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Implementation of a Novel Bioclimatic-Passive Architecture Concept in Serbian and Polish Residential Building Sectors

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Abstract

This paper presents a novel integration of bioclimatic-passive architectural elements—Trombe walls, pergolas, and deciduous climbers—in the context of residential buildings in Eastern and Central Europe, a combination that remains largely underexplored in the current literature. The innovativeness of the proposed concept is reflected in the combined use of the following building elements: three types of passive Trombe wall (single-glazed, double-glazed, and triple-glazed), pergolas, and four types of deciduous climbers (*V. coignetiae*, *H. lupulus*, *W. sinensis*, and *A. macrophylla*). By using meteorological data for the towns Kragujevac and Kielce, the influence of location parameters for two dominant European climate zones (moderate continental and continental) is also included in this investigation. The initial single-family building models were created following the Serbian and Polish rulebooks on energy efficiency for new buildings and equipped with the same thermo-technical systems and people occupancy conditions. Based on the conducted simulations (using Google SketchUp 8 and EnergyPlus 7.1) and obtained results on the annual level, the following main conclusions can be drawn: (1) a moderate continental climate is more suitable for implementing the proposed concept; (2) a single-glazed passive Trombe wall is not energy or environmentally justified; (3) the energy, environmental, and economic benefits for both selected locations are greatest in the case of the combined use of pergolas, *V. coignetiae*, and triple-glazed passive Trombe wall; and (4) before the wider commercial application of the proposed concept in the future, efforts should be made to explore economic opportunities, which, among other things, involve a focus on market stability and accessibility.

Keywords: continental climate; moderate continental climate; deciduous climbers; pergolas; simulation; Trombe wall

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1. Introduction

To bring the residential building sector (RBS) closer to the basic (primary) concept of sustainable development [1], the European scientific community intensively promotes auxiliary (secondary) concepts where buildings are treated as structures that need to meet the following criteria: (1) provide optimal (air, thermal, lighting, and sound) and comfortable conditions [2] for human occupancy, health, work, and functionality; (2) minimize final and primary energy consumption [3]; (3) reduce dependence on conventional energy sources [4]; (4) decrease greenhouse gas emissions [5]; (5) preserve the environment [6]; and (6) mitigate climate change [7].

All RBS concepts (basic and auxiliaries) represent a combination of multidisciplinary measures and strategies that include: (1) location choice; (2) building form factor; (3) thermal envelope structure and design; (4) internal project temperature; and (5) smart thermotechnical systems (space heating, space cooling, ventilation, air conditioning, heat recovery, lighting, electric equipment, water heating, etc.), renewable energy sources (RESs), and mandatory responsible occupant behavior.

Experimental, numerical, and theoretical studies and investigations in the available literature indicate that passive RES measures and strategies, primarily those using solar and geothermal energy, are gaining increasing importance, including building orientation [8], room layout, sustainable materials [9], window–wall ratio, different soil layers [10], Trombe wall (TW), deciduous climbers, selective facade walls, phase change materials (PCMs), overhangs [11], blinds, pergolas, awnings, curtains, etc. They can significantly reduce final and primary energy consumption for space heating and cooling, and lower financial costs and greenhouse gas emissions.

An interesting massive construction element that is always oriented toward the equator [12], known as TW [13] and solar wall [14], is intended to indirectly accumulate solar energy [15] and transmit it to heated spaces (heating rooms or thermal zones, i.e., TZs) by convection and radiation [16]. In [17], the two basic types of TWs can be found: (1) active Trombe wall (ATW) and (2) passive Trombe wall (PTW). The first type, i.e., ATW, has dampers of various shapes, sizes, and purposes. Also, their number can vary from case to case. Depending on the purpose, dampers can be placed toward TZs [18] and the outside [19] to ensure air circulation. Air circulation provides better forced [20] or natural [21] convective heating (during the winter season) and cooling (during the summer season) of the TZs [22]. The second type, i.e., PTW, has neither external nor internal dampers [23], which means that the air mass is trapped between the glazed surface and the selectively coated massive wall. This variant is simpler and cheaper, but also less favorable due to the elimination of air circulation and convective heating.

Pergolas are shading building elements [24] because they are primarily intended for sun protection. Pergolas can be used for protection from rain and other weather conditions. Their aesthetic aspect is also important. The following table (Table 1) shows the different criteria for classifying pergolas used in practice.

Table 1. Different classification criteria and types of pergolas.

Classification Criteria	Types
Material	Wood, Aluminum, PVC, Wrought iron, Glass, and Recycled
Space position	Horizontal, Vertical, Inclined, and Criss/cross
Visibility	Open, Semi-open, and Closed
Profile shape	Rectangular, Square, Oval, Round, and Aero
Application area	External and Internal
Mobility	Mobile and Immobile
Building element	Wall, Roof, and Combined
Installation location	Terraces, Balconies, Gardens, and Cafes

Climbers [25] are plants used to decorate yards, pergolas, terraces, balconies, external walls (green facades [26]), etc. In some special circumstances, they are also used in internal spaces. The primary feature of climbers is their rapid growth, enabling them to achieve the desired spatial form in a relatively short period. Besides their decorative role (such as beautifying spaces, enhancing aesthetics, and providing privacy), they have significant energy potential that becomes evident during the summer [27]. Particularly interesting are deciduous climbers [28], which offer energy and environmental benefits throughout the year. The dense foliage and flowers create natural shade (bio-shading effects [29]) in the summer, reducing cooling energy needs.

1.1. Literature Review

Investigations of the passive solar systems, such as TW, in Serbia are primarily based on the application of mathematical and numerical methods. The following table (Table 2) presents their scientific contributions in chronological order. The situation in the Polish literature is somewhat better, due to the larger number of experimental papers (Table 3).

Table 2. Literature examples of the Trombe wall implemented in Serbian residential buildings.

Model Type	Model Description	TW Description	Main Results	Year	Source
Mathematical	Steady-state, One-dimensional	Double-glazing, Four operation modes	η = 57.19%	2009	[30]
				2011	[31]
Numerical	EnergyPlus, Weather file for Belgrade	Triple-glazing, Vertical position, Inclined position, Combined position	-, $e_{heat,fin}$ = 118.52 kWh/m^2, $e_{heat,fin}$ =106.77 kWh/m^2, $e_{heat,fin}$ =104.24 kWh/m^2	2013	[32]
Numerical	EnergyPlus, Weather file for Lion	"Mozart" house, Double-glazing with shade	$S_{heat,fin}$ = 20%, PB = 8 years	2014	[33]
Numerical	Ansys FLUENT, Three-dimensional, Weather file for Belgrade	Single-glazing, Five operation modes	t_{TZ} = 14.7 °C (in winter), t_{TZ} = 29.8 °C (in summer)	2015	[34]
Numerical	EnergyPlus, jEplus, Weather file for Niš	Thermal mass (three types), Convection (two types), Glazing (three types)	$S_{heat,fin}$ = 77%	2021	[35]
Numerical *	EnergyPlus, Weather file for Niš	Double-glazing, Green roof (three types)	$S_{heat,fin}$ = 3.4%	2022	[36]
Numerical	MATLAB 2022, One-dimensional	Thermal mass (three types), Insulation (two types)	There is no significant difference	2023	[37]
Numerical	EnergyPlus, Weather file for Kragujevac	Country cottage, Single-glazing	$S_{heat,fin}$ = 18.67%	2024	[38]

* Refers to the contribution of green roofs to reducing the final energy consumption for space cooling. Legend: η [-]—thermal efficiency, $e_{heat,fin}$ [kWh/m^2]—specific final energy consumption for space heating, $S_{heat,fin}$ [%]—percentage final energy savings for space heating, PB [years]—payback period, and t_{TZ} [°C]—internal temperature of the thermal zone.

Pergolas are an under-researched strategy in Serbian and Polish RBSs. Currently, there are few studies in the Polish literature on this topic, which are mainly analyzed from an architectural perspective: the Museum of King John III's Palace at Wilanów [46], a neo-Gothic chapel located in the Stradom district of Czestochowa [47], and the implementation of environmental architectural projects in the areas of historic urban spaces [48].

Table 3. Literature examples of the Trombe wall implemented in Polish residential buildings.

Model Type	Model Description	TW Description	Main Results	Year	Source
Theoretical	Review paper	Different modification	Implementation in Central Europe	2017	[39]
Numerical	Ansys FLUENT, Three-dimensional, Weather file for Wrocław	Optimization options (two types), Triple-glazing, Thermal mass (two types)	- t_{TZ} increases by 8.5 °C, t_{TZ} increases by 0.4 °C	2019	[40]
Experimental	Test chamber	Interactive glass wall	Heat gains higher than heat losses	2020	[41]
Theoretical	Review paper	Characteristic, Thermal performance, Simple case study	Implementation in different climate conditions	2021	[42]
Experimental, Numerical	Laboratory conditions, ADINA, Three-dimensional	PMC materials, Glazing (three types)	Minimum heat flux values are achieved after 16–18 h	2021	[43]
Theoretical	Review paper	Evolution from 1967 to 2022	-	2022	[44]
Experimental	Laboratory test	Thermo-Diode	η = 21.58–30.3%	2022	[45]

However, an experiment in the Transylvania region showed that properly dimensioned fixed pergolas can block up to 90% of incident summer solar radiation, while still allowing winter sunlight to pass through [49]. For instance, Indian buildings (with an emphasis on energy, environmental, and economic benefits that can be achieved by installing pergolas and various roof strategies) were the research subject in [50]. In [51], the specific engineering solution is presented that combines active (photovoltaic panels) and passive (pergolas) solar systems. The presented concept maximizes solar shading effects, natural ventilation, and electricity production, while ensuring sufficient daylight and without violating privacy. Verheijen et al. [52] utilized the roof pergolas to reduce thermal stress and improve temperature and visual comfort conditions. They opted for a simple and free-standing variant. Thermal and structural analyses have confirmed that, among passive solar systems, such building elements have great commercial potential.

The situation is somewhat better when it comes to the implementation of deciduous climbers in Serbian and Polish RBSs to achieve energy and environmental goals.

Dimitrijević-Jovanović et al. [53] presented a paper that investigates the correlations between the next adopted “nodes”: (1) building thermal envelope, (2) green (climatic) systems, and (3) the environment. Energy flows characteristic of public buildings located in the Balkan Peninsula (Serbia and Croatia), equipped with nature-based solutions, were investigated by Savić et al. in [54]. Jovanović et al. [55] considered various passive design strategies, including ventilated green facades, to increase building status (in energy efficiency terms). The main goal presented in [56] is the integration of buildings with green and sustainable energy efficiency practices.

