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Approaching the single-family building to the zero residential building status by implementing photovoltaic panels and external wall-roof pergolas for different locations in the Western Serbia region

Aleksandar Nešović [a], Aleksandar Radaković [a], Dragan Cvetković [a], Robert Kowalik [b,*], Igor Saveljić [a]

[a] Institute for Information Technologies, University of Kragujevac, Jovana Cvijića bb, 34000 Kragujevac, Serbia
[b] Faculty of Environmental Engineering, Geodesy and Renewable Energy, Kielce University of Technology, Tysiaclecia P.P. 7, 25-314 Kielce, Poland

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ABSTRACT

With the legislative strengthening of the Energy Efficiency Directive in October 2023, Europe established a new green energy policy that mandates reducing total final energy consumption to 763 Mtoe by 2030. Given that the residential building sector currently accounts for approximately 25 % of this consumption, it is clear that promoting energy-efficient residential buildings will be significantly intensified in the near future.

Following current trends, this paper critically investigates the energy, ecological and economic aspects of active (photovoltaic panels) and passive (external wall-roof pergolas) solar systems to approach the single-family building to the zero residential building status in the Western Serbia region for the following two main reasons: (1) Serbia (the same applies to the Balkan Peninsula) represents critical link in the European energy transformations chain and (2) solar potential for a moderate continental climate is about 40% higher than the European average.

All three residential building models (building without solar systems – scenario S1, building with photovoltaic panels – scenario S2 and building with photovoltaic panels and external wall-roof pergolas – scenario S3) were created in the Google SketchUp software following the Serbian Rulebook on Energy Efficiency for New Buildings. All thermo-technical systems (home appliances, internal lighting, water heating, space heating – central heating system with pellet boiler and radiators, space cooling – individual air-conditioner units, photovoltaic panels and pergolas) and people occupancy are simulated using the EnergyPlus software.

Based on the conducted simulations and obtained results (for 10 different locations in the adopted region) the following main conclusions can be drawn: (1) the Western Serbia region is suitable for green (sustainable) architecture and energy-efficient residential buildings, (2) depending on the location parameters, pergolas can reduce the area of photovoltaic panels by 0.92–5.07 m^2 without endangering the zero-energy residential building status, (3) thermo-technical systems based on renewable energy sources for space heating and cooling positively contribute to the zero-emission residential building status (carbon footprint), but not always zero-cost residential building status and (4) zero residential building concept is not possible without responsible occupancy behavior.

1. Introduction

1.1 Research topic – Basic definitions.

The European residential building sector faces challenges in reducing energy consumption [1], dependence on fossil fuels [2], and greenhouse gas emissions [3] – key factors in achieving sustainable development [4].

On the way to achieving the goals mentioned above, the scientific community firstly defined the boundary (annual specific final energy consumption for space heating is $e_{fin,heat} = 30–50\ kWh/m^2$ [5]) between non-energy-efficient residential buildings (NEERBs) and energy-efficient residential buildings (EERBs), and then additional sub-criteria for further classifying EERBs [6]: low-energy residential buildings (LERBs), passive residential buildings (PRBs), zero residential buildings (ZRBs), autonomous residential buildings (ARBs) and plus-energy residential buildings (PERBs).

To keep pace with technological development, the criteria for

* Corresponding author.
E-mail address: rkowalik@tu.kielce.pl (R. Kowalik).

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Nomenclature

Mark	Description [Unit]
A	Area [m^2]
a	Direction [°]
C	Specific price [€/t]
c	Speed [m/s]
CHG	Convective heat gains [–]
COP	Coefficient of performance [–]
D	Depreciation price [€]
E	Energy consumption [kWh]
e	Specific final energy consumption [kWh/m^2]
F	Fraction [–]
f	Form factor [1/m]
FR	Fraction radiant [–]
FV	Fraction visible [–]
g	Specific CO_2 emission [kg/kWh]
I	Solar irradiance [W/m^2]
J	Specific calorific value [kWh/t]
M	Price [€]
m	Mass [kg]
MR	Metabolic activity rate of the people [W/per]
n	Air changes [1/h]
P	People occupancy [per]
PB	Payback period [a]
Q	Power [W]
R	Primary energy conversion factor [–]
RAF	Return air fraction [–]
S	Percentage savings [%]
t	Temperature [°C]
U	Heat transfer coefficient [W/m^2K]
V	Volume [m^3]
WW	Window-wall ratio [%]
X	Investment costs [€]

