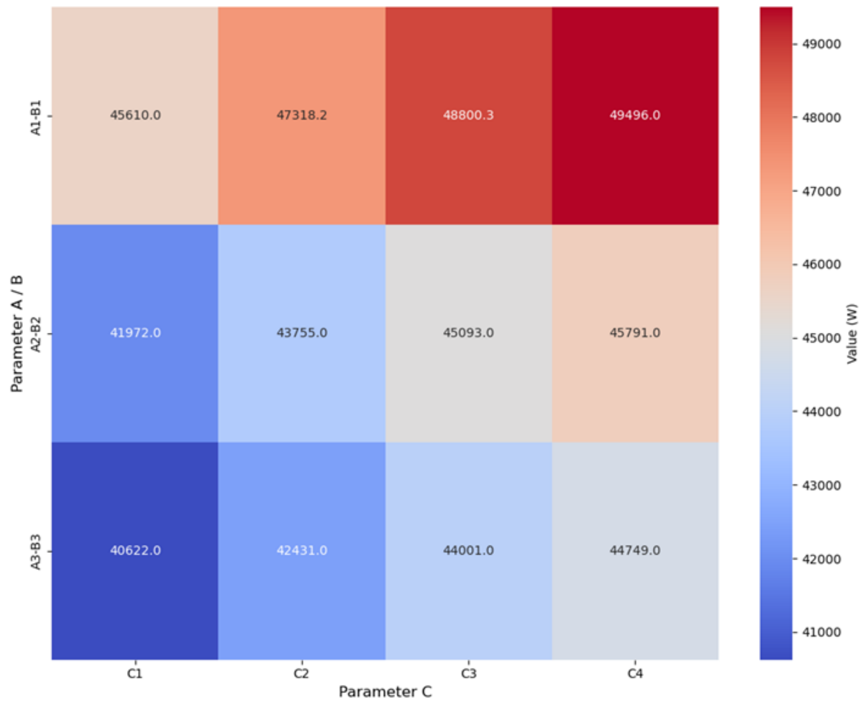

Fig. 2. Heat loss values for building parameters

Some of the necessary data for this study are parameters related to the heat production system. The basic parameters for the biomass boiler are the efficiency of the heat production system. $\eta_{HP} = 0.65$, the primary energy factor of the source $F_P = 0.1$, the quality factor of the source $F_{q,s} = 0.95$, the maximum supply temperature $T_{s,max} = 70°C$ and the auxiliary energy $p_{aux,HP} = 1.8 \frac{W}{kWh_{heat}}$.

The data for the heat pump are the efficiency of the heat production system and the coefficient of performance $COP = 2.5$, the primary energy factor of the source. $F_P = 3$, the quality factor of the source $F_{q,s} = 1$, the maximum supply temperature $T_{s,max} = 80°C$ and the auxiliary energy $p_{aux,HP} = 2 \frac{W}{kWh_{heat}}$.

Some of the data for DHW energy demand for the biomass boiler are the efficiency of DHW. $\eta_{DHW} = 2.15$, the primary energy factor of the source $F_{P,DHW} = 0.1$, the quality factor of the source $F_{P,DHW} = 0.95$. For the heat pump, the DHW efficiency is $\eta_{DHW} = 0.6$, the primary energy factor of the source $F_{P,DHW} = 3$ and the quality factor of the source $F_{P,DHW} = 1$ [11].

4. RESULTS AND DISCUSSION

The following results, as shown in Table 5, were obtained using calculation software (Excel). The results of this study provide a detailed insight into the energy and exergy performance of various heating systems, analyzing their efficiencies, exergy destruction, and sustainability in different configurations.

The energy efficiency analysis (η_{sys}) showed that the CS34 system has the highest efficiency of 10.9%, making it the leader. Additionally, the CS31 (10.7%) and CS28 (10.4%) systems follow closely behind, while the lowest efficiency values were recorded for systems with more traditional configurations, such as CS15 and CS16.

Systems with underfloor heating and heat pumps generally show higher efficiency compared to combinations that include radiators. This can be attributed to the more even heat distribution and the lower temperature range required for underfloor heating.

The exergy analysis indicated similar trends. The CS34 system also achieved the highest exergy efficiency (ψ_{sys}) of 38.1%, while the CS31 (37.6%) and CS46 (36.9%) systems showed competitive performance.