On the other hand, a conceptual framework for the design of vertical green (and bioclimatic) facades was presented by Seyrek Şık et al. in [57]. Costa and James [58] concluded that vegetation offers the opportunity to create, at low cost, building service installations that make negligible noxious discharges to its surroundings. Mitigation of the overheating effects using greenery in Polish climate conditions was numerically investigated in [59]. A significant scientific contribution to the development of solar shading elements (pergolas, pavilions, tents, cables, and plants) as PSSs was made by Petschek and Gas in [60]. Finally, a mathematical model of the climbing vegetation was created in [61]. After laboratory validation, the model was tested in different European climate zones (monitoring energy and environmental parameters). The results showed that climbing foliage on facades does not behave in the same way in selected climate zones, which can significantly reduce techno-economic efficiency.

1.2. State-of-the-Art

Based on a review of the available literature, it was observed that Eastern and Southeastern Europe underutilize available climatic (meteorological) resources for energy purposes. The promotion and implementation of passive solar measures and strategies to achieve energy efficiency in buildings have not reached their full potential. In other words, these regions lag behind the leading global trends in this area.

To change this situation in the coming period, this paper focuses on a novel concept that combines different passive solar measures and strategies in the building sector. Namely, it has been noted that the bioclimatic-passive architecture concept, which combines passive Trombe walls, pergolas, and deciduous climbers, has not yet been investigated. This is precisely the scientific gap that this paper fills.

Since the passive Trombe wall is a type of heating building element, and pergolas and deciduous climbers are types of cooling building elements, a starting hypothesis is based on the claim that final and primary energy consumption, CO_2 emissions, and economic costs can be reduced on an annual level.

The energy, environmental, and economic aspects of the proposed building concept are intended for moderate continental and continental climate zones. Consequently, the study includes two locations (towns): Kragujevac (in the Serbian climate zone) and Kielce (in the Polish climate zone).

Complete numerical research was conducted following the current Serbian and Polish rulebooks on energy efficiency for new buildings. To ensure comparability of the results, both single-family buildings are equipped with the same thermo-technical systems and people occupancy.

Among other things, this paper aims to demonstrate that rather simple strategies, such as energy efficiency measures, can enhance the quality of life in the residential sector in terms of comfort, costs, and environmental attitude.

2. Materials and Methods

2.1. Building Model

The analyzed residential building (Figure 1) is intended to accommodate a family of four during the year. The total floor area and total volume of the single-family building are $A_{fl,tot}$ = 114.45 m^2 and V_{tot} = 297.57 m^3. The form factor is $f_{tot} = A_{tot}/V_{tot}$ = 302.06 m^2/ 297.57 m^3 = 1.02 1/m and the window–wall ratio is WW = 8.74%. The external door is located on the west side.

The arrangement of rooms is illustrated in Figure 2. On the first floor (ground floor, Figure 2a), there are the hall (H1), staircase (S), toilet (T), study room (SR), kitchen (K), and living room with dining room (LR). The second floor (Figure 2b) contains the bedrooms (BR1 and BR2), another hall (H2), and a bathroom (BT).

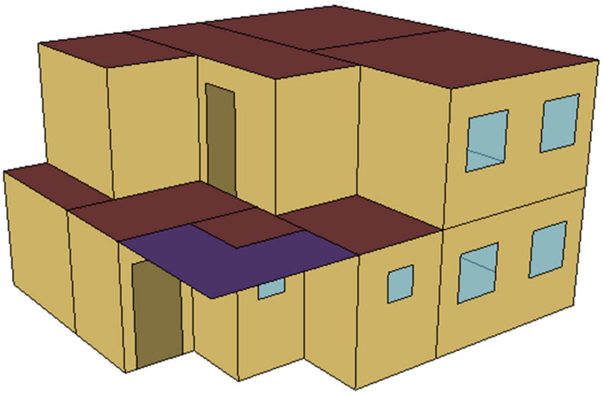

Figure 1. Isometric view of the analyzed building.

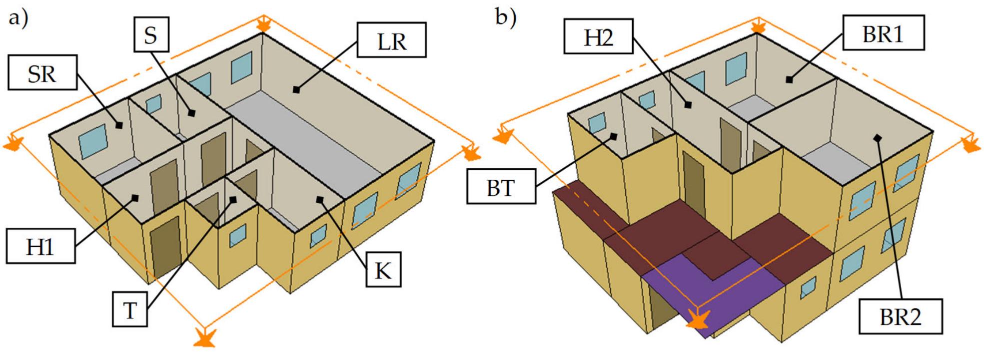

Figure 2. Horizontal cross-section view of the analyzed building and room layouts: (**a**) first floor and (**b**) second floor. Legend: BR1—bedroom 1, BR2—bedroom 2, BT—bathroom, H1—hall 1, H2—hall 2, K—kitchen, LR—living room, S—staircase, SR—study room, and T—toilet.

The heat transfer coefficients U [W/m^{2}K] of the thermal envelope (Figure 3) were adopted following the principles of the Serbian [62] (index SRB) and Polish [63] (index POL) rulebooks on energy efficiency for new buildings.

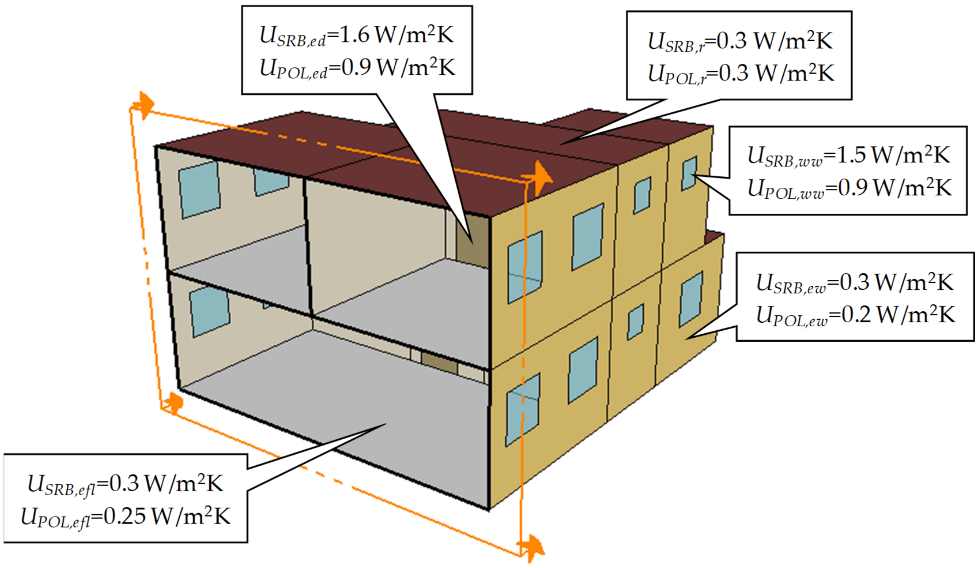

Figure 3. Vertical cross-section view of the analyzed building and thermal characteristics of the thermal envelope following the Serbian and Polish rulebooks. Legend: U_{ed} [W/m^{2}K]—heat transfer coefficient for the external door, U_{efl} [W/m^{2}K]—heat transfer coefficient for the external floor, U_{ew} [W/m^{2}K]—heat transfer coefficient for the external wall, U_{fr} [W/m^{2}K]—heat transfer coefficient for the flat roof, and U_{ww} [W/m^{2}K]—heat transfer coefficient for the window.

U-values for the ground floor are the same in both cases, while the rest energy efficiency criteria are much stricter (almost 1.8 times for the external door) in the Polish rulebook compared to the Serbian rulebook (Figure 3).

2.2. People Occupancy and Thermo-Technical Systems

Simulation settings for people and thermo-technical systems are the same for both locations in the present study: Kragujevac and Kielce.

By the recommendations available in [62–66], internal heat gains were determined based on the next simulation settings: specific daily people occupancy in the analyzed building is p_{pl} = 60 m^2/per, specific metabolic activities level of the people in the analyzed building is q_{pl} = 72.07 W/per, specific annual electricity consumption from electric equipment and lighting in the analyzed building is e_{eel} = 20 kWh/m^2, and specific annual electricity consumption from water heater in the analyzed building is e_{wh} = 10 kWh/m^2. It was also adopted (from the same sources) that the daily presence of people in the analyzed building is τ_{pl} = 12 h (00:00–08:00 h, 17:00–18:00 h, and 21:00–24:00 h) and the specific number of fresh air changes is n_{air} = 0.7 m^3/h/m^2. The analyzed building is also equipped with space heating and cooling systems (Figure 4) to maintain thermal comfort in all rooms (Figure 2) within strictly defined limits during the year: heating control temperature is t_{heat} = 20 °C and cooling control temperature is t_{cool} = 26 °C. The heating system does not allow the temperature to fall below t_{heat} = 20 °C, while the cooling system does not allow the temperature to be higher than t_{cool} = 26 °C. The heating system is very simple because it is based on the use of individual electric heaters. The power of each electric heater is Q_{rad} = 3500 W, while the thermal efficiency is η_{rad} = 0.98. For cooling purposes, classic individual air-conditioned units are used, where cooling power is Q_{acu} = 3500 W and the coefficient of performance is COP_{acu} = 2.61.

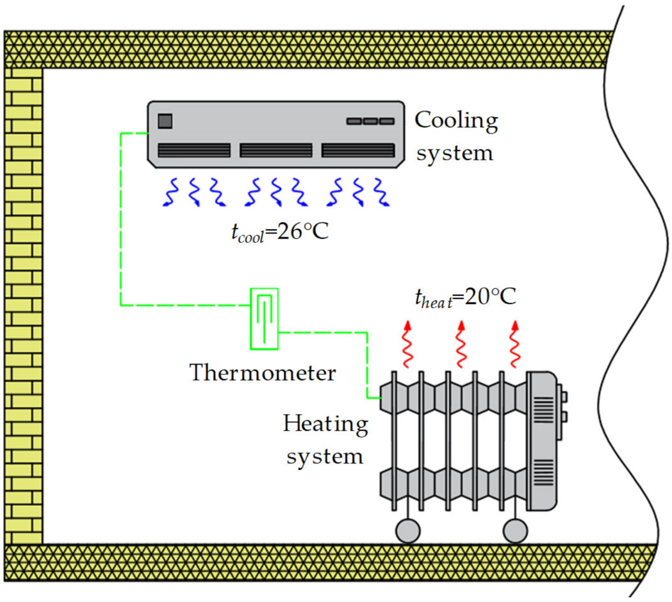

Figure 4. Adopted space heating and cooling systems.