Greek letters

β	Inclination angle [°]
η	Efficiency [–]
φ	Safety factor [–]

Subscripts

acu	Air-conditioner units
beam	Beam solar irradiance
bef	Before
bz	Blue energy zone
cool	Space cooling
diff	Diffuse solar irradiance
el	Electricity
fin	Final
fl	Floor
gz	Green energy zone
ha	Home appliances
heat	Space heating
in	Internal, inlet
inv	Inverter
l	Internal lighting
m	Month
op	Operative (working)
otn	Other needs
out	External, outlet
pb	Pellet boiler
perg	Pergolas
pn	Pipe network
pry	Primary
rad	Radiator
rs	Regulation system
rz	Red energy zone
sr	South roof
tot	Total
use	Useful
wd	Wind
wh	Water heater

Abbreviation

ARB	Autonomous residential building
AS	Attic space
BR	Bedroom
BT	Bathroom
D	Door
DHS	District heating system
EERB	Energy-efficient residential building
EF	External floor
EW	External wall
H	Hall
IFC	Intermediate floor construction
K	Kitchen
KG	Kragujevac
KO	Kopaonik
KV	Kraljevo
KŠ	Kruševac
LERB	Low-energy residential building
LO	Loznica
LR	Living room
NEERB	Non-energy-efficient residential building
NRB	Non-residential building
PCM	Phase change material
PERB	Plus-energy residential building
PRB	Passive residential building
PV	Photovoltaic
PŽ	Požega
RB	Residential building
RES	Renewable energy sources
SJ	Sjenica
SR	Slope roof
STC	Solar thermal collector
T	Toilet
TW	Trombe wall
TZ	Thermal zone
VA	Valjevo
W	Window
ZB	Zero building
ZcRB	Zero-cost residential building
ZemRB	Zero-emission residential building
ZenRB	Zero-energy residential building
ZL	Zlatibor
ZRB	Zero residential building

selecting an adequate EERBs are becoming stricter. Consequently, after LERBSs and PRBs, currently ZRBs [7,8] represent an important transitional concept supported and promoted by the wider scientific community.

In the literature, the ZRB status is achieved if one of the following three conditions is met: (1) annual net-zero energy balance – zero-energy residential buildings (ZenRBs) [9], (2) annual net-zero CO_2 emission balance – zero-emission residential buildings (ZemRBs) [10] and (3) annual net-zero money cost balance – zero-cost residential buildings (ZcRBs) [11].

All three ZRB concepts are based on defining optimal conditions for thermal (internal project temperatures for space heating $t_{in,heat}$ [°C] and cooling $t_{in,cool}$ [°C]) and air comfort (air exchange), minimizing the heat transfer coefficients of building elements within the thermal envelope U-value [W/m^{2}K], using smart thermo-technical (space heating, space cooling, ventilation, internal lighting, home appliances, water heating, etc.) systems and renewable energy sources (RES), as well as the responsible occupant behavior.

Experimental, numerical and theoretical studies proved that the implementation of passive RES systems (primarily solar and geothermal) also contributes to achieving ZRB status. The orientation of the buildings, soil layers, Trombe walls (TWs), selective facade walls, phase change materials (PCMs), shading building elements (overhangs, vegetations, blinds, pergolas, awnings, curtains and similar components), etc., significantly reduce final and primary energy consumption for space heating ($E_{fin,heat}$ [kWh], $E_{pry,heat}$ [kWh]) and cooling ($E_{fin,cool}$ [kWh], $E_{pry,cool}$ [kWh]). For example, properly designed external shading elements can reduce $E_{fin,cool}$ by up to 30 %, which is a significant contribution to achieving zero building (ZB) status.

Pergolas are shading building elements [12] because they are primarily intended for Sun protection – cooling passive solar systems, but also can be used for protection from rain and other weather conditions. In addition, their role extends to the aesthetic aspect, because wooden pergolas with their natural appearance contribute to the visual identity of the building, making it more attractive and valuable in the real estate market. Therefore, they are often treated as bioclimatic systems in the literature [13]. Pergolas can be classified according to many criteria: (1) material (wood, aluminum, PVC, wrought iron, glass, recycled), (2) space position (horizontal, vertical, inclined, gris/cross), (3) visibility (open, semi-open, closed), (4) profile shape (rectangular, square, oval, round, aero), (5) application area (external, internal), (6) mobility (mobile, immobile), (7) building element (wall, roof) and (8) installation location (terraces, balconies, gardens, cafes).