It is significant to note that systems with higher energy efficiency also record higher exergy efficiency, which indicates a reduction in irreversible processes within the system. On the other hand, systems with lower values of ψ_{sys} are characterized by increased exergy destruction ($\dot{E}x_{dest}$). Exergy destruction was significantly lower in the best systems. For example, CS34 achieved an exergy destruction of value, the lowest among the analyzed systems. This indicates greater sustainability and fewer thermodynamic irreversibilities in this system. In comparison, systems such as CS20 and CS15 showed higher values of exergy destruction, reflecting lower overall efficiency.

Table 5. Review of Calculation for Key Parameters

Cases						η_{SYS} (%)	ψ_{SYS} (%)	$\dot{E}x_{dest}$ (kW)	$\dot{E}"_{tot,pa}$ (W/m^2)	$\dot{E}"_{tot,pv}$ (W/m^3)	F_{flex}	SI
A1	B1	C1	D1	E1	CS1	9.5	29.1	400.1	751.0	172.6	0.376	1.41
A2	B2	C1	D1	E1	CS2	8.8	26.9	410.7	747.7	171.9	0.348	1.37
A3	B3	C1	D1	E1	CS3	8.5	26.1	414.7	746.5	171.6	0.337	1.35
A1	B1	C2	D1	E1	CS4	9.9	30.2	393.9	751.0	172.6	0.39	1.43
A2	B2	C2	D1	E1	CS5	9.2	28.1	404.3	747.8	171.9	0.36	1.39
A3	B3	C2	D1	E1	CS6	8.9	27.3	408.2	746.6	171.6	0.352	1.37
A1	B1	C3	D1	E1	CS7	10.2	31.2	388.6	751.0	172.6	0.403	1.45
A2	B2	C3	D1	E1	CS8	9.5	28.9	399.4	747.7	171.9	0.374	1.41
A3	B3	C3	D1	E1	CS9	9.2	28.3	402.6	746.7	171.6	0.365	1.39
A1	B1	C4	D1	E1	CS10	10.3	31.6	386.1	751.0	172.6	0.408	1.46
A2	B2	C4	D1	E1	CS11	9.6	29.4	396.9	747.7	171.9	0.379	1.42
A3	B3	C4	D1	E1	CS12	9.4	28.8	400.0	746.8	171.6	0.371	1.4
A1	B1	C1	D2	E1	CS13	8.5	32.1	452.6	882.5	202.8	0.393	1.47
A2	B2	C1	D2	E1	CS14	7.8	29.5	470.0	882.8	202.9	0.361	1.42
A3	B3	C1	D2	E1	CS15	7.6	28.6	475.4	881.7	202.6	0.35	1.4
A1	B1	C2	D2	E1	CS16	8.78	33.2	447.2	885.9	203.6	0.406	1.5
A2	B2	C2	D2	E1	CS17	8.15	30.8	461.6	882.8	202.9	0.376	1.44
A3	B3	C2	D2	E1	CS18	7.9	29.9	467.0	881.7	202.7	0.365	1.43
A1	B1	C3	D2	E1	CS19	9	34.2	440.2	885.8	203.6	0.418	1.52
A2	B2	C3	D2	E1	CS20	8.4	31.7	455.2	882.7	202.9	0.388	1.46
A3	B3	C3	D2	E1	CS21	8.2	31	459.6	881.7	202.7	0.379	1.45
A1	B1	C4	D2	E1	CS22	9.2	34.7	436.9	885.8	203.6	0.425	1.53
A2	B2	C4	D2	E1	CS23	8.5	32.2	451.9	882.7	202.9	0.394	1.48
A3	B3	C4	D2	E1	CS24	8.3	31.5	456.1	881.8	202.7	0.386	1.46
A1	B1	C1	D1	E2	CS25	10	35.1	347.4	713.1	163.9	0.44	1.54
A2	B2	C1	D1	E2	CS26	9.3	32.4	360.4	710.6	163.3	0.41	1.48
A3	B3	C1	D1	E2	CS27	9	31.4	365.3	709.6	163.1	0.394	1.46
A1	B1	C2	D1	E2	CS28	10.4	36.4	340.1	712.8	163.8	0.457	1.57
A2	B2	C2	D1	E2	CS29	9.7	33.8	352.9	710.3	163.3	0.424	1.51
A3	B3	C2	D1	E2	CS30	9.4	32.8	357.6	709.4	163.1	0.412	1.49
A1	B1	C3	D1	E2	CS31	10.7	37.6	333.8	712.5	163.8	0.472	1.6
A2	B2	C3	D1	E2	CS32	10	34.9	347.1	710.0	163.2	0.437	1.54
A3	B3	C3	D1	E2	CS33	9.7	34	351.0	709.2	163.0	0.427	1.52
A1	B1	C4	D1	E2	CS34	10.9	38.1	330.8	712.4	163.8	0.479	1.62
A2	B2	C4	D1	E2	CS35	10.1	35.4	344.1	709.8	163.2	0.444	1.55
A3	B3	C4	D1	E2	CS36	9.9	34.6	347.9	709.1	163.0	0.435	1.53
A1	B1	C1	D2	E2	CS37	9	34	415.5	834.0	191.7	0.416	1.52
A2	B2	C1	D2	E2	CS38	8.3	31.4	430.8	831.6	191.1	0.384	1.46
A3	B3	C1	D2	E2	CS39	8	30.4	436.4	830.8	190.9	0.372	1.44
A1	B1	C2	D2	E2	CS40	9.3	35.3	407.2	833.6	191.6	0.432	1.54
A2	B2	C2	D2	E2	CS41	8.7	32.7	422.1	831.3	191.1	0.4	1.49
A3	B3	C2	D2	E2	CS42	8.4	31.7	427.7	830.4	190.9	0.389	1.46
A1	B1	C3	D2	E2	CS43	9.6	36.4	400.0	833.2	191.5	0.445	1.57
A2	B2	C3	D2	E2	CS44	8.9	33.7	415.5	830.8	191.0	0.413	1.51
A3	B3	C3	D2	E2	CS45	8.7	32.9	420.1	830.1	190.8	0.403	1.49
A1	B1	C4	D2	E2	CS46	9.8	36.9	396.6	833.1	191.5	0.452	1.58
A2	B2	C4	D2	E2	CS47	9.1	34.2	412.1	830.7	190.9	0.419	1.52
A3	B3	C4	D2	E2	CS48	8.9	33.5	416.5	830.0	190.8	0.41	1.5

