EARTH-SHELTERED BUILDING WITH TROMBE WALL AND PERGOLAS AS A FUTURE BIOCLIMATIC AND PASSIVE SOLAR ENERGY-EFFICIENT BUILDING STRATEGY

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In October 2023, the European Union adopted a new green energy policy, mandating a reduction in total final energy consumption to 763 Mtoe by 2030. To achieve these rigorous targets, which include the residential sector (accounting for approximately 25%), the scientific community must intensify efforts to integrate passive solar systems in energy-efficient buildings in the coming period. This paper numerically (using Google SketchUp and EnergyPlus software) investigates the novel energy-efficient building strategy that combines various traditional, bioclimatic, passive solar and green architectural solutions: earth-sheltered building, Trombe wall and horizontally placed pergolas (with seasonal tracking mechanism). The energy benefits of the presented strategy (scenario S3) are proven compared to the earth-sheltered building (scenario S2) and the above-ground building (scenario S1). All buildings are intended for the permanent residence of four-member families during the year and with the same room layout, habits and thermo-technical (space heating, space cooling, water heating, artificial lights and electric equipment) performance. Simulation results indicate that the annual electricity consumption for space heating in the earth-sheltered building with Trombe wall and pergolas (scenario S3) is 52.56% and 15.79% lower than the above-ground building (scenario S1) and the earth-sheltered building (scenario S2), respectively. Using pergolas (in front of the Trombe wall), the annual electricity consumption for space cooling in scenario S3 does not increase compared to scenario S2, while the savings compared to scenario S1 exceed 19%.

Key words: Bioclimatic architecture; Building simulation; Earth-sheltered building; Energy efficiency; Passive solar systems; Pergolas; Trombe wall.

1. Introduction

1.1. Basic terms and definitions

Worldwide energy consumption continues to grow unabated, driven by population growth and increased demand for more computing power by technologies such as artificial intelligence. Between 2015 and 2019, global final energy use climbed about 6.6%, from 392 EJ to 418 EJ [1]. Even more recently, the International Energy Agency (IEA) reported a 2.2% rise in global energy demand in 2024 alone, nearly double the average annual growth of the previous decade [2]. These trends underscore increasing pressure on energy-producing countries and the urgency of improving efficiency and sustainability in all sectors.

Bioclimatic design, green architecture and sustainable development are closely related scientific terms that are often used to describe similar environmental concepts. They all share a unifying goal – minimise the negative impact of buildings on the environment by improving efficiency and exercising restraint in the use of materials, energy, land and ecosystems as a whole [3, 4]. Social needs, traditional and cultural aspects [5, 6], as well as local climatic parameters [7] are also taken into account. In other words, these designs prioritize life cycle thinking, use of renewable and low-impact materials [8] and achieving energy efficiency by design, without overreliance on technology. Essentially, all these descriptions outline an approach that pursues harmony between a building and its occupants, while attaining sustainability through efficiency, moderation and responsiveness to local culture and climate [9].

An exemplary design solution that meets all the mentioned principles is the earth-sheltered building (ESB) – the residential facility is completely or partially covered by soil, which envelops much of its walls and roof. The surrounding soil serves as a natural thermal mass, keeping indoor temperatures steady and drastically reducing energy needs for space heating and cooling. In this way, ESB inherently achieves exceptional energy efficiency passively using renewable energy sources (RES) as geothermal and solar. ESB design uses mainly local materials (soil and rock) and can be very durable and disaster-resistant. Importantly, ESB represents a vernacular architectural tradition worldwide, from prehistoric pit-buildings to Balkan cellar dwellings, indicating a culturally rooted approach in tune with nature. Modern ESBs build on these time-honored ideas while overcoming past challenges [10]. Earlier ESB generations often suffered issues like dampness and structural stress from the surrounding soil, but modern technology has largely solved these problems. For instance, advanced waterproofing membranes and nano-technology enhanced coatings can now prevent moisture intrusion and mold in underground walls [11] and improved structural systems (reinforced concrete shells) bear heavy soil loads with ease. Innovative construction techniques and materials have thus removed the historical limitations of underground building, making ESBs more viable than ever. The result is an extremely energy-efficient dwelling type with great potential for truly sustainable architecture in the future.

The bioclimatic building element developed by Felix Trombe is also of great scientific importance. The passive solar system, known as the Trombe wall (TW), is primarily intended for indirect building heating [12]. TW is always oriented to the south (valid for the northern hemisphere) and consists of the glazing layer, the air gap, and the thick, selective coated [13] thermal mass wall, which is usually made of concrete or masonry [14]. The thermal mass, aided by the selective coating, absorbs solar energy that passes through the glazing. It then stores the heat and gradually transfers it into the building [15]. Contemporary developments, among others, utilize (natural and forced) ventilation [16] and photovoltaic (PV) panels [17], thereby making TW as responsive, multifunctional building elements adaptable to various building types.

Bioclimatic shading elements, such as overhangs [18] and pergolas [19], allow controlling the entry of solar energy into the building, both during the summer and winter seasons. In the first case, they reduce cooling energy consumption, and in the second case, they maximize solar gains. Properly designed external shading elements can reduce cooling energy consumption by up to 20% [20], making a significant contribution to achieving energy efficiency. Although under-researched (unlike overhangs), the contribution of pergolas in buildings is manifold [21]. Given their ability to improve the thermal characteristics of a building, pergolas are gaining increasing importance. In addition, their role extends to the aesthetic aspect. The use of wooden or recycled materials (in combination with climbing plants) further increases the ecological footprint of pergolas, making them sustainable and mainstream solutions [22].

1.2. Literature review

The Republic of Serbia offers numerous advantages for the implementation of ESBs, TWs and pergolas. It features a moderate continental climate with a significant portion of the country characterized by mountainous terrain, including hills and slopes [23]. Steep slopes (5-25°) are prevalent in Western Serbia [24], which makes the region particularly suitable for in-hill ESB designs.