1.1. Literature review

Many examples of the ZBs can be found in European literature. Annunziata et al. [14] showed (by a multidisciplinary approach) the importance of harmonizing national regulations and strategies with the ZB concept. The connection between ZBs and embodied energy using life cycle energy analysis was investigated in [15]. Differences between deep, major and ZBs renovation are investigated in [16]. The same paper provides an overview of best practice policies and measures to target retrofit and investment related to non-residential buildings (NRBs). A review paper, presented in [17], focused on the real ZBs. The idea of the paper was to investigate the future development strategies of the ZB concept through an overview and analysis of technical aspects. D'Agostino et al. [18] analyzed technologies and costs to (1) evaluate the progress of ZBs in Europe and (2) define future directions of development based on the previous definition of the main challenges. For example, in [19] a review paper was presented which, among other things, established that the ZB performances vary greatly in European countries and that the contribution of RES is 9–55 %. The significance of the use of photovoltaic (PV) panels for the achieved ZB status in different European climate areas (Mediterranean, Continental, Oceanic and Nordic) was numerically investigated in [20].

The financial and energy aspects of applying solar systems within the ZB concept, in the example of a single-family home in Southern Europe, were investigated using dynamic thermal simulation [21]. Attia et al. [22] detected current and future problems and challenges faced by ZBs in the same region (Southern Europe). Based on empirically substantiated evidence, in the same paper, recommendations are given for overcoming existing and future barriers (climatic, societal and technical) characteristic of the analyzed region. In [23], EnergyPlus is used as a support tool for the early stages of zero-energy building design in Egypt. Resende and Corvacho [24] applied the multi-objective optimization to reduce thermal discomfort in the ZBs. For this purpose, the authors used current construction solutions and ZB regulations for different climate zones in the Southern Europe region.

The situation in the Balkan Peninsula (also applies to Serbia) is similar to the global trend [25], with the residential building sector taking part in more than 30 % of total final energy consumption $E_{fin,tot}$ [kWh]. Various ZB concepts, strategies, case studies, optimization examples, etc., have been discussed in Bosnia and Herzegovina [26], Slovenia [27], Croatia [28], Bulgaria [29], North Macedonia [30], Montenegro [31], Turkey [32], Greece [33] and Albania [34].

Within the Serbian legislative framework, Bojić et al. [35] numerically (using EnergyPlus software) analyzed the installation of PV systems of different production capacities to achieve the ZB status. For example, Todorović [36] pointed out the importance of rehabilitation of existing buildings in Belgrade (Serbia), which also represent objects with large ZB potential. In the study presented in [37], optimization (using the Hooke-Jeeves algorithm) of the PV panel area was performed for the specific ZB model designed in Google SketchUp software. Minimum requirements to reach ZB for different categories of buildings in Serbia were investigated in [38].

Unlike the majority of passive systems, pergolas have not received sufficient attention in the ZB concepts, although their contribution can be manifold [39,40]. Papers available in [41–43] showed that wood materials, as a renewable resource, further increase the ecological footprint of pergolas, making them a sustainable solution – bioclimatic passive elements. Combining wooden pergolas with climbing plants to improve thermal comfort in a building during the summer season was investigated in [44]. Sadevi and Agrawal [45], within the framework of roof design strategies for energy conservation (in Indian buildings), paid special attention to pergolas and their multiple importance. In the literature, pergolas are often covered with PV panels [46]. This solution was implemented in the building to ensure solar radiation protection, electricity production, optimize daylight harvesting, facilitate natural ventilation, and provide privacy. Verheijen et al. [47] used a simple free-standing roof structure with pergolas to reduce thermal stress and achieve Comfortable Spaces. They conducted thermal and structural analyses, which indicated the importance of these passive solar elements.

1.2. Knowledge gap

Improving the energy efficiency of the residential building sector is not possible without implementing energy efficiency measures on RBs.

For example, the Serbian Rulebook on the Close Conditions for the Distribution and Use of Funds for the Implementation of Energy Efficiency Measures from 2024 [48] defined target groups related to: (1) insulation of the thermal envelope and replacement of carpentry, (2) improvement of thermo-technical systems, (3) modernization of internal lighting, (4) installation of solar thermal collectors (STCs), (5) modernization of public lighting, (6) rehabilitation of the district heating system (DHS), (7) installation of PV panels and (7) other measures following national incentives.

The same Rulebook [48] does not include measures that imply the application of passive solar systems, so this is the first gap pointed out by this paper.