The Sustainability Index (SI) values for various configurations are illustrated in Fig. 3, highlighting the performance differences between systems. Additionally, the energy and exergy efficiency for combinations A1/B1, A2/B2, and A3/B3 are reviewed in Figs. 4, 5, and 6, respectively. Fig. 7 presents the total exergy input rate per area.

The Sustainability Index (SI) further confirms the superiority of systems such as CS34, which has an SI value of 1.62, the highest among the analyzed systems. This is directly linked to its high-efficiency values and low exergy destruction. Other highly ranked systems, such as CS31 and CS46, also have SI values above 1.5, making them suitable for practical application in energy-efficient buildings.

The results show that combinations of heat pump systems with underfloor heating are the most sustainable choice for modern applications due to their high energy and exergy efficiency values. On the other hand, systems with radiators show lower performance due to higher temperature differences and increased exergy destruction.

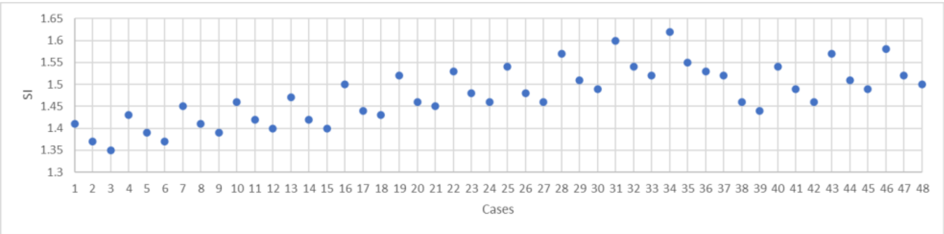

Fig. 3 SI index for cases

Radiator systems with boilers (CS1–CS12) have SI values between 1.37 and 1.47, indicating lower sustainability. This is due to high irreversibilities and significant energy losses. Underfloor heating with a boiler (CS13–CS24) improves sustainability with SI values ranging from 1.46 to 1.54. This is due to the reduction in exergy destruction. Radiator systems with heat pumps (CS25–CS36) show higher SI values than boilers, ranging from 1.46 to 1.55, thanks to better environmental energy utilization. Underfloor heating with heat pumps (CS37–CS48) achieves the highest SI values (1.52 to 1.56), confirming this is the most sustainable configuration.

In radiator heating systems (CS1–CS12), ψ_{sys} ranges between 26.9% and 32.1%. These results indicate significant exergy losses in the system due to the high-temperature differences between the heat source (boiler) and the heated space.