Recent ESB research in Serbia and the broader Balkans has begun documenting the performance gains of this design, affirming its sustainability merits. Milanović et al. [25] investigated the modern ESB in central Serbia. Due to the insulating effect of the surrounding soil, the studied building required much less energy for space heating. The authors noted that such designs can maintain comfortable indoor temperatures with minimal auxiliary heating or cooling, since the surrounding soil provides free insulation equivalent to very high thermal resistance R [m^2KW^{-1}]. The same study highlighted that contemporary materials and technologies (such as improved waterproofing and integration of solar and geothermal systems) now enable ESBs to achieve maximum sustainability and even better energy performance than earlier models. Another recent investigation by Nešović et al. [26] explored the feasibility of the plus-energy ESB in various European climates. Overall, although ESB has not been mainstream, these emerging Balkan studies demonstrate growing interest and confirm that ESB can drastically reduce building energy demands and provide comfortable living conditions. The research momentum in Serbia is building upon both historical precedents and new technology to re-establishing the ESB as a viable model for sustainable building in the region.

Although early Balkan studies on TWs were mostly descriptive, the last decade has seen several quantitative investigations focused on Serbian conditions. A three-dimensional computational fluid dynamics (CFD) study for a passive solar building (with TW) in Belgrade by Bajc et al. [27] showed that optimising glazing and cavity depth cut the modeled annual heating demand by around 20% compared with an identical building without TW. Field-calibrated simulations by Ranđelović et al. [28] demonstrated that, for Niš climate data, increasing the concrete storage layer to its “critical thickness” can lower peak-season heating loads by 40-50%, while also dampening daily indoor temperature swings. A broader parametric study for Niš by Bogdanović et al. [29] demonstrated that enlarging the thermal-mass thickness from 15 cm to 30 cm and properly sizing the ventilating vents reduced peak-season heating loads by ≈33% and improved daily temperature stability. Both papers emphasise vent management and mass thickness as the two dominant design levers for Serbia's continental climate, reinforcing earlier qualitative observations.

Pergolas, timber or metal, supporting seasonal vegetation, are only now appearing in Serbian multi-storey housing, almost exclusively on top-floor terraces. Currently, there are no peer-reviewed Serbian studies on this topic; however, an experiment in a neighboring climate (Transylvania) showed that properly dimensioned fixed pergolas can block up to 90% of incident summer solar radiation while still allowing winter sunlight to pass through [19]. For instance, Sadevi and Agrawal [30], in the context of roof design strategies for energy conservation in Indian buildings, paid special attention to pergolas and their multiple benefits. In [31], pergolas are covered with PV panels. This configuration was implemented in a building to provide solar protection, generate electricity, optimize daylight use, enhance natural ventilation, and ensure privacy. Verheijen et al. [32] utilized a simple free-standing roof structure with pergolas to reduce thermal stress and achieve Comfortable Spaces. They conducted thermal and structural analyses, indicating the significance of these passive solar elements.

1.3. Scientific contribution

Across the reviewed literature, all bioclimatic (and passive) solar elements are considered as a smart design strategy, demonstrating energy and ecological benefits.

For ESB, a numerical investigation for Kragujevac found that infiltrated ESB variants cut final (electrical) energy consumption by between 2.5% and 21.6%, while the elevational ESB archetype exceeded 40% savings for space heating compared with a conventional above-ground building, same geometric, construction and thermotechnical performances [33]. CFD (for Belgrade [27]) and EnergyPlus (for Niš [29]) studies for TW indicate heating-energy reductions in the range of 20-33%, depending on wall thickness, glazing type and vent control strategies. Research on external shading in temperate continental climates shows that fixed pergolas can block up to 90% of direct solar radiation, leading to modeled energy savings exceeding 20% during the summer period [19]. Individually, therefore, all three adopted concepts have confirmed energy- and environment-saving potential in practice.

The residential sector in Serbia remains the single largest electricity consumer, accounting for ≈46% of national final electricity use in 2022 [1]. In parallel, the European revised Energy Performance of Buildings Directive (EPBD) now mandates zero-emission buildings (ZemB) by 2030 and a fully decarbonised building stock by 2050 [23]. Coupled with increasingly volatile energy markets and the intensifying effects of climate change, these policy and market developments demand substantial energy reductions from the residential sector.

By integrating ESB, TW and a seasonally responsive and tracking pergolas into the earth-sheltered building with Trombe wall and pergolas (ESB with TWPs), this numerical study (using Google SketchUp and EnergyPlus software) proposes the bioclimatic and passive solar system that has not yet been examined in the scientific literature, so concept may find greater commercial application in the near future. While the present analysis targets for Serbian moderate continental climate conditions, the underlying simulation workflow and performance indicators are transferable to other European and global regions seeking cost-effective pathways toward ZemB.

2. Building model

2.1. Construction physics

An isometric view of the analyzed building is presented in Fig. 1. The building has a rectangular base, dimensions 20.5×5 m^2, height 2.6 m, so the total floor area and total volume are $A_{fl,tot}$=102.5 m^2 and V_{tot}=266.5 m^3. The form factor is f=1.27 m^{-1} and the window-wall ratio is WW=0.16. All transparent elements (external windows and external door) are located on the south side (Fig. 1).