Figure 5 shows the vertical cross-section view (Figure 5a) and isometric view (Figure 5b) of the adopted PTW (example for triple-glazing) in the analyzed building. The geometric and thermal characteristics of all layers in the PTW construction are shown in Table 4.

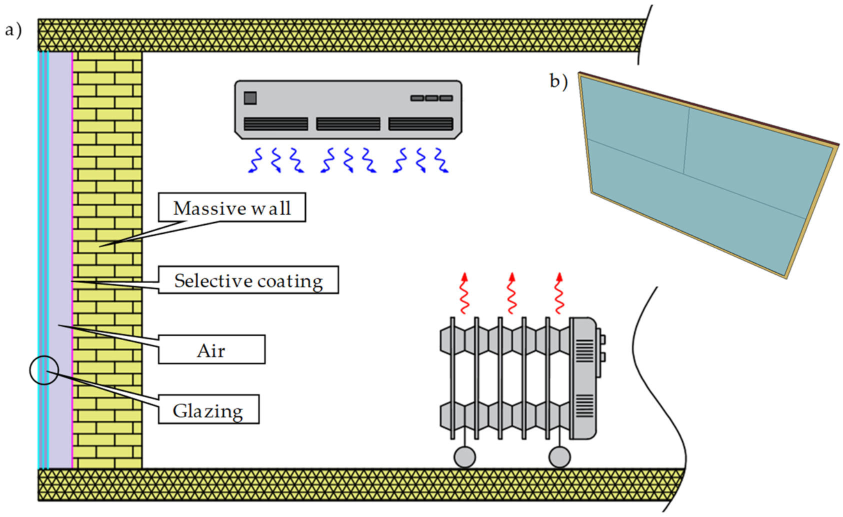

Figure 5. Triple-glazed passive Trombe wall: (**a**) vertical cross-section view and (**b**) isometric view.

Table 4. The geometric-thermal performance of the triple-glazed passive Trombe wall [67].

Parameter	Layer							
	Triple-Glazing *					Air	Selective Coating	Massive Wall
	Glass	Air	Glass	Air	Glass			
δ [mm]	3	30	3	30	3	100	1.6	400
λ [W/mK]	0.9	-	0.9	-	0.9	-	393	1.73
ρ [kg/m^3]	2300	-	-	-	-	-	8907	2242
c_p [J/kgK]	-	-	-	-	-	-	370	837
ST [-]	0.899	-	0.899	-	0.899	-	-	-
SR [-]	0.079	-	0.079	-	0.079	-	-	-
α [-]	-	-	-	-	-	-	0.94	0.65
ε [-]	-	-	-	-	-	-	0.06	0.9

* Since this paper, among other things, considers the influence of different types of glazing (single-glazing, double-glazing, and triple-glazing) on the energy flow in the analyzed building, in the remaining variants, the number of glasses and filling is reduced accordingly: for double-glazing (glass-air-glass) and single-glazing (only one layer of glass). Legend: c_p [J/kgK]—specific heat of the layer for the passive Trombe wall in the analyzed building, *SR* [-]—solar reflectance of the layer for the passive Trombe wall in the analyzed building, *ST* [-]—solar transmittance of the layer for the passive Trombe wall in the analyzed building, α [-]—absorptance of the layer for the passive Trombe wall in the analyzed building, δ [mm]—thickness of the layer for the passive Trombe wall in the analyzed building, ε [-]—emissivity of the layer for the passive Trombe wall in the analyzed building, λ [W/mK]—thermal conductivity of the layer for the passive Trombe wall in the analyzed building, and ρ [kg/m^3]—density of the layer for the passive Trombe wall in the analyzed building.

Figure 6 shows the adopted pergolas concept. In this case, the pergolas are made of wooden planks with a square cross-section measuring 40 × 40 mm.

In this case, reducing the final energy consumption for space cooling is a secondary issue and not a priority. The specific shape of the vertically placed supporting frame (Figure 6), in front of the PTW (Figure 5), indicates that the primary purpose of the pergolas is to provide support for the vegetative development of deciduous climbers. Through the side frame holders (13 of them), the pergolas are attached to the PTW and placed at a distance of 1 m from it (Figure 6). This provides enough space for the unhindered growth of plants and their maintenance (on the one hand), and also prevents possible mechanical, optical, and thermal damage to the PTW (on the other hand). The external dimensions of the frame correspond to the external dimensions of the southern facade (8 × 5.2 m), and the total length of the wooden planks is 79 m.

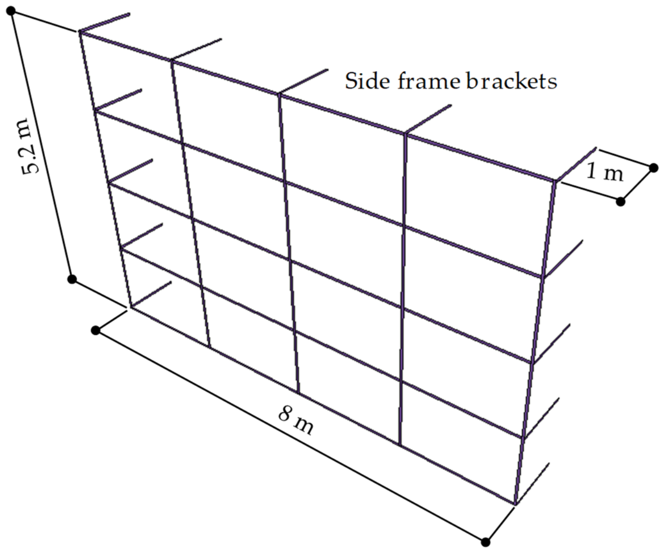

Figure 6. Isometric view of the wooden pergolas.

Bioclimatic solar shading during the summer season is provided by deciduous climbers (Figure 7). In this paper, opportunities and barriers to applying the following four types of plants are numerically investigated and analyzed (Table 5): *V. coignetiae*, *H. lupulus*, *W. sinensis*, and *A. macrophylla*. Table 5 displays the average monthly bioshading coefficients *BSC* [-] for each of these plants.

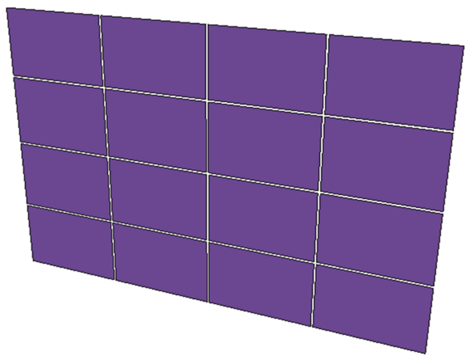

Figure 7. Approximation and isometric view of the deciduous climbers.

Based on the values shown, it can be concluded that the intuitive leafing of plants takes place during May (*V. coignetiae*, *H. lupulus*, and *A. macrophylla*) and June (*W. sinensis*). The benefits are maximal in the period from June to October (*V. coignetiae*), from June to November (*H. lupulus* and *A. macrophylla*), and from July to December (*W. sinensis*). Leaf fall, depending on the type of plant, occurs during October (*V. coignetiae*), November (*H. lupulus* and *A. macrophylla*), and December (*W. sinensis*).

The geometric and graphic approximation of the deciduous climbers was performed in Google SketchUp using the New EnergyPlus Shading Group tool from the Legacy OpenStudio palette, creating flat panels that fill the space between the wooden planks (Figure 7). The same methodology was applied during the graphic design of the pergolas. These two elements differ by the *BSC* parameter (for deciduous climbers, Table 5), which is defined in the EnergyPlus software.

Table 5. Average monthly bioshading coefficients of the adopted deciduous climbers [68].

Month	*V. coignetiae*	*H. lupulus*	*W. sinensis*	*A. macrophylla*
January	0.73	0.69	0.77	0.71
February	0.74	0.67	0.74	0.7
March	0.62	0.69	0.72	0.73
April	0.57	0.63	0.66	0.7
May	0.39	0.3	0.58	0.43
June	0.16	0.14	0.48	0.19
July	0.12	0.08	0.23	0.12
August	0.13	0.09	0.16	0.14
September	0.14	0.1	0.16	0.13
October	0.5	0.21	0.16	0.18
November	0.64	0.42	0.24	0.35
December	0.71	0.63	0.6	0.59

2.3. Location Parameters

The thermal performance of all thermo-technical systems (applies to bioclimatic-passive solar systems) in the analyzed building, during the year, is monitored depending on the meteorological conditions for two characteristic locations: Kragujevac town (an area with a moderate continental climate, Table 6) and Kielce town (an area with a continental climate, Table 7).

Table 6. Average monthly meteorological data for Kragujevac [69].

Month	t_{air} [°C]	φ_{air} [%]	c_{wd} [m/s]	D_{wd} [°]	H_{beam} [W/m^2]	H_{diff} [W/m^2]
January	0.40	83.47	1.85	220.38	84.84	32.33
February	4.10	73.55	2.57	235.82	139.87	36.98
March	8.15	68.59	1.49	208.78	161.25	59.75
April	13.22	65.75	1.28	202.62	228.28	68.91
May	16.64	72.95	1.73	211.34	213.88	84.29
June	20.81	66.44	2.18	232.16	241.83	85.07
July	22.83	66.80	1.68	215.98	266.77	77.38
August	23.19	59.35	1.73	205.57	257.56	65.90
September	18.46	64.80	1.91	204.22	196.95	59.22
October	13.39	78.28	1.96	202.43	133.99	47.14
November	7.79	78.92	2.15	205.41	101.45	31.48
December	3.02	81.13	1.97	210.24	73.99	24.50

Legend: c_{wd} [m/s]—average monthly wind speed for the analyzed location, D_{wd} [°]—average monthly wind direction for the analyzed location, H_{beam} [W/m^2]—average monthly beam solar irradiance on the horizontal plane for the analyzed location, H_{diff} [W/m^2]—average monthly diffuse solar irradiance on the horizontal plane for the analyzed location, t_{air} [°C]—average monthly external air temperature for the analyzed location, and φ_{air} [%]—average monthly external relative humidity for the analyzed location.