In underfloor heating systems (CS13–CS24), ψ_{sys} is slightly improved (30.2% to 35.1%). This results from the lower operating temperatures of underfloor heating, which reduce thermodynamic irreversibilities.

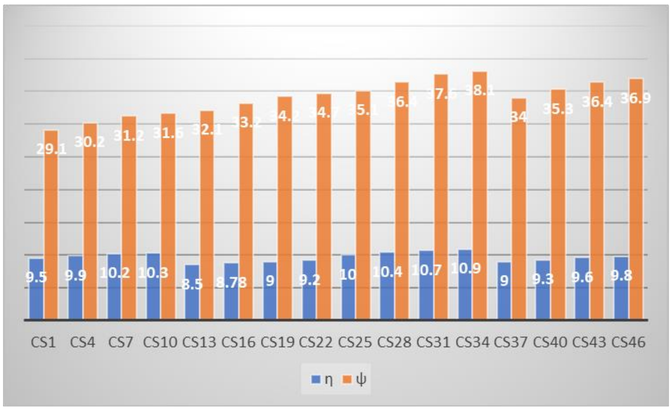

Fig. 4 Review energy and exergy efficiency for parameters A1/B1

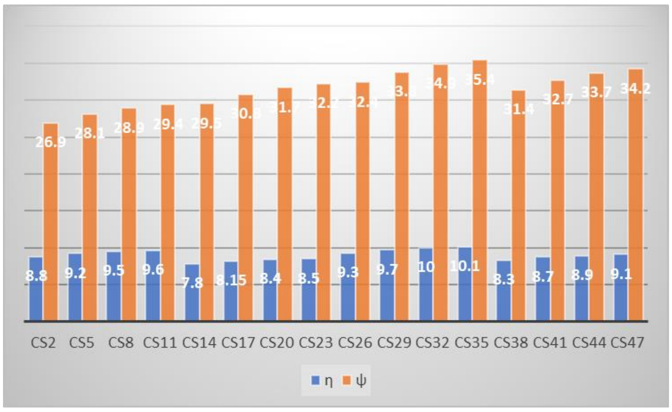

Fig. 5 Review energy and exergy efficiency for parameters A2/B2

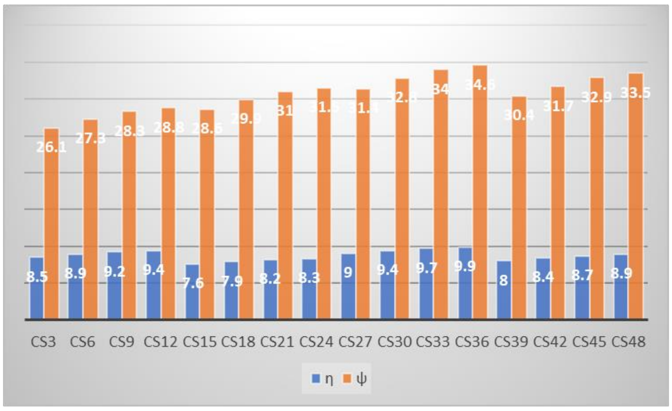

Fig. 6 Review energy and exergy efficiency for parameters A3/B3

Heat pump systems:

In radiator systems (CS25–CS36), ψ_{sys} is higher than boiler systems, ranging from 31.2% to 36.4%. This is due to the greater degree of exergy return from the environment, characteristic of heat pumps.

In underfloor heating systems (CS37–CS48), ψ_{sys} reaches the highest values, from 32.7% to 36.4%. The combination of low-temperature heating and heat pump efficiency leads to optimal results.