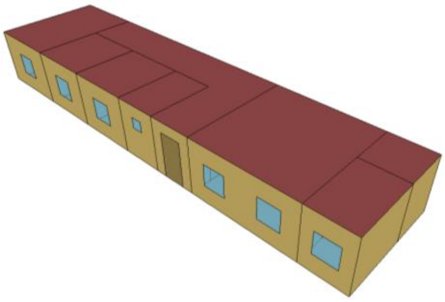
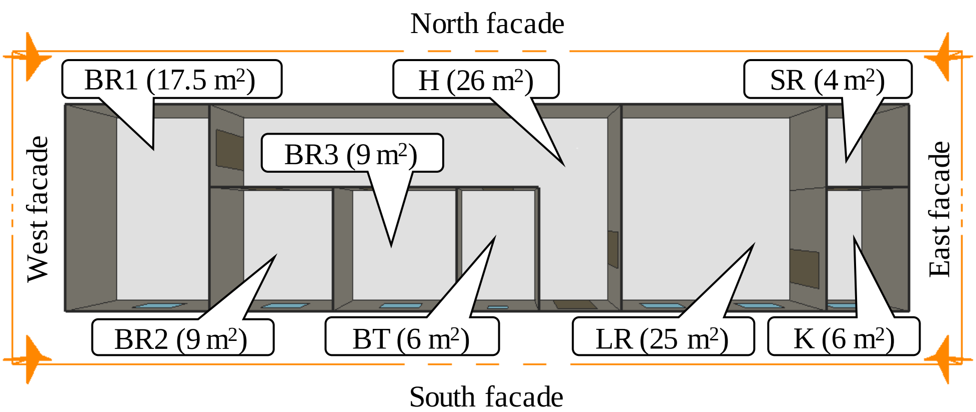


Fig. 1. Isometric view of the analyzed building and south facade wall.

The building interior (arrangement of rooms, i.e. thermal zones) is illustrated in Fig. 2. The building is intended to accommodate a family of four during the year. Parents are accommodated in bedroom 1 (BR1), while children have separate rooms, i.e. bedroom 2 (BR2) and bedroom 3 (BR3). The hall (H) is placed centrally, so that it is directly connected to most rooms, except the kitchen (K) and the storage room (SR).



Legend: BR1 – Bedroom 1; BR2 – Bedroom 2; BR3 – Bedroom 3; BT – Bathroom; H – Hall; K – Kitchen; LR – Living room; SR – Storage room.

Fig. 2. Cross-section view of the analyzed building and room layouts.

The heat transfer coefficients U [Wm^{-2}K^{-1}] of the thermal envelope were adopted following the principles of the Serbian Rulebook on Energy Efficiency of New Buildings [34]. In other words, they are less than the maximum allowed values: U=0.3 Wm^{-2}K^{-1} (for external walls and external floors), U=0.15 Wm^{-2}K^{-1} (for flat roofs), U=1.5 Wm^{-2}K^{-1} (for external windows) and U=1.6 Wm^{-2}K^{-1} (for external door).

The adopted values for the air change n [1/h] (following the same source [34]) for each thermal zone are n=0.5 1/h (BR1, BR2, BR3, H, LR and SR) and n=1.5 1/h (BT and K).

2.2. People, electric equipment, artificial lights and water heater

As previously noted, the building is occupied by parents and their two children. According to their daily routines (going to work and kindergarten), it is expected that no one is present in the building from 08:00 h to 16:00 h. The morning schedule is set for 06:00-08:00 h (waking up, getting ready for work and kindergarten, making meals, breakfast, etc.). The latter part of the day (16:00-23:00 h) includes lunch (16:30-17:00 h), family time in the LR (17:30-19:30 h and 21:00-22:00 h) and dinner (20:00-20:30 h). The children go to bed at 22:00 h, while the parents remain in the LR until 23:00 h.

According to [35], $P_{pl,z}$ and $Q_{pl,z}$ values are defined for each room, i.e. thermal zone (Tab. 1). In the case $Q_{pl,z}$, values are adopted based on dominant metabolic activities: walking (207 $Wper^{-1}$), cooking (171 $Wper^{-1}$), seating (108 $Wper^{-1}$) and sleeping (72 $Wper^{-1}$). Schedules for H and SR are not defined. Namely, H is a transient room, while SR is rarely used on a monthly basis.

Tab. 1. Simulation settings for people, water heater, artificial lights and electric equipment in the thermal zones of the analyzed building.

Thermal zone	$P_{pl,z}$ [per]	$Q_{pl,z}$ [$Wper^{-1}$]	$Q_{eq,z}$ [W]	$Q_{al,z}$ [W]	$L_{al,z}$ [lux]	$Q_{wh,z}$ [W]
BR1	2	72	250	27	100	-
BR2	1	72	200	18	100	-
BR3	1	73	200	18	100	-
BT	1	207	4900	54	700	2000
H	-	-	-	-	-	-
K	4	171	3000	54	700	-
LR	4	108	150	36	100	-
SR	-	-	-	-	-	-

Legend: $L_{al,z}$ [lux] – Reference illuminance values in the thermal zones of the analyzed building; $P_{pl,z}$ [W] – Number of occupants in the thermal zones of the analyzed building; $Q_{al,z}$ [W] – Power of the artificial lights in the thermal zones of the analyzed building; $Q_{eq,z}$ [W] – Power of the electric equipment in the thermal zones of the analyzed building; $Q_{pl,z}$ [$Wper^{-1}$] – Heat gains from one person in the thermal zones of the analyzed building; $Q_{wh,z}$ [W] – Power of the electric water heater in the thermal zones of the analyzed building.

Hourly average heat gains from one person in the analyzed building $Q_{pl,avg}$ [$Wper^{-1}$] increases in the period between 06:00-08:00 h (148.5 $Wper^{-1}$) and 16:00-23:00 h (145.29 $Wper^{-1}$), while the value $Q_{pl,avg,max}$=177.75 $Wper^{-1}$ is reached in the period between 20:00-21:00 h. The electric equipment, analogous an electric water heater, are closely related to the P_{pl} values, so the maximum value of the $Q_{eq,tot,max}$=2822.5 W (hourly total power of the electric equipment in the analyzed building) is reached in the period from 21:00-22:00 h (the largest number of electric equipment are used in the evening hours).