Table 7. Average monthly meteorological data for Kielce [69].

Month	t_{air} [°C]	φ_{air} [%]	c_{wd} [m/s]	D_{wd} [°]	H_{beam} [W/m^2]	H_{diff} [W/m^2]
January	−1.65	88.97	3.75	209.93	52.18	23.99
February	−1.18	88.08	3.49	208.95	59.32	46.46
March	3.20	80.62	3.90	218.64	116.89	56.96
April	8.55	72.27	3.40	173.67	176.31	69.37
May	13.43	74.25	2.73	180.63	198.82	90.80
June	17.84	74.91	2.66	174.94	209.95	89.46
July	19.68	71.41	2.40	231.31	203.00	82.56
August	18.50	71.03	2.28	212.23	192.00	72.32
September	14.59	76.06	2.38	207.36	135.53	59.29
October	8.28	85.81	2.58	178.84	101.97	37.01
November	4.75	87.02	2.66	198.98	69.89	22.74
December	1.29	87.94	2.98	154.18	51.65	16.23

Kragujevac (latitude is Φ = 44.02° N, longitude is θ = 20.92° E, and time zone is tz = +1 h) is a town in central Serbia (about 100 km south of Belgrade). Town elevation is el = 185 m. The climate is moderate continental (Table 6).

Kielce (with the same time zone) is a town in south Poland (Φ = 50.81° N, θ = 20.69° E and el = 261 m). Unlike Kragujevac, the climate is somewhat harsher, so it is classified as continental. Meteorological data for the adopted location in Poland, analogous to Table 4, are shown in Table 7.

2.4. Analyzed Scenarios

Figure 8 describes two basic simulation scenarios. In the first case (Figure 8a), numerical simulations are conducted on the classic analyzed building. It is a building without additional construction elements. This building serves as a control, as all subsequent modifications and improvements, utilizing various bioclimatic and passive elements, are compared against its performance.

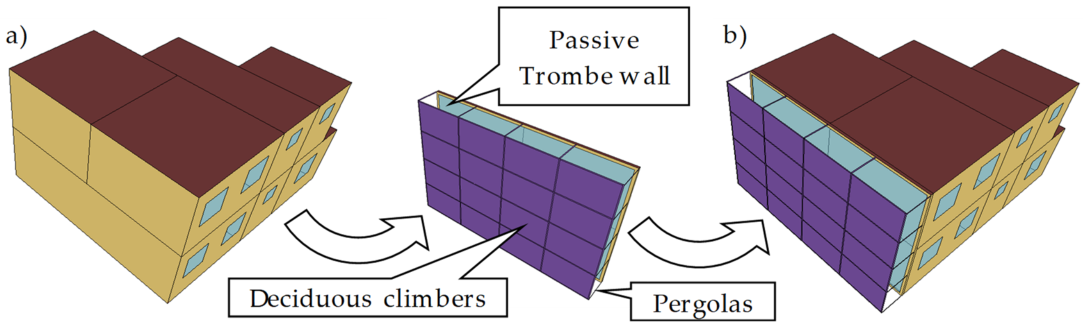

Figure 8. Analyzed building: (**a**) without and (**b**) with bioclimatic-passive elements.

In the second case (Figure 8b), a potential solution that has not been explored in the existing literature as a measure of energy efficiency in buildings is presented. It involves a building equipped with various elements classified by the profession as passive, bioclimatic, green, and environmentally friendly. Measures have been implemented that complement each other, creating the potential for the building to gain energy and environmental benefits throughout the year: (1) PTW in the winter season, and (2) pergolas and deciduous climbers in the summer season.

To better understand the opportunities and barriers that such systems can offer, this paper uses real-time data from two major climate regions in Europe (Tables 6 and 7). The building designs are justified by adherence to the National Energy Efficiency Rulebooks. The additional bioclimatic-passive elements are estimated using experimental data, available technical solutions, and market conditions (Section 2.2). Additionally, the paper examines four types of plants and three types of glazing (Figure 9, Table 8). This approach aims to use numerical simulations to produce results of practical scientific relevance.

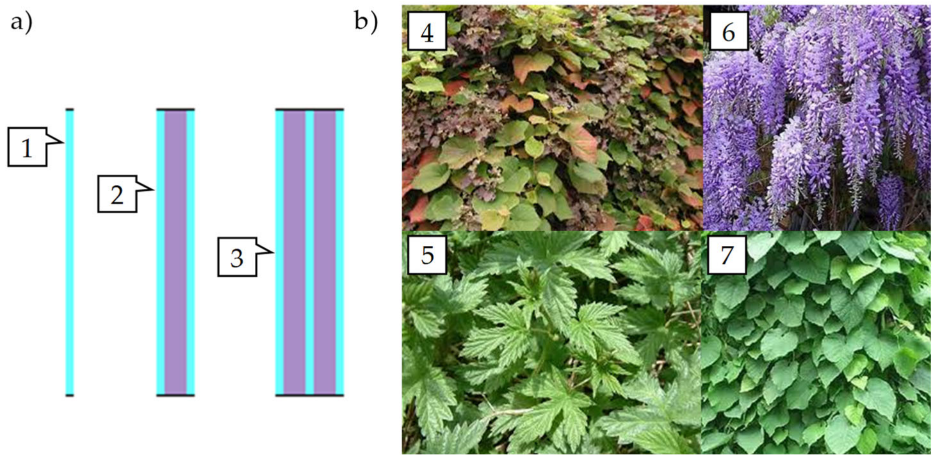

Figure 9. Simulation scenarios: (**a**) glazing and (**b**) plant types. Legend: 1—single-glazing, 2—double-glazing, 3—triple-glazing, 4—*V. coignetiae*, 5—*H. lupulus*, 6—*W. sinensis*, and 7—*A. macrophylla*.

Table 8. Variables used in numerical simulations.

Location	Kragujevac	Kielce
Rulebook	Serbian Rulebook	Polish Rulebook
Climate region	Moderate continental climate	Continental climate
Building type (Figures 8 and 9)	Without and with additional bioclimatic-passive elements	

2.5. Mathematical Model

2.5.1. Space Heating

Useful heating energy consumption (useful, final, primary, embodied, and full energy consumptions, CO_2 emissions, and monetary costs are tracked on an annual basis (Sections 2.5 and 3)) (from electricity) $E_{heat,use}$ [kWh] in the analyzed building can be calculated as Equation (1):

$$E_{heat,use} = \sum_{TZ=1}^{10} \left(E_{heat,TZ} - E_{ihg} \right) - E_{PTW} \quad (1)$$

where: $E_{heat,TZ}$ [kWh]—total heating energy losses (transmission and ventilation) for the one thermal zone in the analyzed building [67], E_{ihg} [kWh]—energy production from the internal heat gains (people, electric equipment and lighting) for the one thermal zone in the analyzed building (Section 2.2), and E_{PTW} [kWh]—energy production from the passive Trombe wall in the analyzed building (Equation (2)).

$$E_{PTW} = E_{PTW,abs} - E_{PTW,loss} \quad (2)$$

where: $E_{PTW,abs}$ [kWh]—total absorbed solar energy (radiation) by the passive Trombe wall in the analyzed building (Figure 10, Equation (3)), and $E_{PTW,loss}$ [kWh]—total heating energy losses from the passive Trombe wall in the analyzed building (Figure 11, Equation (4)).

$$E_{PTW,abs} = E_{PTW,beam} + E_{PTW,diff} + E_{PTW,refl} \tag{3}$$

$$E_{PTW,loss} = \frac{Q_{PTW,loss}}{\tau} = \frac{A_{PTW}\sum U_{PTW,loss}(T_{SC} - T_{air})}{\tau} \tag{4}$$

where: $E_{PTW,beam}$ [kWh]—absorbed beam solar energy (radiation) by the passive Trombe wall in the analyzed building, $E_{PTW,diff}$ [kWh]—absorbed diffuse solar energy (radiation) by the passive Trombe wall in the analyzed building, $E_{PTW,refl}$ [kWh]—absorbed reflected solar energy (radiation) by the passive Trombe wall in the analyzed building, $Q_{PTW,loss}$ [W]—total heat losses from the passive Trombe wall in the analyzed building, A_{PTW} [m^2]—area of the passive Trombe wall in the analyzed building, $\Sigma U_{PTW,loss}$ [W/m^{2}K]—total heat transfer coefficient for the passive Trombe wall in the analyzed building, T_{SC} [°C]—absolute temperature of the selective coating surface for the passive Trombe wall in the analyzed building, and T_{air} [°C]—absolute temperature of the external air.

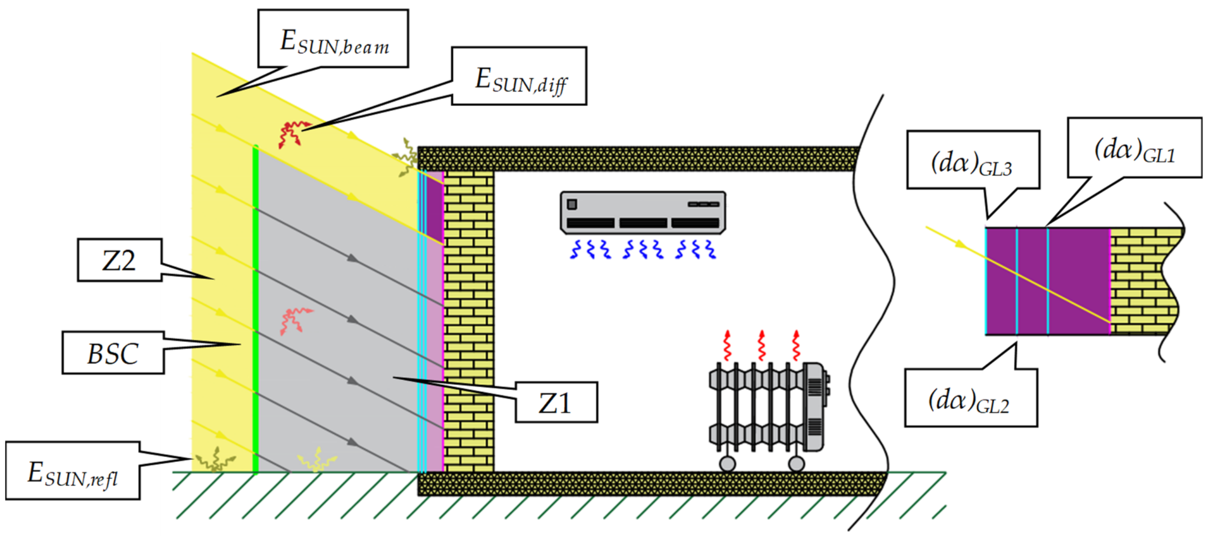

Figure 10. Total absorbed solar energy (radiation) by the passive Trombe wall. Legend: Z1—shading zone, Z2—sun-exposed zone, $(d\alpha)_{GL1}$ [-]—optical efficiency of the first glazing layer for the passive Trombe wall in the analyzed building, $(d\alpha)_{GL2}$ [-]—optical efficiency of the second glazing layer for the passive Trombe wall in the analyzed building, and $(d\alpha)_{GL3}$ [-]—optical efficiency of the third glazing layer for the passive Trombe wall in the analyzed building.