Although in practice there are isolated cases of installing pergolas (top floors of multi-storey RBs, outdoor cafes, independent garden systems), a wider commercial application cannot be expected without the inclusion of scientific and technical support, which, in addition to the aesthetic aspects that are currently in focus, will also indicate energy and environmental benefits.

In the available literature (also valid for the Balkan Peninsula and Serbia), it was observed that the papers primarily focus on capital investments to achieve the EERB status, even though energy classes can be enhanced with simple solutions that require low financial investments.

Theoretical and numerical research (characteristic for the Balkan Peninsula and Serbia) is mainly applied to individual cases of ZRBs in specific circumstances. In other words, the literature lacks studies and papers where ZRBs are analyzed over a wider territorial area, in moderate continental climate conditions, taking into account the specificity of the locations and recent meteorological data, i.e. ongoing climate change.

The same applies to a multidisciplinary approach based on the use of energy, environmental and economic indicators.

1.3. Scientific contribution

Based on the review of available literature and the detected knowledge gaps, this paper presents the ZRB concept, where the single-family building is equipped with PV panels and external wall-roof pergolas. This ZRB concept can give a positive impulse to regions with a moderate continental climate to follow the binding European strategy, whereby the specific design of an external pergola with seasonal (manual) tracking mechanism has not been investigated in scientific circles so far.

Energy, environmental and economic aspects of the proposed solution (based on the combined use of active and passive solar systems) are being investigated in a specific territorial area, i.e. Western Serbia Region, including 10 different locations (towns).

The entire research involves numerical analysis, using Google SketchUp and EnergyPlus software. Unlike other ZRB examples, in this case, the central heating system with a pellet boiler and radiators (for space heating) and individual air-conditioner units (for space cooling) were adopted. The reason is their wide distribution in Serbia in general.

Among other things, this paper aims to show that relatively simple passive measures can reduce the required capacity of PV panels without compromising the ZenRB and ZemRB status, as well as that the issue of reaching the ZcRB status is very sensitive.

2. Materials

2.1. Research subject – thermal envelope

Design of the single-family buildings in Western Serbia relies heavily on traditional architecture [49]. These are most often simple and compact objects [50]. All functional rooms are located on the ground floor, while above them is attic space (AS). AS is formed by a double-pitched roof and two opposite calcaneus walls. Due to the stepped shape of the base, AS has the role of passive solar cooling elements (like overhangs). The mentioned characteristics make them suitable for the application of active and passive solar systems, as well as other heating and cooling thermo-technical systems.

One such residential building, intended for the permanent residence of a family of four, is the subject of research (Fig. 1). The isometric view is shown in Fig. 1a, the cross-section view in Fig. 1b, while all four (South, West, North and East) facade views are shown in Fig. 1c. From the attached, it can be concluded that the entrance door is oriented to the West, while the balcony door is oriented to the East. The cross-section view provides an insight into the room layout, i.e. thermal zones (TZ), described in Table 1.

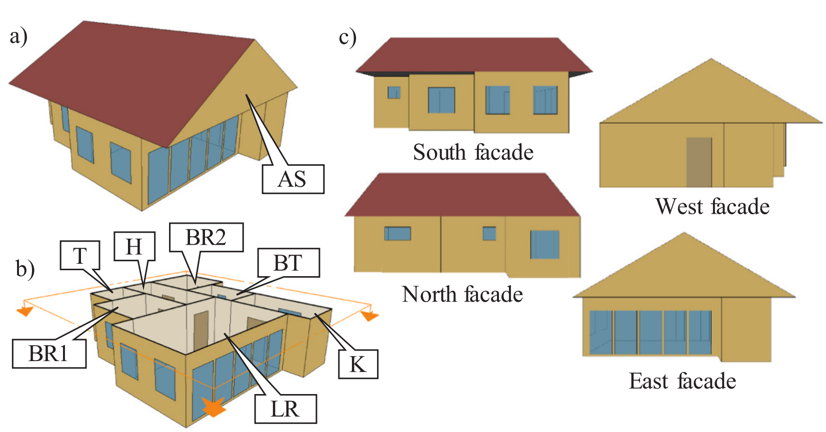
The total net floor area of the residential building is $A_{fl,tot} = 160$ m^2, while the total volume of the residential building is $V_{tot} = 299$ m^3. The total window-wall ratio of the residential building is $WW_{tot} = 13.27$ % and the total form factor of the residential building is $f_{tot} = A_{tot}/V_{tot} = 0.535$ 1/m (where A_{tot} [m^2] is the total thermal envelope area of the residential building). The total intermediate floor construction (IFC) area of the residential building is $A_{IFC,AS} = 13$ m^2 (Table 2). This surface participates in the creation of passive solar cooling elements for the following thermal zones (Table 1): T (4 m^2), BR1 (3 m^2) and LR (6 m^2).