All rooms are equipped with the surface mount lights [36]. For these bulbs (Tab. 1), the return air fraction is RAF=0, the fraction radiant is FR=0.72, the fraction visible is FV=0.18 and the convective heat gain is CHG=0.1. Switching artificial lights on and off is done manually. At a height of 0.8 m from the middle of the floor of each room, a daylight control device, i.e. device for measuring the intensity of illumination is placed (Fig. 3). Although the artificial lights are switched on manually, they work if the measured $L_{al,z}$ values are lower than the set (reference) values (Tab. 1).

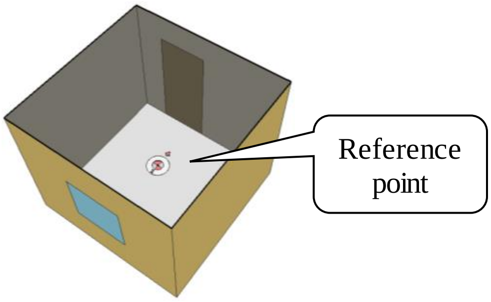
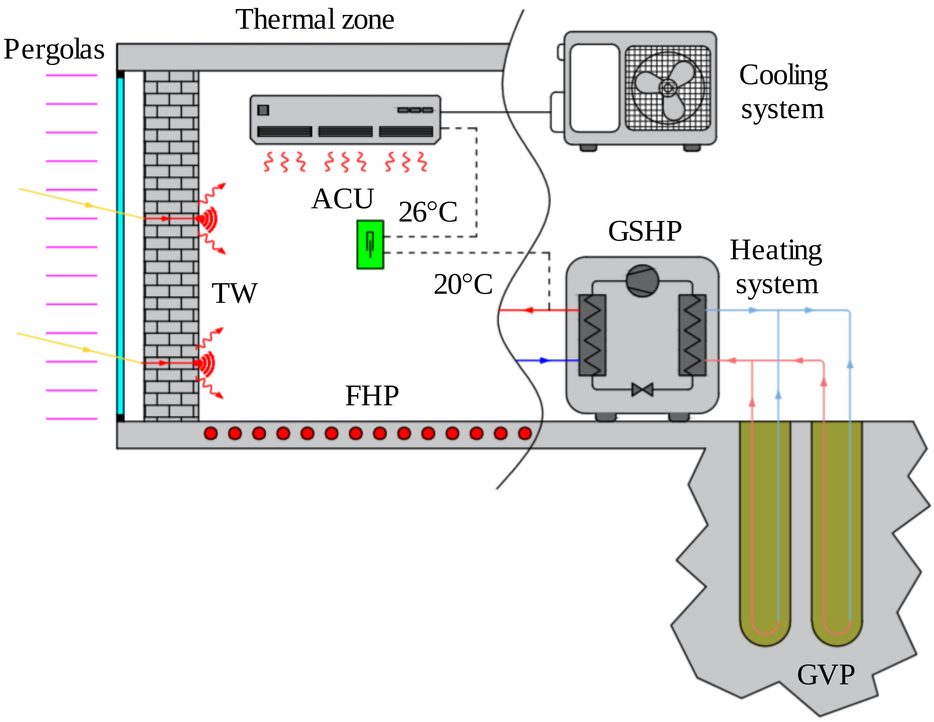


Fig. 3. The zone daylight control system in the analyzed building.

Thermal energy for water heating is provided by an electric water heater, i.e. electric boiler (volume is V_{wh}=80 L and electric power is Q_{wh}=2000 W) positioned in BT (Tab. 1). Hot domestic water is used for washing, showering and other needs. The electric water heater is engaged between 06:00-08:00 h, 16:00-18:00 h and 19:00-21:00 h (preparing meals and maintaining personal hygiene).

2.3. Space heating and space cooling systems

Space heating and space cooling systems (Fig. 4) provide thermal comfort in the building during the year. This is achieved by maintaining temperatures between 20°C and 26°C. The space heating system is activated when the temperature is below 20°C, while the space cooling system is activated when the temperature is above 26°C.



Legend: ACU – Air-conditioner unit; FHP – Floor heating panel; GSHP – Ground source heat pump; GVP – Geothermal vertical probe; TW – Trombe wall.

Fig. 4. Adopted space heating and space cooling systems in the analyzed building.

The heat energy generator (Fig. 4) is the ground-source heat pump (GSHP). The condenser power is $Q_{GSHP,cond}$=7300 W, the compressor power is $Q_{GSHP,comp}$=1600 W, so the coefficient of performance is COP_{GSHP}=4.56. The evaporator power ($Q_{GSHP,evp}$=5700 W) corresponds to the power of two geothermal vertical probes (GVP). The depth of each GVP is D_{GVP}=73.2 m. Thermal energy is supplied to the rooms (thermal zones) by floor heating panels (FHP). The heating installation works with variable water flow (water operating temperature in the secondary circulation circuit between FHP and GSHP is constant and set on t_w=37°C), so it is equipped with appropriate thermostats, circulation pumps, valves, splitters, mixers and by-pass lines.

For space cooling (Fig. 4), the individual air-conditioner units (ACUs) are used (simple solution). The thermal performance of the cooling units is the same for all rooms: $Q_{ACU,evp}$=3500 W and COP_{ACU}= 2.61.

3. Materials and methods

3.1. Trombe wall

TW (Fig. 5) is classified in the literature [37, 38] as a bioclimatic and passive solar heating system because it reduces final energy consumption during the heating season. By combining architectural and mechanical solutions [39], this external building element accumulates absorbed solar energy as thermal energy. The absorbed thermal energy is delivered to the boundary rooms (thermal zones) by well-known principles of heat energy transfer: conduction through the wall, convection and radiation from the wall.