The absorbed beam (Equation (5)), diffuse (Equation (6)), and reflected (Equation (7)) solar energy (radiation) are, respectively:

$$E_{PTW,beam} = (d\alpha)_{beam} E_{SUN,beam} \frac{\cos\beta}{\cos Z} \tag{5}$$

$$E_{PTW,diff} = VF(d\alpha)_{diff} E_{SUN,diff} \frac{1+\cos\beta}{2} \tag{6}$$

$$E_{PTW,refl} = VF(d\alpha)_{refl} a E_{SUN,refl} \frac{1-\cos\beta}{2} \tag{7}$$

where: $(d\alpha)_{beam}$ [-]—optical efficiency of the beam solar energy (radiation) for the passive Trombe wall in the analyzed building (Table 9), $E_{SUN,beam}$ [kWh]—incoming beam solar energy (radiation) for the passive Trombe wall in the analyzed building (Table 10), $cos\beta$ [rad]—solar incident angle for the passive Trombe wall in the analyzed building, $cosZ$

[rad]—solar incident angle for the horizontal surface, *VF* [-]—view factor, $(d\alpha)_{diff}$ [-]—optical efficiency of the diffuse solar energy (radiation) for the passive Trombe wall in the analyzed building (Table 9), $E_{SUN,diff}$ [kWh]—incoming diffuse solar energy (radiation) for the passive Trombe wall in the analyzed building (Table 10), $(d\alpha)_{refl}$ [-]—optical efficiency of the reflected solar energy (radiation) for the passive Trombe wall in the analyzed building (Table 9), a [-]—ground albedo, and $E_{SUN,refl}$ [kWh]—incoming reflected solar energy (radiation) for the passive Trombe wall in the analyzed building (Table 10).

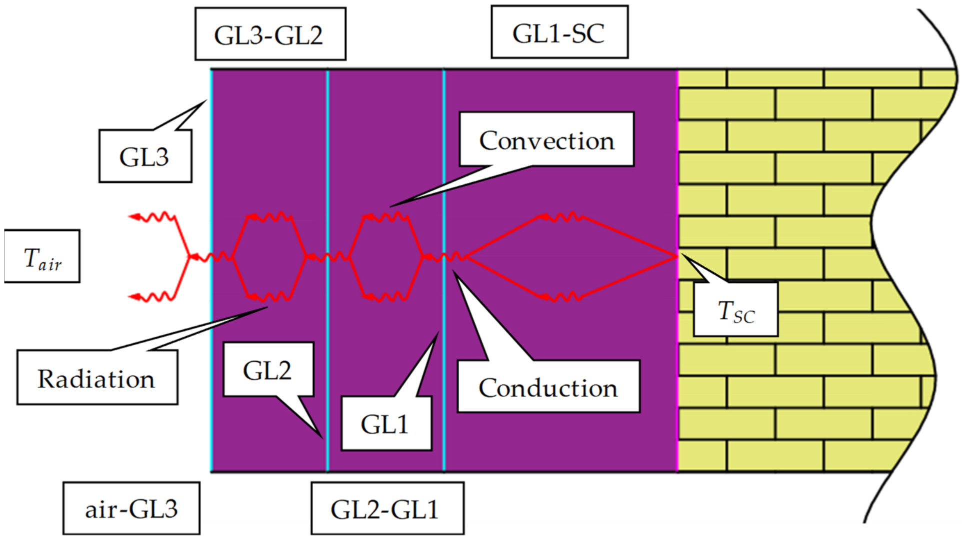

Figure 11. Total heating energy losses from the passive Trombe wall.

Table 9. Correlation between optical efficiency and glazing type for the passive Trombe wall.

Glazing Type	Optical Efficiency in General *
Single-glazing	$(d\alpha)_{SG} = (d\alpha)_{GL1}$
Double-glazing	$(d\alpha)_{DG} = (d\alpha)_{GL1}(d\alpha)_{GL2}$
Triple-glazing	$(d\alpha)_{TG} = (d\alpha)_{GL1}(d\alpha)_{GL2}(d\alpha)_{GL3}$

* Equations from Table 9 are applied for each component (beam (Equation (5)), diffuse (Equation (6)), and reflected (Equation (7))) incoming solar energy (radiation). Legend: $(d\alpha)_{SG}$ [-]—optical efficiency of the single-glazing for the passive Trombe wall in the analyzed building, $(d\alpha)_{DG}$ [-]—optical efficiency of the double-glazing for the passive Trombe wall in the analyzed building, and $(d\alpha)_{TG}$ [-]—optical efficiency of the triple-glazing for the passive Trombe wall in the analyzed building.

Table 10. Correlation between bioshading coefficient and incoming solar energy (radiation) for the passive Trombe wall.

Solar Component	Zone Z1	Zone Z2
Beam	$E_{SUN,beam} = e_{SUN,beam}A_{PTW,Z1}BSC$	$E_{SUN,beam} = e_{SUN,beam}A_{PTW,Z2}$
Diffuse	$E_{SUN,diff} = e_{SUN,diff}A_{PTW,Z1}BSC$	$E_{SUN,diff} = e_{SUN,diff}A_{PTW,Z2}$
Reflected	$E_{SUN,refl} = \left(e_{SUN,beam} + e_{SUN,diff}\right)A_{PTW,Z1}BSC$	$E_{SUN,refl} = \left(e_{SUN,beam} + e_{SUN,diff}\right)A_{PTW,Z2}$

Legend: $e_{SUN,beam}$ [kWh/m^2]—specific incoming beam solar energy (radiation) for the passive Trombe wall in the analyzed building, $A_{PTW,Z1}$ [m^2]—shading area of the passive Trombe wall in the analyzed building, $A_{PTW,Z2}$ [m^2]—sun exposed area of the passive Trombe wall in the analyzed building, $e_{SUN,diff}$ [kWh/m^2]—specific incoming diffuse solar energy (radiation) for the passive Trombe wall in the analyzed building, and $e_{SUN,refl}$ [kWh/m^2]—specific incoming reflected solar energy (radiation) for the passive Trombe wall in the analyzed building.

Value $\Sigma U_{PTW,loss}$ can be calculated as the sum of the $U_{PTW,loss,frn}$ and $U_{PTW,loss,edg}$ values using Equation (8):

$$\sum U_{PTW,loss} = U_{PTW,loss,frn} + U_{PTW,loss,edg} \quad (8)$$

where: $U_{PTW,loss,frn}$ [W/m^{2}K]—heat transfer coefficient for the front side of the passive Trombe wall in the analyzed building (Table 11), and $U_{PTW,loss,edg}$ [W/m^{2}K]—heat transfer coefficient for the edges of the passive Trombe wall in the analyzed building.

Table 11. Correlation between heat transfer coefficient and glazing type for the passive Trombe wall.

Glazing Type	Heat Transfer Coefficient in General *
Single-glazing	$U_{PTW,loss,frn,SG} = \frac{1}{\frac{1}{h_{SC-GL1}} + \frac{\delta_{GL1}}{\lambda_{GL1}} + \frac{1}{h_{GL1-air}}}$
Double-glazing	$U_{PTW,loss,frn,DG} = \frac{1}{\frac{1}{h_{SC-GL1}} + \frac{\delta_{GL1}}{\lambda_{GL1}} + \frac{1}{h_{GL1-GL2}} + \frac{\delta_{GL2}}{\lambda_{GL2}} + \frac{1}{h_{GL2-air}}}$
Triple-glazing	$U_{PTW,loss,frn,TG} = \frac{1}{\frac{1}{h_{SC-GL1}} + \frac{\delta_{GL1}}{\lambda_{GL1}} + \frac{1}{h_{GL1-GL2}} + \frac{\delta_{GL2}}{\lambda_{GL2}} + \frac{1}{h_{GL2-GL3}} + \frac{\delta_{GL3}}{\lambda_{GL3}} + \frac{1}{h_{GL3-air}}}$

* Equations from Table 11 are applied for each type of the passive Trombe wall (Equation (8)) in the analyzed building. Legend: $U_{PTW,loss,frn,SG}$ [W/m^{2}K]—heat transfer coefficient for the front side of the single-glazed passive Trombe wall in the analyzed building, $h_{SC\text{-}GL1}$ [W/m^{2}K]—heat transfer by the convection and radiation between the selective coating and the first glazing layer for the passive Trombe wall in the analyzed building, δ_{GL1} [m]—thickness of the first glazing layer for the passive Trombe wall in the analyzed building, λ_{GL1} [W/mK]—thermal conductivity of the first glazing layer for the passive Trombe wall in the analyzed building, $h_{GL1\text{-}air}$ [W/m^{2}K]—heat transfer by the convection and radiation between the first glazing layer and the external air for the passive Trombe wall in the analyzed building, $U_{PTW,loss,frn,DG}$ [W/m^{2}K]—heat transfer coefficient for the front side of the double-glazed passive Trombe wall in the analyzed building, $h_{GL1\text{-}GL2}$ [W/m^{2}K]—heat transfer by the convection and radiation between the first glazing layer and the second glazing layer for the passive Trombe wall in the analyzed building, δ_{GL2} [m]—thickness of the second glazing layer for the passive Trombe wall in the analyzed building, λ_{GL2} [W/mK]—thermal conductivity of the second glazing layer for the passive Trombe wall in the analyzed building, $h_{GL2\text{-}air}$ [W/m^{2}K]—heat transfer by the convection and radiation between the second glazing layer and the external air for the passive Trombe wall in the analyzed building, $U_{PTW,loss,frn,TG}$ [W/m^{2}K]—heat transfer coefficient for the front side of the triple-glazed passive Trombe wall in the analyzed building, $h_{GL2\text{-}GL3}$ [W/m^{2}K]—heat transfer by the convection and radiation between the second glazing layer and the third glazing layer for the passive Trombe wall in the analyzed building, δ_{GL3} [m]—thickness of the third glazing layer for the passive Trombe wall in the analyzed building, λ_{GL3} [W/mK]—thermal conductivity of the third glazing layer for the passive Trombe wall in the analyzed building and $h_{GL3\text{-}air}$ [W/m^{2}K]—heat transfer by the convection and radiation between the third glazing layer and the external air for the passive Trombe wall in the analyzed building.