The residential building model (Fig. 1) was created in Google SketchUp software following the Serbian Rulebook on Energy Efficiency for New Buildings [51]. Air changes (Table 1) are adopted depending on the TZ purpose, while *U*-values (Table 2), for all building elements that participate in the creation of the thermal envelope, do not exceed the

Table 1
Description of the thermal zones [51].

TZ	AS	BR1	BR2	BT	H	K	LR	T
$A_{fl,TZ}$ [m^2]	90	9	9	6	10	8	24	4
V_{TZ} [m^3]	117	23.4	23.4	15.6	26	20.8	62.4	10.4
n_{TZ} [1/h]	0.5	0.5	0.5	1.5	0.5	1.5	0.5	1.5

Legend: $A_{fl,TZ}$ [m^2] – Net floor area of the thermal zone, V_{TZ} [m^3] – Net volume of the thermal zone and n_{TZ} [1/h] – Air changes in the thermal zone.



Legend: AS – Attic space, BR1 – Bedroom 1, BR2 – Bedroom 2, BT – Bathroom, H – Hall, K – Kitchen, LR – Living room and T – Toilet.

Fig. 1. Single-family building: a) Isometric view, b) Cross-section view and c) Facade views.

Table 2
Heat transfer coefficients of the building elements [51].

U [W/m^{2}K]	D	EF	EW	IFC	SR	W
	1.6	0.3	0.3	0.2	0.3	1.5

Legend: D – Door, EF – External floor, EW – External wall, SR – Slope roof and W – Window.

maximum allowed values.

2.2. People occupancy, home appliances, internal lighting and water heating

As already mentioned, the residential building (Fig. 1) is occupied by four people during the year (parents with two small children). Based on their daily work (kindergarten) habits and other activities (Table 3), the four occupancy scenarios were developed, using EnergyPlus software: the weekday schedule, the Saturday schedule, the Sunday schedule and the schedule without occupancy due to winter (from 11 February to 20 February) and summer (26 July to 5 August) vacations. The first three scenarios can be seen in the following figures: Fig. 2 (people occupancy), Fig. 3 (home appliances) and Fig. 4 (internal lighting).

The working day starts at 06:00 h (Fig. 2). Until then, the parents are in BR1, and the children are in BR2 (sleep time). The time frame from 06:00–08:00 h is reserved for usual preparations for work and kindergarten: using T and BT, dressing, preparing breakfast (06:30–07:00 h) and having breakfast together (07:00–07:30 h). From 08:00 h to 16:00 h there is no occupancy in the single-family building (parents are at work and children are at kindergarten). Lunch lasts from 16:30–17:00 h, and dinner from 20:00–20:30 h. Joint socializing (in LR) is reserved from 17:30–19:30 h and 21:00–22:00 h. Children go to sleep at 22:00 h. Parents stay in LR until 23:00 h, and after that (from 23:00 h) they go to BR1.

Saturday is the first non-working day, so a long period is dedicated to rest. In other words, BR1 and BR2 leave at 09:00 h. During this day, family activities are somewhat different. Breakfast is from 09:30–10:00 h, lunch is from 16:00–16:30 h, and dinner is from 20:30–21:00 h. The family is together in LR on two occasions (13:00–15:30 h and 21:30–23:00 h). Joint activities (walking, going to the cinema or something similar) outside the home are planned between lunch and dinner (17:00–20:00 h).

Sunday starts a little later than the working day (at 07:30 h). The morning routine ends with the first meal of the day (until 08:30 h). After certain preparations (from 08:30–09:00 h), the family leaves the single-family building. They return home at 13:00 h. The second daily meal starts at 16:30 h, and the third at 20:30 h. During the duration of all meals, K is maximally occupied (4 of them). LR is also maximally occupied during some parts of the day (14:00–16:00 h, 17:30–20:00 h and 21:30–22:00 h). Children go to sleep at 22:00 h, when parents do too, because the next day they get up at 06:00 h (the weekdays schedule comes into effect again).