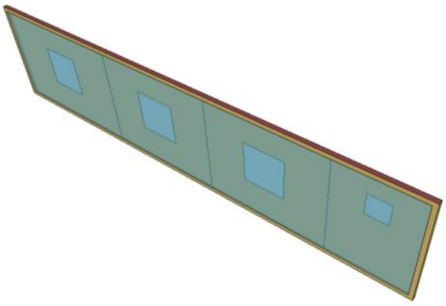


Fig. 5. Isometric view of the Trombe wall in the analyzed building.

The basic TW elements are the glazing layer, the air layer and the selectively coated solid wall. The performance of all of these elements is described in Tab. 2.

Tab. 2. Geometric-thermal performance of the Trombe wall in the analyzed building [35, 36].

Description	Glazing	Air layer	Selective coating	Massive wall
δ [m]	0.003	0.1	0.0016	0.4
k [$Wm^{-1}K^{-1}$]	0.9	-	393	1.73
ρ [kgm^{-3}]	-	-	8907	2242
c_p [$Jkg^{-1}K^{-1}$]	-	-	370	837
τ_s [-]	0.899	-	-	-
r_s [-]	0.079	-	-	-
α [-]	-	-	0.94	0.65
ε [-]	-	-	0.06	0.9

Legend: c_p [$Jkg^{-1}K^{-1}$] – Specific heat of the Trombe wall elements; k [$Wm^{-1}K^{-1}$] – Thermal conductivity of the Trombe wall elements; r_s [-] – Solar reflectance of the glazing layer; α [-] – Absorptance of the Trombe wall elements; δ [m] – Thickness of the Trombe wall elements; ε [-] – Emissivity of the Trombe wall elements; ρ [kgm^{-3}] – Density of the Trombe wall elements; τ_s [-] – Solar transmittance of the glazing layer.

The scientific and professional public indicates that the best location for TW installation is the southern facade wall (due to the longest exposure to sunlight during the day [40]). However, in this case, the external door prevents the complete TW integration with the southern facade wall. This problem is overcome by using the so-called double TW. One TW is placed on the southern facade wall to the right side of the external door. The other TW is placed on the same wall to the left side of the external door.

3.2. Pergolas

Pergolas (Fig. 6) are a type of bioclimatic and passive solar cooling system [41, 42] primarily intended for protection from the Sun and reducing final energy consumption during the cooling season.

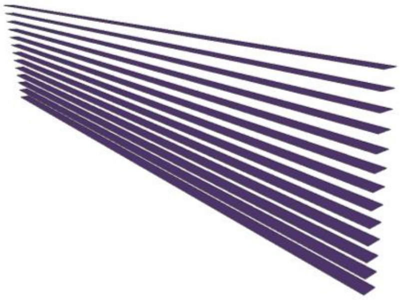


Fig. 6. Isometric view of the pergolas in the analyzed building.

Pergolas can be classified according to many criteria: construction material (wood, aluminum, PVC, wrought iron, glass, recycled, etc.), space position (horizontal, vertical, inclined, gris/cross), visibility (open, semi-open, closed), profile shape (rectangular, square, oval, round, aero, etc.), application area (external, internal), mobility (mobile, immobile), building element (wall, roof) and installation location (terraces, balconies, gardens, cafes, etc.).

Fig. 6 shows the adopted model of pergolas. Pergolas are formed by horizontally placed wooden rectangular boards in front of the double TW. The dimensions of one board in cross-section are 20×2 cm^2. The distance between two adjacent boards is also 20 cm. The length and number of boards are various depending on their position: on the left side of the external door (11.5 m, 13 pieces), on the right side of the external door (7 m, 13 pieces).

To avoid unnecessary solar shading during the heating season, a seasonal tracking mechanism was applied, following the duration of the heating season in Serbia [34]. Pergolas are working from April 16 to October 14 and are not working between October 15 to April 15.

3.3. Meteorological data

Kragujevac (latitude is Φ=44.15°N and longitude is λ=21.03°E) is a city in central Serbia (about 100 km south of Belgrade). City elevation is el=185 m. The climate is moderate continental (Tab. 3).

Tab. 3. Meteorological data for Kragujevac [43].

Month	t_{air} [°C]	φ_{air} [%]	p_{air} [bar]	c_{wd} [m/s]	d_{wd} [°]	H_{beam} [Wm^{-2}]	H_{diff} [Wm^{-2}]
January	0.63	81.03	0.998	1.62	187.39	59.19	39.14
February	3.03	77.50	0.994	1.91	177.82	119.46	49.52
March	7.29	69.86	0.996	1.64	175.24	154.08	74.61
April	12.58	66.82	0.987	1.51	182.53	194.99	91.84
May	16.67	73.47	0.994	1.76	175.78	189.57	115.46
June	20.82	67.78	0.993	2.18	185.08	242.50	111.96

July	22.84	67.52	0.994	1.68	182.68	255.34	101.75
August	23.17	61.86	0.994	1.68	178.58	244.08	87.87
September	17.61	68.94	0.994	1.75	169.02	170.67	80.30
October	12.50	81.08	0.998	1.65	163.90	112.11	62.77
November	8.31	76.66	1	1.98	176.97	103.71	40.14
December	4.23	78.39	0.997	2.22	176.46	60.57	32.57

Legend: c_{wd} [m/s] – Wind speed; d_{wd} [°] – Wind direction; H_{beam} [Wm^{-2}] – Beam solar irradiance on a horizontal plane; H_{diff} [Wm^{-2}] – Diffuse solar irradiance on a horizontal plane; p_{air} [bar] – Atmosferic preasure; t_{air} [°C] – External air temperature; φ_{air} [%] – External relative humidity.

The average monthly t_{air} values are between 0.63°C (January) and 23.17°C (August). The average monthly value of φ_{air} is above 65% and c_{wd} (southeast, south and southwest) is less than 2.3 m/s. H_{beam} and H_{diff} values are the highest during July and May (Tab. 3): 255.34 Wm^{-2} and 115.46 Wm^{-2}.