Final $E_{heat,fin}$ [kWh] (Equation (9)) and primary $E_{heat,pry}$ [kWh] (Equation (10)) heating energy consumption (from electricity) are as follows:

$$E_{heat,fin} = \frac{E_{heat,use}}{\eta_{rad}} \quad (9)$$

$$E_{heat,pry} = R_{el} E_{heat,fin} \quad (10)$$

where: R_{el} [-]—primary conversion factor for electricity (Section 2.5.5).

2.5.2. Space Cooling

Useful cooling energy consumption (from electricity) $E_{cool,use}$ [kWh] in the analyzed building can be calculated using Equation (11):

$$E_{cool,use} = \sum_{TZ=1}^{10} \left(E_{cool,TZ} + E_{ihg} \right) + E_{PTW} \quad (11)$$

where $E_{cool,TZ}$ [kWh]—total cooling energy gains (transmission and ventilation) for the one thermal zone in the analyzed building [67].

Analogous to heating energy, final $E_{cool,fin}$ [kWh] (Equation (12)) and primary $E_{cool,pry}$ [kWh] (Equation (13)) cooling energy consumption (from electricity) are as follows:

$$E_{cool,fin} = \frac{E_{cool,use}}{COP_{acu}} \tag{12}$$

$$E_{cool,pry} = R_{el} E_{cool,fin} \tag{13}$$

2.5.3. Energy Indicators

Total useful $E_{tot,use}$ [kWh] (Equation (14)), final $E_{tot,fin}$ [kWh] (Equation (15)), and primary $E_{tot,pry}$ [kWh] (Equation (16)) energy consumption (from electricity) for space heating and cooling in the analyzed building are as follows:

$$E_{tot,use} = E_{heat,use} + E_{cool,use} \tag{14}$$

$$E_{tot,fin} = E_{heat,fin} + E_{cool,fin} \tag{15}$$

$$E_{tot,pry} = E_{heat,pry} + E_{cool,pry} \tag{16}$$

Total embodied energy $E_{tot,emb}$ [kWh] (Equation (17)) for the novel bioclimatic-passive architecture concept in the analyzed building is the sum of the embodied energy for the passive Trombe wall $E_{emb,PTW}$ [kWh] (Equation (18)) and embodied energy for the wooden pergolas $E_{emb,PER}$ [kWh] (Equation (19)) (embodied energy for the deciduous climbers can be eliminated):

$$E_{tot,emb} = E_{emb,PTW} + E_{emb,PER} \tag{17}$$

$$\begin{aligned} E_{emb,PTW} &= E_{emb,MW} + E_{emb,SC} + E_{emb,GL} = \\ &= \frac{e_{emb,MW} m_{MW}}{25} + \frac{e_{emb,SC} m_{SC}}{25} + \frac{n_{GL} e_{emb,GL} m_{GL}}{25} \end{aligned} \tag{18}$$

$$E_{emb,PER} = \frac{e_{emb,PER} m_{PER}}{25} \tag{19}$$

where: $E_{emb,MW}$ [kWh]—embodied energy of the massive wall for the passive Trombe wall in the analyzed building, $E_{emb,SC}$ [kWh]—embodied energy of the selective coating for the passive Trombe wall in the analyzed building, $E_{emb,GL}$ [kWh]—embodied energy of the glazing for the passive Trombe wall in the analyzed building, $e_{emb,MW}$ [kWh/kg]—specific embodied energy of the massive wall for the passive Trombe wall in the analyzed building (Table 12), m_{MW} [kg]—mass of the massive wall for the passive Trombe wall in the analyzed building (Table 12), $e_{emb,SC}$ [kWh/kg]—specific embodied energy of the selective coating for the passive Trombe wall in the analyzed building (Table 12), m_{SC} [kg]—mass of the selective coating for the passive Trombe wall in the analyzed building (Table 12), n_{GL} [-]—number of the glazing for the passive Trombe wall in the analyzed building (Table 12), $e_{emb,GL}$ [kWh/kg]—specific embodied energy of the glazing for the passive Trombe wall in the analyzed building (Table 12), m_{GL} [kg]—mass of the glazing for the passive Trombe wall in the analyzed building (Table 12), $e_{emb,PER}$ [kWh/kg]—specific embodied energy of the pergolas in the analyzed building (Table 12), and m_{PER} [kg]—mass of the pergolas in the analyzed building (Table 12).

At the end, full energy E_{full} [kWh] consumption (from electricity) for space heating and cooling in the analyzed building can be presented as Equation (20):

$$E_{full} = E_{tot,pry} + E_{tot,emb} \tag{20}$$

Table 12. Correlation between embodied energy, investment costs, and bioclimatic-passive elements in the analyzed building [70].

Layer	e_{emb} [kWh/kg]	m [kg]	E_{emb} [kWh]	Y_{inv} [EUR]
Massive wall	0.833	37,306.88	1243.07	2455
Selective coating	0.389	661.26	10.29	194
Glazing	3.53	$m_{GL} = m_{SG} = m_{GL1} = 269.1$	38	585
		$m_{GL} = m_{DG} = m_{GL1} + m_{GL2} = 538.2$	75.99	1170
		$m_{GL} = m_{TG} = m_{GL1} + m_{GL2} + m_{GL3} = 807.3$	113.99	1755
Wooden pergolas	3.05	75.84	9.25	155

Legend: m_{SG} [kg]—mass of the single-glazing for the passive Trombe wall in the analyzed building, m_{GL1} [kg]—mass of the first glazing for the passive Trombe wall in the analyzed building, m_{DG} [kg]—mass of the double-glazing for the passive Trombe wall in the analyzed building, m_{GL2} [kg]—mass of the second glazing for the passive Trombe wall in the analyzed building, m_{TG} [kg]—mass of the triple-glazing for the passive Trombe wall in the analyzed building, m_{GL3} [kg]—mass of the third glazing for the passive Trombe wall in the analyzed building, and Y_{inv} [EUR]—investment costs for the bioclimatic-passive element in the analyzed building.

2.5.4. Environmental Indicators

The main parameter representing this group of indicators is CO_2 emissions. In this case, for the needs of space heating and cooling, the total CO_2 emissions $M_{tot,CO2}$ [kg] can be determined using Equation (21):

$$M_{tot,CO2} = M_{heat,CO2} + M_{cool,CO2} = g_{CO2}\left(E_{heat,pry} + E_{cool,pry}\right) \tag{21}$$

where: $M_{heat,CO2}$ [kg]—CO_2 emissions for the space heating in the analyzed building, $M_{cool,CO2}$ [kg]—CO_2 emissions for the space cooling in the analyzed building, and g_{CO2} [kg/kWh]—specific CO_2 emissions for the electricity in the analyzed building (Section 2.5.5).

2.5.5. Economic Indicators

Total investment costs $Y_{tot,inv}$ [EUR] (without taking deciduous climbers into account) are as follows (Equation (22)):

$$Y_{tot,inv} = Y_{inv,PTW} + Y_{inv,PER} = Y_{inv,MW} + Y_{inv,SC} + Y_{inv,GL} + Y_{inv,PER} \tag{22}$$

where: $Y_{inv,PTW}$ [EUR]—investment costs for the passive Trombe wall in the analyzed building (Section 2.5.3), $Y_{inv,PER}$ [EUR]—investment costs for the pergolas in the analyzed building (Section 2.5.3), $Y_{inv,MW}$ [EUR]—investment costs of the massive wall for the passive Trombe wall in the analyzed building (Section 2.5.3), $Y_{inv,SC}$ [EUR]—investment costs of the selective coating for the passive Trombe wall in the analyzed building (Section 2.5.3), and $Y_{inv,GL}$ [EUR]—investment costs of the glazing for the passive Trombe wall in the analyzed building (Section 2.5.3).

The last (economic) indicator is the payback period PB [years]. This indicator is shown in Equation (23):

$$PB = \frac{Y_{tot,inv}}{Y_{el,before} - Y_{el,after}} = \frac{Y_{tot,inv}}{y_{el}\left(E_{tot,fin,before} - E_{tot,fin,after}\right)} \tag{23}$$

where: $Y_{el,before}$ [EUR]—electricity price for the heating and cooling before implementation of the bioclimatic-passive elements in the analyzed building, $Y_{el,after}$ [EUR]—electricity price for the heating and cooling after implementation of the bioclimatic-passive elements in the analyzed building, y_{el} [EUR/kWh]—specific price for the electricity in the analyzed building (Table 13), $E_{tot,fin,before}$ [kWh]—total final energy consumption (from electricity) for space heating and cooling before implementation of the bioclimatic-passive elements in the analyzed building, and $E_{tot,fin,after}$ [kWh]—total final energy consumption (from electricity) for space heating and cooling after implementation of the bioclimatic-passive elements in the analyzed building.

Table 13. Specific energy, environmental, and economic indicators for the bioclimatic-passive elements in the analyzed building.

Specific Indicator	Serbia	Poland
R_{el} [-]	2.5 [62]	2.32 [71]
g_{CO2} [kg/kWh]	0.53 [62]	0.758 [72]
y_{el} [EUR/kWh]	0.124 * [73]	0.24 [74]

* Calculating the price for the electricity in Serbia, additional taxes were taken into account in this case, unlike the paper available in [75], where they were not considered.

3. Results and Discussion

Table 14 shows the values of $E_{tot,use}$, $E_{tot,fin}$, and $E_{tot,pry}$ (Section 2.5.3), $M_{tot,CO2}$ (Section 2.5.4), and $Y_{el,before}$ (Section 2.5.5) for the analyzed building without (Section 2.4) bioclimatic-passive elements for two adopted climate zones (Section 2.3): moderate continental climate (Kragujevac) and continental climate (Kielce).

Table 14. Energy, environmental, and economic indicators in the analyzed building without bioclimatic-passive elements, depending on location parameters.