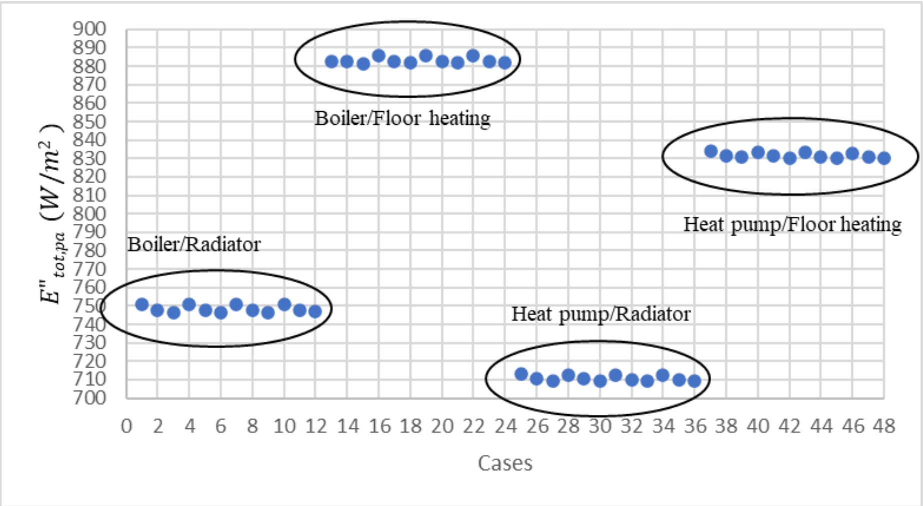

Fig. 7 The total exergy input rate per area

5. Conclusion

Based on the results, the CS34 system represents the optimal choice for application in buildings with high energy and exergy efficiency requirements. Combining the highest energy efficiency (10.9%) and the lowest exergy destruction confirms its superiority. Other systems with similar characteristics, such as CS31 and CS46, also stand out as competitive options with high sustainability (SI > 1.5).

For future analyses, additional factors such as implementation costs, maintenance, and environmental impact assessments could be included to provide a comprehensive overview of the system's suitability. Furthermore, further research could focus on applying low-temperature technologies and integrating renewable energy sources for even better efficiency and sustainability. Additionally, the analysis shows that system optimization can significantly reduce exergy destruction, increasing efficiency and sustainability. The key focus for future development should be reducing thermodynamic irreversibilities through better system design and integration.

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REFERENCES

1. Torıo, H., Angelotti A., Schmidt, D., 2009, *Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view*, Energy and Buildings Vol. 41 pp. 248–271.
2. Baniasadi, E., Ziaei-Rad, M., Behvand, M. A., Javani, N., 2023, *Exergy-economic analysis of a solar-geothermal combined cooling, heating, power and water generation system for a zero-energy building*. International Journal of Hydrogen Energy Vol. 48.
3. Rey-Hernandez, J. M., Rey-Martínez, F. J., Sala-Lizarraga J. M., Picallo-Perez, A., 2024, *Innovative exergy indicators for analyzing an nZEB building to promote new areas of improvement*, Sustainable Energy Technologies and Assessments Vol. 69.
4. Açikkalp, E., Hepbasli, A., Palmero-Marrero, A. I., Borge-Diez, D., 2023, *Application of net zero extended exergy buildings concept for sustainable buildings analysis*. Journal of Building Engineering Vol. 68.
5. Liu, Y., Bi, D., Yin, M., Zhang, K., Liu, H., Liu, S., 2024, *Modeling and exergy-economy analysis of residential building energy supply systems combining torrefied biomass gasification and solar energy*. Thermal Science and Engineering Progress Vol. 50.
6. Fohagui, F. C. V., Yemeli Wenceslas Kohol, Y. W., Njimboh Henry Alombah, N. H., Asoh, D. A., Tchuen, G., 2024, *Optimum insulation thickness and exergy savings of building walls in Bamenda: a comparative analysis*. Energy Storage and Saving Vol. 3 pp. 60–70.
7. Ibrahim, M., Harkouss, F., Biwole, P., Fardoun, F., Ouldboukhitine, S., 2024, *Building retrofitting towards net zero energy: A review*. Energy & Buildings Vol. 322.
8. Hepbasli, A., 2012, *Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies*, Renewable and Sustainable Energy Reviews Vol. 16 pp. 73– 104.
9. Randelović, D., Jovanović, V., Ignjatović, M., Marchwinski, J., Kopyłow, O., Milošević, V., 2024, *Improving Energy Efficiency of School Buildings: A Case Study of Thermal Insulation and Window Replacement Using Cost-Benefit Analysis and Energy Simulations*. Energies Vol. 17, Issue 23.
10. Schmidt, D., 2004, *Design of low exergy buildings e method and pre-design tool*, The International Journal of Low Energy and Sustainable Buildings, Vol. 3, pp. 1-47.
11. Dincer, I., Abu-Rayash, A. 2020, *Chapter 6 - Sustainability modeling*, Energy Sustainability, Academic Press, pp. 119-164
12. Balta, M. T., Dincer, I., Hepbasli, A., 2011, *Development of sustainable energy options for buildings in a sustainable society*, Sustainable Cities and Society Vol. 1, pp. 72– 80.