3.4. Simulation scenario

Fig. 7a shows the initial simulation model of the single-family building. A simple architectural form and design, a flat roof and transparent elements on the southern facade wall characterize it. The building is not equipped with any passive solar system. From the above, it can be concluded that in scenario S1, the energy flows in the above-ground building (AGB) are investigated.

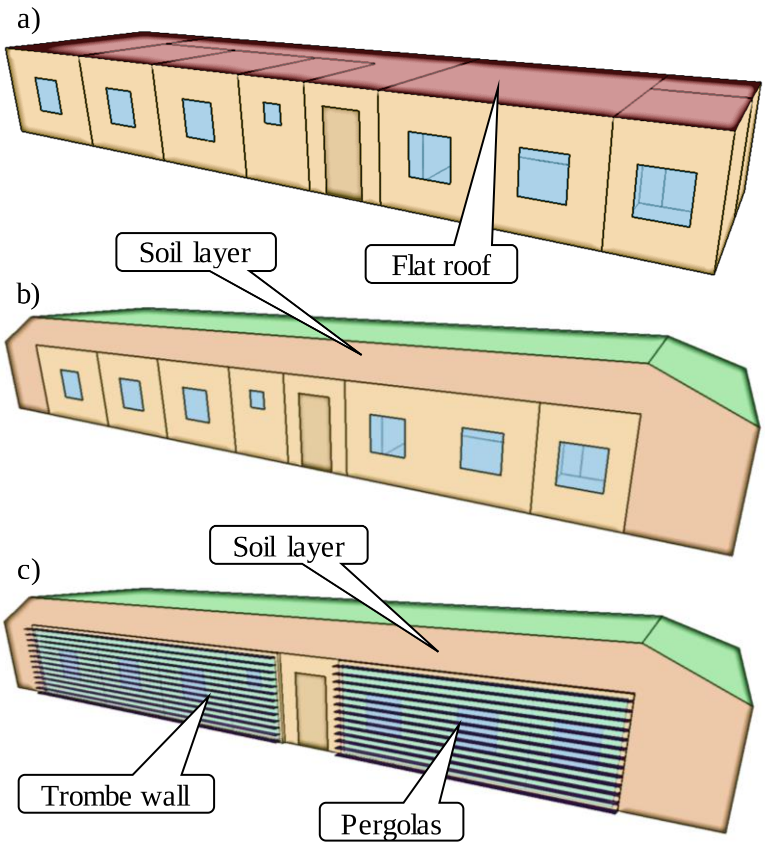


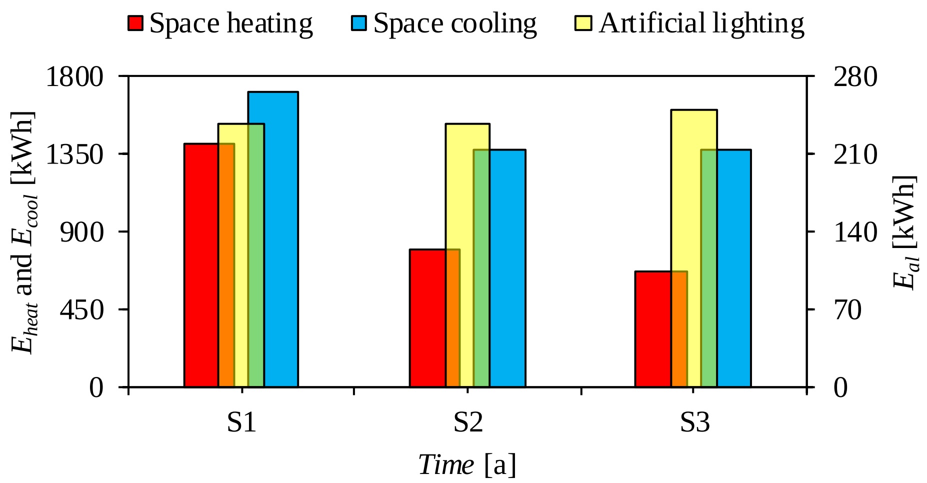
Fig. 7. Scenario simulation od the analyzed building: a) Above-ground building (scenario S1); b) Earth-sheltered building (scenario S2); c) Earth-sheltered building with Trombe wall and pergolas (scenario S3).

In the next phase (scenario S2), the single-family building was modified using a soil layer. This change transfers the building from the above-ground category to the underground category. Therefore, Fig. 7b depicts ESB.

In the last simulation scenario (scenario S3), the single-family building is additionally improved by the integrated use of bioclimatic and passive solar elements: soil layer as building element (ESB), passive solar heating element (TW) and a passive solar cooling element (pergolas). This novel concept (ESB with TWPs) is intended to reduce electricity energy consumption for space heating and space cooling and is graphically presented in Fig. 7c.

4. Results and discussion

The following figure (Fig. 8) separately shows the annual electricity consumption for space heating E_{heat} [kWh] (Fig. 8a), space cooling E_{cool} [kWh] (Fig. 8b) and artificial lights E_{al} [kWh] (Fig. 8c) depending on the simulation scenario: scenario S1 (AGB), scenario S2 (ESB) and scenario S3 (ESB with TWPs).



Legend: E_{heat} [kWh] – Electricity consumption for space heating in the analyzed building; E_{cool} [kWh] – Electricity consumption for space cooling in the analyzed building; E_{al} [kWh] – Electricity consumption for artificial lights in the analyzed building.

Fig. 8. Annual electricity consumption in the analyzed building depending on the simulation scenario: a) Space heating; b) Space cooling; c) Artificial lights.