Town	$E_{tot,use}$ [kWh]	$E_{tot,fin}$ [kWh]	$E_{tot,pry}$ [kWh]	$M_{tot,CO2}$ [kg]	$Y_{el,before}$ [EUR]
Kragujevac	5931.21	4647.48	11,618.7	6157.91	576.29
Kielce	7036.65	6788.06	15,748.3	11,937.21	1629.13

The numerical results (Table 14) on the initial geometric building model (the classic building, Figure 8a) demonstrate that a moderate continental climate, in terms of energy, is more favorable to its tenants. Namely, the energy needs of the analyzed building without bioclimatic-passive elements, located in Kielce, are 18.64% (for $E_{tot,use}$), 46.06% (for $E_{tot,fin}$), and 35.54% (for $E_{tot,pry}$) higher than in the case of the same building located in Kragujevac. CO_2 emissions from the Polish building are 93.85% higher, while the price is 2.83 times higher.

$E_{cool,use}$ makes up 37.17% (for Kragujevac) and 8.75% (for Kielce) of the $E_{tot,use}$. The structure additionally changes in favor of heating if the share of $E_{cool,fin}$ in $E_{tot,fin}$ is followed: 18.17% (for Kragujevac) and 3.47% (for Kielce). In the remaining cases ($E_{tot,pry}$, $M_{tot,CO2}$, and $Y_{el,before}$), the share of $E_{cool,fin} = E_{cool,pry} = M_{tot,CO2} = Y_{el,before}$ does not change, which is also logical if specific indicators are taken into account (Section 2.5.5).

Contrary to the parameters shown in Table 14, Table 15 shows $E_{tot,use}$, $E_{tot,fin}$, $E_{tot,pry}$, $M_{tot,CO2}$, and $Y_{el,after}$ in the analyzed building with bioclimatic-passive elements, located in Kragujevac, taking into account two additional groups of variables: (1) three types of glazing and (2) four types of deciduous climbers. Table 16 shows the same parameters for another location, i.e., Kielce town. Pergolas are also included in all the mentioned numerical scenarios.

Table 15. Energy, environmental, and economic indicators in the analyzed building with bioclimatic-passive elements located in Kragujevac.

Glazing Type	Deciduous Climber	$E_{tot,use}$ [kWh]	$E_{tot,fin}$ [kWh]	$E_{tot,pry}$ [kWh]	$M_{tot,CO2}$ [kg]	$Y_{el,after}$ [EUR]
Single-glazing	***V. coignetiae***	**6428.28**	**4646.90**	**11,617.25**	**6157.14**	**576.22**
	H. lupulus	6647.06	4894.81	12,237.03	6485.62	606.96
	W. sinensis	6848.92	4978.85	12,447.13	6596.98	617.38
	A. macrophylla	6757.28	4950.93	12,377.33	6559.98	613.92
Double-glazing	***V. coignetiae***	**6295.31**	**4085.4**	**10,213.5**	**5413.16**	**506.59**
	H. lupulus	6515.58	4347.41	10,868.53	5760.32	539.08
	W. sinensis	6774.72	4457.93	11,144.83	5906.76	552.78
	A. macrophylla	6667.06	4425.85	11,064.63	5864.25	548.81
Triple-glazing	***V. coignetiae***	**6386.13**	**3879.05**	**9697.63**	**5139.74**	**481**
	H. lupulus	6515.97	4081.47	10,203.68	5407.95	506.1
	W. sinensis	6820.69	4214.4	10,536	5584.08	522.59
	A. macrophylla	6697.91	4174.44	10,436.1	5531.13	517.63

Table 16. Energy, environmental, and economic indicators in the analyzed building with bioclimatic-passive elements located in Kielce.

Glazing Type	Deciduous Climber	$E_{tot,use}$ [kWh]	$E_{tot,fin}$ [kWh]	$E_{tot,pry}$ [kWh]	$M_{tot,CO2}$ [kg]	$Y_{el,after}$ [EUR]
Single-glazing	***V. coignetiae***	**7950.09**	**7534.5**	**17,480.04**	**13,249.87**	**1808.28**
	H. lupulus	8185.77	7797.71	18,090.69	13,712.74	1871.45
	W. sinensis	8373.35	7870.6	18,259.79	13,840.92	1888.94
	A. macrophylla	8244.67	7819.13	18,140.38	13,750.41	1876.59
Double-glazing	***V. coignetiae***	**7241.56**	**6475.35**	**15,022.81**	**11,387.29**	**1554.08**
	H. lupulus	7491.12	6763.18	15,690.58	11,893.46	1623.16
	W. sinensis	7769.67	6877.15	15,954.99	12,093.88	1650.52
	A. macrophylla	7595.65	6807.99	15,794.54	11,972.26	1633.92
Triple-glazing	***V. coignetiae***	**6902.82**	**5908.07**	**13,706.72**	**10,389.7**	**1417.94**
	H. lupulus	7169.09	6218.23	14,426.29	10,935.13	1492.38
	W. sinensis	7480.46	6341.65	14,712.63	11,152.17	1522
	A. macrophylla	7298.26	6275.73	14,559.69	11,036.25	1506.18

In all considered glazing scenarios (Table 15), it was shown that, in comparison with other types of deciduous climbers, *V. coignetiae* contributes the most to the reduction in $E_{tot,use}$, $E_{tot,fin}$, and $E_{tot,pry}$ consumptions. The same goes for $M_{tot,CO2}$ and $Y_{el,after}$ indicators. On the other hand, for the tenants of the analyzed building, the least favorable option is the use of *W. sinensis*. If, for example, the mentioned two climbers are compared using the $Y_{el,after}$ indicator, the number values in the case of *W. sinensis* are higher than *V. coignetiae* by 7.14% (single-glazing), 9.12% (double-glazing), and 8.65% (triple-glazing). The best results are achieved by combining *V. coignetiae* and triple glazing, because in that case the indicators are, respectively (Table 15), $E_{tot,use}$ = 6386.13 kWh, $E_{tot,fin}$ = 3879.05 kWh, $E_{tot,pry}$ = 9697.63 kWh, $M_{tot,CO2}$ = 5139.74 kg, and $Y_{el,after}$ = EUR 481. If the results from

Table 15 are compared with the results for Kragujevac from Table 14, it is clear that the option involving combining deciduous climbers and single-glazing cannot be considered an acceptable solution, i.e., a solution that can have practical and wider commercial use application.

The same deciduous climbers are the most energetically acceptable (*V. coignetiae*) and least favorable (*W. sinensis*) options in the continental climate area, i.e., Kielce town (Table 16). From the attached table, it can be concluded that the biggest differences are between the following two options: *V. coignetiae* with triple-glazing (first and best option), and *W. sinensis* with single-glazing (second and worst option). If this comparison were to be expressed in percentages, the values in the second case are higher by 21.3% ($E_{tot,use}$) and 33.22% ($E_{tot,fin}$, $E_{tot,pry}$, $M_{tot,CO2}$, and $Y_{el,after}$). Compared to the basic building model (Table 14), better results can be expected (by all parameters) when deciduous climbers are placed in front of triple-glazed PTW.

The hourly external (t_{air}) and internal (t_{PTW}, t_{LR}, t_{BR1}, and t_{BR2}) temperatures during the year in the analyzed building with pergolas, *V. coignetiae*, and triple-glazed PTW (best solution based on Tables 15 and 16) located in Kragujevac (Figure 12) and Kielce (Figure 13) are shown below.

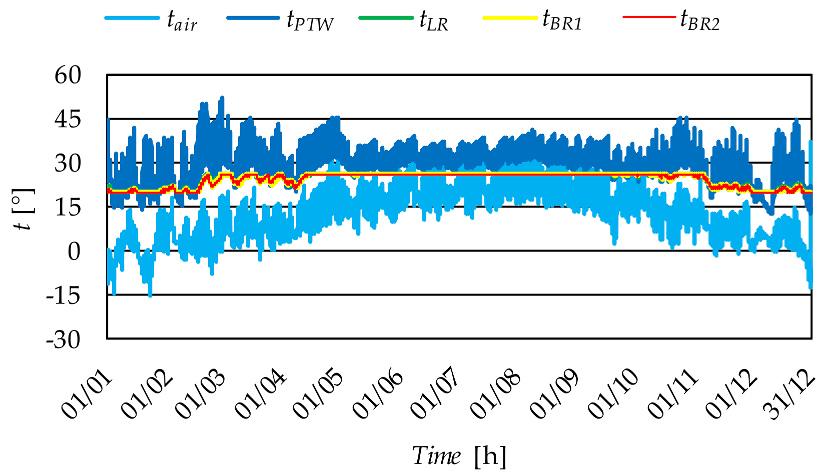

Figure 12. Hourly external and internal temperatures during the year in the analyzed building with bioclimatic-passive elements (pergolas, *V. coignetiae*, and triple-glazed passive Trombe wall) located in Kragujevac.

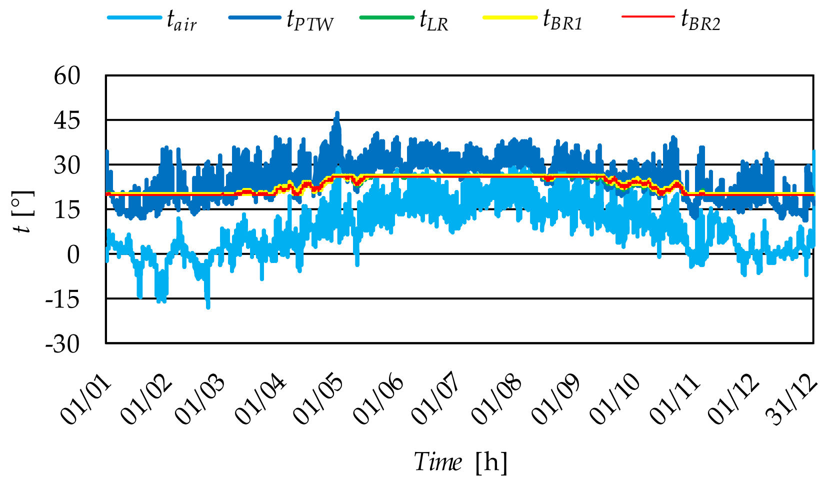

Figure 13. Hourly external and internal temperatures during the year in the analyzed building with bioclimatic-passive elements (pergolas, *V. coignetiae*, and triple-glazed passive Trombe wall) located in Kielce.