Annual electricity consumption for space heating E_{heat}, depending on the examined scenario, is respectively (Fig. 8a): 1412.69 kWh (S1), 795.88 kWh (S2) and 670.24 kWh (S3). By introducing the specific heating indicator e_{heat} [kWhm^{-2}] ($e_{heat}=E_{heat}/A_{fl,tot}$), it can be concluded that in the first case annual heating electricity consumption is slightly higher than 10 kWhm^{-2} (13.78 kWhm^{-2} in S1), while in the remaining two cases it is lower than 10 kWhm^{-2} (7.76 kWhm^{-2} in S2 and 6.54 kWhm^{-2} in S3). The percentage savings S_{heat} [%] compared to the reference building model (S1) are 43.66% (for S2) and 52.56% (for S3). This means that E_{heat} in ESB with TWPs can be reduced by over 15% compared to the ESB.

Analogous to Fig. 8a, annual electricity consumption for space cooling E_{cool} is the highest (1705.71 kWh) in S1, while the lowest (1374.11 kWh) is in S3. Fig. 8b shows that E_{cool} is approximately the same in scenarios S2 (1377.4 kWh) and S3, which means that the percentage savings S_{cool} [%] compared to the S1 scenario are 19.25% (S2) and 19.44% (S3). Unlike e_{heat}, annual specific cooling indicator e_{cool} [kWhm^{-2}] (e_{cool}=E_{cool}/$A_{fl,tot}$) is greater than 10 kWhm^{-2} in all analyzed scenarios (Fig. 8b): 16.64 kWhm^{-2} (S1), 13.44 kWhm^{-2} (S2) and 13.41 kWhm^{-2} (S3).

Contrary to the indicators E_{heat} and E_{cool} (which are characterized by the decreasing trend), annual electricity consumption for artificial lights (Fig. 8c) is described by the growing trend in scenario S3 (E_{al}=249.79 kWh). Compensating for the reduced yield of daylight by additional use of artificial lights is justified for two reasons: (1) the existence of the additional glass layer and (2) increasing solar shading due to pergolas. In scenarios S1 and S2, this consumption is identical (237.28 kWh). The reasons are justified because the daylight yields in the mentioned buildings are the same (due to the use of windows with the same orientation and identical geometric, optical and thermal characteristics), regardless of the use of the soil layer.

If all three simulation scenarios are compared with each other based on the total energy balance (E_{tot}=E_{heat}+E_{cool}+E_{al}) in which the variables analyzed in Fig. 8, the (total) annual electricity consumption in scenario S1 is 3355.68 kWh, while in the remaining scenarios S2 and S3 it is lower by S_{tot}=27.17% (2410.54 kWh) and by S_{tot}=31.63% (2294.14 kWh).

The results shown in Fig. 8 draw attention to the fact that E_{cool} in all scenarios is higher than E_{heat} and with a growing tendency: for 293.02 kWh (in scenario S1), for 581.52 kWh (in scenario S2) and for 703.87 kWh (in scenario S3). On the one hand, current climate changes [44] and the used weather files are responsible for this and on the other hand, internal heat gains[1] (from people, artificial lights, electric equipment, i.e. E_{eq}=4703.94 kWh and water heater, i.e. E_{wh}=1697.25 kWh), which simultaneously reduces the heating system engagement and increases the cooling system engagement. Simulations in scenario S2 (for the soil layer) showed that these differences can be further increased because the reduction gradient of electricity consumption is greater on the heating system side than on the cooling system side. The differences are maximized (in this case, in scenario S3) when TW is used to additionally reduce the thermal energy consumption and pergolas to prevent an increase in the cooling energy consumption.

A more detailed (on the monthly level) structure of the annual electricity consumption for space heating (Fig. 9a), space cooling (Fig. 9b) and artificial lights (Fig. 9c) is shown in Fig. 9.

In the case of heating E_{heat}, the highest electricity amount is used during January (Fig. 9a): 439.41 kWh in S1, 269.87 kWh in S2 and 251.43 kWh in S3. December shows the second highest (the same diagram): 338.49 kWh in S1, 189.24 kWh in S2 and 173.41 kWh in S3. April (E_{heat}<10 kWh in all cases) and October (E_{heat}<45 kWh in all cases) are transitional periods of the year when there are small needs for heat energy. In the period from May to September, the heating system does not work (Fig. 9a). When the monthly heat curves are compared with each other, the S1 heat curve is positioned the highest in all months except October (in that case, the S3 heat curve can be said to be positioned the lowest, except during the mentioned month). This discontinuity in E_{heat} consumption is the result of the solar shading effect of the working regime (until October 14) in which pergolas is engaged.

Cooling needs E_{cool} are highest during August (Fig. 9b): 381.8 kWh in S1, 267.45 kWh in S2 and 202.97 kWh in S3. During May, June, July, August, September and October, the S2 cooling curve is completely above the S3 cooling curve, while the S1 cooling curve is completely above the S2 cooling curve. This means that the monthly electricity consumption for space cooling is the highest in scenario S1 and the lowest in scenario S3. However, during November (for 81.06% and 73.82%), December (for

[1] Electricity consumption for electric equipment and water heater is the same in all simulation scenarios.

5.81% and 1.79%), January (for 9.12% and 4.87%), February (for 42.65% and 35.86%), March (for 88.26% and 83.11%) and April (for 116.99% and 112.56%), the S3 cooling curve is above the S1 and S2 cooling curves, which proves that during the mentioned months, in ESB with TWPs, additional amounts of cooling energy enter to avoid overheating.

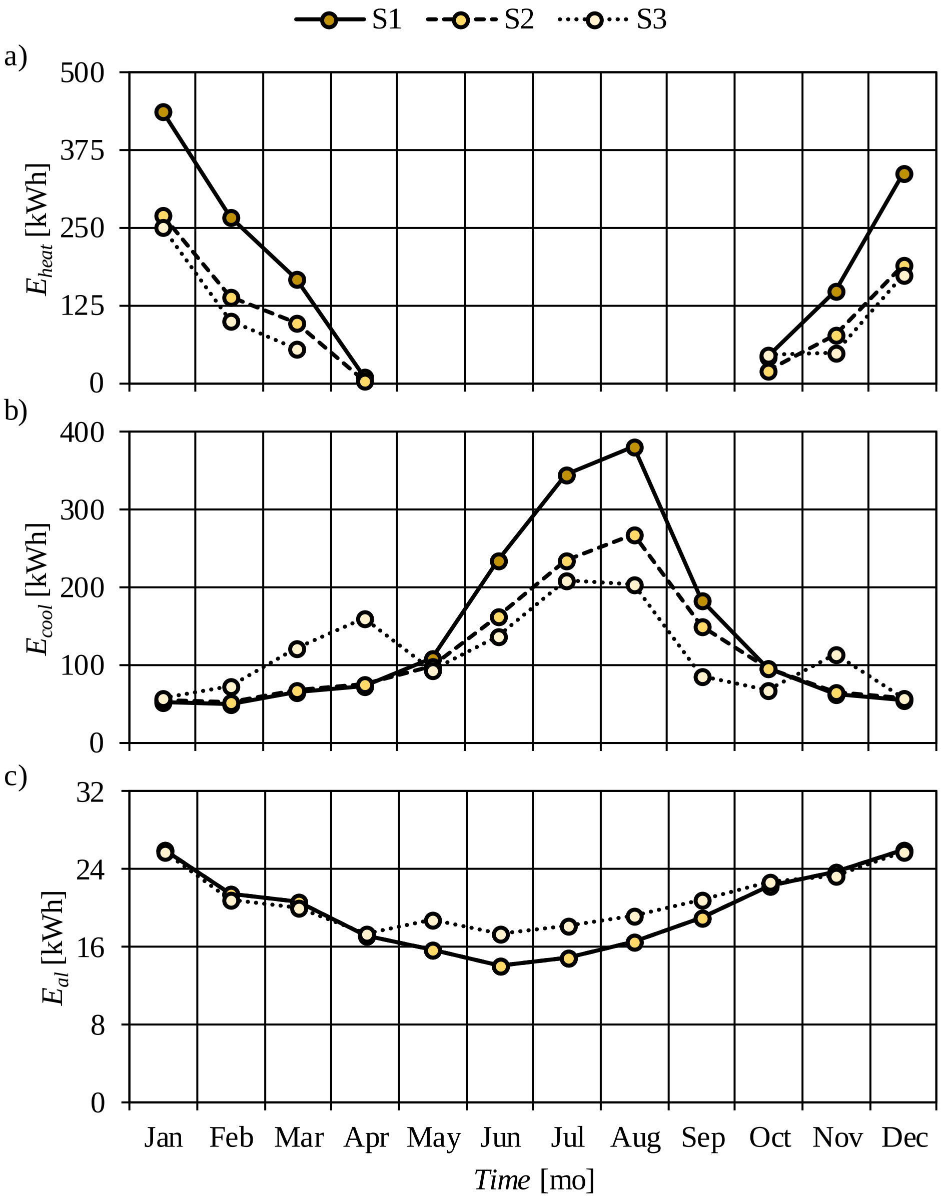


Fig. 9. Monthly electricity consumption in the analyzed building depending on simulation scenario: a) Space heating; b) Space cooling; c) Artificial lights.

Analogous to Fig. 8c, E_{al} monthly consumption is the same in scenarios S1 and S2 (the highest is in December (26.02 kWh), while the lowest is in June (14.1 kWh). If the monthly values in scenario S1 and scenario S2 are used as reference, the percentage increase in consumption in scenario S3 will proceed as follows (Fig. 9c): -0.86% (January), -2.91% (February), -3.33% (March), 0.29% (April), 19.63% (May), 23.49% (June), 21.71% (July), 16.87% (August), 9.59% (September), 2.26% (October), -1.82% (November) and -1.09% (December). The mentioned data for E_{al} indicate the negative features (during the summer season) of the proposed (novel) concept, but these are not of crucial importance in the overall energy balance.

5. Conclusion and future research directions

The research subject in this paper was the earth-sheltered building with Trombe wall and pergolas. The presented building concept was based on the active (heating and cooling thermo-technical systems) and bioclimatic and passive solar (Trombe wall and pergolas) use of the renewable energy sources (solar and geothermal energy) and location parameters (terrain slope and soil performance). This is a novel architectural style that is in line with European principles of energy efficiency in buildings, sustainable development, circular economy and environmental protection.

The building model was created in Google SketchUp software following the Serbian Rulebook on Energy Efficiency of New Buildings. The thermo-technical systems (space heating, space cooling, water heating, artificial lights and electric equipment), people occupations and equipment usage schedules are defined in EnergyPlus software. It is assumed that a family of four will permanently reside in the building.

The results of numerical simulations emphasize the positive aspects (in the total balance) of such buildings during the year, which are primarily reflected in reduced energy consumption for space heating (to 6.54 $kWhm^{-2}$ due to using the soil layer and Trombe wall) and space cooling (to 13.41 $kWhm^{-2}$ due to using the soil layer and pergolas). On the other hand, the two main negative aspects were also detected, which relate to: (1) visual comfort (due to the use of pergolas from April 16 to October 14) and (2) thermal comfort (due to potential overheating during the winter season, which is directly dependent on indoor heat gains). The results of the numerical research passed validation because the percentage energy saving values for all bioclimatic and passive building elements individually showed agreement with the results of similar research in the available literature.

Future research directions should focus on better understanding the cause-and-effect relationships between heat gains, heating and cooling systems and the passive solar (heating and cooling) systems. This includes defining measures for maximizing daylights (minimizing artificial lights), exploring the possibilities of implementing photovoltaic panels and other renewable energy sources (for example, passive cooling using wind energy), optimizing geometry design of the pergolas and developing strategies for Trombe wall cooling, investigation of the solar shading elements with various tracking mechanisms and working scenarios.

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