In Figures 12 and 13, it can be seen that the temperature in PTW (as non-treated TZ) is always above t_{air} (valid for both locations). The maximum measured t_{PTW} temperatures were 36.96 °C (for Kragujevac) and 34.68 °C (for Kielce). Due to the fact that Kragujevac is located in a moderate continental climate area, the temperature differences ($\Delta t = t_{PTW}$-t_{air}) are smaller than in the case of Kielce, a place in the continental climate area. Temperatures in thermally treated TZs (LR, BR1, and BR2) are within the permissible limits defined by t_{heat} = 20 °C and t_{cool} = 26 °C. In the transition periods of the year, it can be observed that these temperatures are between 20 and 26 °C, which means that the heat gains from the passive solar systems are sufficient to not engage the heating or cooling system. This time range is shorter in Figure 13, which is also explained by climatic and meteorological conditions. For the same reasons (by comparing the results with Figures 12 and 13), it can be concluded that the cooling season in Kragujevac is longer than the cooling season in Kielce.

The next table (Table 17) summarizes embodied energy $E_{tot,emb}$ and investment costs $Y_{tot,inv}$ in the analyzed building depending on the number of the glazing layer.

Table 17. Embodied energy and investment costs for different types of passive Trombe walls in the analyzed building.

Glazing Type	$E_{tot,emb}$ [kWh]	$Y_{tot,inv}$ [EUR]
Single-glazing	1300.61	3389
Double-glazing	1338.6	3974
Triple-glazing	1376.6	4559

Considering the various values from Tables 15–17, Table 18 shows the remaining two indicators: one energy (E_{full}) and one economic (*PB*). The results are shown for all analyzed cases, which means that they take into account the types of glazing, deciduous climbers, and locations.

Table 18. Full energy consumption and payback period in the analyzed building, depending on the simulation scenario.

Glazing Type	Deciduous Climber	E_{full} [kWh]		*PB* [Years]	
		Kragujevac	Kielce	Kragujevac	Kielce
Single-glazing	***V. coignetiae***	**12,917.86**	**18,780.65**	**>50**	**np**
	H. lupulus	13,537.64	19,391.3	np	np
	W. sinensis	13,747.74	19,560.4	np	np
	A. macrophylla	13,677.94	19,440.99	np	np
Double-glazing	***V. coignetiae***	**11,552.1**	**16,361.41**	**>50**	**>50**
	H. lupulus	12,207.13	17,029.18	>50	>50
	W. sinensis	12,483.43	17,293.59	>50	np
	A. macrophylla	12,403.23	17,133.14	>50	np
Triple-glazing	***V. coignetiae***	**11,074.23**	**15,083.32**	**40–50**	**20–30**
	H. lupulus	11,580.28	15,802.89	>50	30–40
	W. sinensis	11,912.6	16,089.23	>50	40–50
	A. macrophylla	11,812.7	15,936.29	>50	30–40

Legend: np—not possible.

The simulation results shown in Table 18 again confirm that *V. coignetiae* has the greatest energy, environmental, and economic potential compared to *H. lupulus*, *W. sinensis*, and *A. macrophylla* for application both in moderate continental and continental zones.

If this plant were used within the proposed concept, the E_{full} indicator would still favor the Serbian building. In other words, the E_{full} indicator for a Polish building would be higher by (Table 18): 45.39% (*V. coignetiae* and single-glazing), 41.63% (*V. coignetiae* and double-glazing), and 36.2% (*V. coignetiae* and triple-glazing). In the Serbian case, E_{full} is higher by 11.82% (*V. coignetiae* and double-glazing) and by 16.65% (*V. coignetiae* and triple-glazing) compared to the base case (*V. coignetiae* and single-glazing). In the Polish case, these differences are even more pronounced compared to *V. coignetiae* and single-glazing: 14.79% (*V. coignetiae* and double-glazing) and 24.51% (*V. coignetiae* and triple-glazing).

The results of the payback period calculation indicate that the proposed concept should be approached carefully because the payback period can be very long. In some cases, it can be even longer than 50 years. This can be explained by the fact that deciduous climbers cannot, in practice, ensure complete solar insolation (during the winter season) and complete solar shading (during the summer season) of passive Trombe walls. There are also economic circumstances that contribute to a certain extent to the extension of this period.

Table 18 also shows that, in some cases, the payback period can be half as short (20–30 years for Kielce), which represents a positive impetus for the future development of the proposed concept. For this bioclimatic-passive architecture concept to be economically justified in the future, attention should be directed toward amortizing the market prices of key components: selective coatings, glazing, deciduous climbers, pergola materials, etc. The involvement of multiple government sectors should also be considered—subsidizing the implementation of passive measures to achieve energy efficiency could become a good practice. Using recycled materials, adopting a responsible strategy in the design phase (which includes planting climbers before installing the PTW), and ensuring proper maintenance and management of all components are also very important. Planting climbers in front of the PTW would also create a natural shield that would protect the glass layers from weather conditions and mechanical damage.

4. Conclusions

This paper investigated the impact of passive, bioclimatic, green solar systems for heating (passive Trombe walls) and cooling (pergolas and deciduous climbers) on the performance of residential buildings located in two different and dominant European climate areas: moderate continental (Kragujevac) and continental (Kielce). This paper aims to show a novel building concept, unknown in the literature.

The research subject was residential buildings equipped with electric equipment, lighting, water heating, individual electric heaters (for space heating), and individual air-conditioner units (for space cooling).

The analyzed building was created in compliance with the Serbian and Polish rulebooks. The proposed energy-efficient building concept was numerically (with Google SketchUp and EnergyPlus) analyzed and tested, using three passive Trombe wall types (single-glazed, double-glazed, and triple-glazed) and four deciduous climber types (*V. coignetiae*, *H. lupulus*, *W. sinensis*, and *A. macrophylla*).

The initial results showed that the total useful, final, and primary energy consumption, CO_2 emission, and investment costs in the Serbian residential building without bioclimatic-passive elements are 5931.21 kWh, 4647.48 kWh, 11,618.7 kWh, 6157.91 kg, and EUR 576.29. On the other side, the same energy, environmental, and economic indicators for the Polish residential building, also bioclimatic-passive elements, are, respectively, 7036.65 kWh, 6788.06 kWh. 15,748.3 kWh, 11,937.21 kg, and EUR 1629.13.

By applying bioclimatic-passive elements, such as pergolas, *V. coignetiae*, and triple-glazed passive Trombe walls, the best energy results are achieved: E_{full} = 11,074.23 kWh (for Kragujevac) and E_{full} = 15,083.32 kWh (for Kielce). Compared to the initial model of the house, the CO_2 emission (economic indicator) can be reduced by 19.81% (for Kragujevac) and 14.89% (for Kragujevac). Taking into account the current market conditions, the results showed that the payback period (economic indicator) is not yet on the side of the end users (tenants in the analyzed building), but also that there is a huge space for progress to commercialize the proposed concept, due to, as already stated, positive energy and environmental effects.

Based on all of the above, the future directions of investigation should focus on the next critical points: (1) deeper analysis of the use of different deciduous climbers (bioshading coefficients, CO_2 reductions, vegetative developments, etc.); (2) optimization of geometric, optical, and thermal performance of the combined application of bioclimatic-passive elements; (3) the possibility of implementing other passive solar systems whose positive characteristics have been proven in the literature (for example overhangs); (4) researching the potential of application in other regions of Europe and the world; and (5) the possibility of implementing active Trombe walls.

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Nomenclature

Nomenclature:		
A	Area	[m^2]
a	Ground albedo	[-]
BSC	Bioshading coefficients	[-]
c	Wind speed	[m/s]
COP	Coefficient of performance	[-]
$cosZ$	Solar incident angle on the horizontal plane	[rad]
$cos\beta$	Solar incident angle for the passive Trombe wall	[rad]
c_p	Specific heat	[J/kgK]
D	Wind direction	[°]
d	Transmissivity	[-]
E	Energy	[kWh]
e	Specific energy	[kWh/m^2]
el	Elevation	[m]
f	Form factor	[1/m]

g	Specific CO_2 emission	[kg/kWh]
H	Solar irradiance on the horizontal plane	[W/m^2]
h	Heat transfer coefficient	[W/m^{2}K]
M	CO_2 emissions	[kg]
m	Mass	[kg]
n	Specific air change	[m^3/h/m^2]
p	Specific people indicator	[m^2/per]
PB	Payback period	[years]
Q	Power	[W]
q	Specific metabolic activities	[W/per]
R	Primary conversion factor	[-]
S	Energy savings	[%]
SR	Solar reflectance	[-]
ST	Solar transmittance	[-]
T	Absolute temperature	[K]
t	Temperature	[°C]
tz	Time zone	[h]
U	Heat transfer coefficient	[W/m^{2}K]
V	Volume	[m^3]
VF	View factor	[-]
WW	Window–wall ratio	[%]
Y	Costs	[EUR]
y	Specific costs	[EUR/kWh]
Greek letters:		
α	Absorptance	[-]
β	Inclination angle	[-]
Δ	Temperature difference	[°C]
δ	Thickness	[mm]
ε	Emissivity	[-]
η	Thermal efficiency	[-]
θ	Longitude	[°]
λ	Thermal conductivity	[W/mK]
ρ	Density	[kg/m^3]
τ	Time period	[h]
Φ	Latitude	[°]
φ	Relative humidity	[%]
Subscripts:		
abs	Absorbed	
acu	Air-conditioned unit	
after	After implementation	
air	Air	
beam	Beam	
before	Before implementation	
cool	Space cooling	
CO_2	Greenhouse gases	
DG	Double-glazing	
diff	Diffuse	
ed	External door	
edg	Edges	
eel	Electric equipment and lighting	
efl	External floor	
el	Electricity	
emb	Embodied	

ew	External wall
fin	Final
fl	Floor
fr	Flat roof
frn	Front
full	Full
GL	Glazing layer
GL1	Glazing layer 1
GL2	Glazing layer 2
GL3	Glazing layer 3
heat	Space heating
ihg	Internal heat gains
inv	Investment
loss	Losses
MW	Massive wall
PER	Pergolas
pl	People
POL	Poland
pry	Primary
rad	Radiator
refl	Reflection
SC	Selective coating
SG	Single-glazing
SRB	Serbia
SUN	Sun
TG	Triple-glazing
tot	Total
use	Useful
wd	Wind
wh	Water heating
ww	Window
Abbreviation:	
ATW	Active Trombe wall
BR1	Bedroom 1
BR2	Bedroom 2
BT	Bathroom
H1	Hall 1
H2	Hall 2
K	Kitchen
LR	Living room
np	Not possible
PCM	Phase change material
PTW	Passive Trombe wall
RESs	Renewable energy sources
RBS	Residential building sector
S	Staircase
SR	Study room
T	Toilet
TW	Trombe wall
TZ	Thermal zone
Z1	Shading zone
Z2	Sun-exposed zone

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