Electricity consumption from home appliances $E_{ha,TZ}$ [kWh] (Fig. 3) and internal lighting $E_{l,TZ}$ [kWh] (Fig. 4) in the single-family building is closely related to the people occupancy defined in Fig. 2. To make it easier to understand the mentioned diagrams (Fig. 3, Fig. 4), Table 4 shows the zonal power of home appliances and internal lighting.

Table 3
Simulation settings for people occupancy [52].

TZ	AS*	BR1	BR2	BT	H*	K	LR	T
$P_{max,TZ}$ [per]	–	2	2	1	–	4	4	1
MR [W/per]	Sleeping 72		Cooking 171		Sitting 108		Walking 207	

Legend: $P_{max,TZ}$ [per] – Maximum number of people in the thermal zone and MR [W/per] – Metabolic activity rate of the people.

* H is the transient room with no long stay during the day. AS is the room that is used very rarely during the year. The mentioned TZs are not equipped with home appliances (Table 4).

In all scenarios (Fig. 3), home appliances consume the most energy in K (preparing meals) and BT (washing and drying clothes, using a hair dryer), while the consumption in other TZs is much lower, which is shown in Table 4.

Peaks in electricity consumption can be observed in the following time intervals (Fig. 3): for weekday (06:00–08:00 h, 16:00–22:00 h), for Saturday (09:00–11:00 h, 15:00–17:00 h, 20:00–22:00 h) and for Sunday (07:00–09:00 h, 16:00–18:00 h, 20:00–22:00 h). The use of devices is intensive in the evening hours. The BT zone is particularly interesting, with a consumption of 2.7 kWh, due to the simultaneous use of various devices in the period from 19:00 to 22:00 h (Fig. 3): hair dryer, washing machine and clothes dryer.

Unlike home appliances, in the case of the $E_{l,TZ}$ values, LR is in second place, while K is in first place (Table 4). All TZ are equipped with the same light sources, i.e. surface mount lights [53]. For these bulbs, 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 $CHG = 0.1$.

Three TZs in the single-family building use hot domestic water (Fig. 1): BT, K and T. Thermal energy for water heating is provided by the flow electric water heater ($V_{wh} = 80$ L and $Q_{wh} = 2$ kW) positioned in BT. Hot domestic water is used for washing, showering and other needs. Regardless of the day of the week, it is predicted that $E_{wh} = 6$ kWh/day is consumed daily – by the schedules of the presence of people (Fig. 2) and recommendations from [54]: Weekday (06:00–08:00 h, 16:00–18:00 h, 19:00–21:00 h), Saturday (09:00–11:00 h, 15:00–17:00 h, 20:00–22:00 h) and Sunday (07:00–09:00 h, 14:00–16:00 h, 19:00–21:00 h).

2.3. Space heating

Among modern central heating systems based on RES [55], combining radiators (heating energy end users) and pellet boiler (heating energy generator) is very common in Western Serbia [56] (Fig. 5).

Wood biomass (an environmentally acceptable solid fuel [57]) is burned in the pellet boiler to provide a sufficient amount of thermal energy for heating water, which serves as the role of working fluid. The circulation pump (in two-pipe distribution) ensures water flow between the pellet boiler and radiators. Radiators provide temperature comfort in TZs (Table 5).

The heat power of the radiators in thermally treated TZ is determined based on two criteria: (1) heat losses (standard EN 12831:2003 [58]) and (2) operating conditions of the heating system Eq. (1).

$$t_{op,TZ,heat} = \frac{t_{in,pb} + t_{out,pb}}{2} - t_{in,TZ,heat} \tag{1}$$

where: $t_{op,TZ,heat}$ [°C] is the operative (working) temperature in the thermal zone for space heating, $t_{in,pb}$ [°C] is the temperature of the working fluid (water) at the inlet to the pellet boiler ($t_{in,pb} = 50$ °C), $t_{out,pb}$ [°C] is the temperature of the working fluid (water) at the outlet from the pellet boiler ($t_{out,pb} = 70$ °C) and $t_{in,TZ,heat}$ [°C] is the internal project temperature in the thermal zone for space heating (Table 5).

Following Table 5 and recommendations from [60], the heat power of the pellet boiler Q_{pb} [W] Eq. (2), for the analyzed residential building (Fig. 1), takes into account the heat power of all radiators $Q_{rad,TZ}$ [W], as well as the corresponding safety factor of the adopted heating system $\varphi_{pb,heat}$ [–].

$$Q_{pb} = \varphi_{pb,heat} \sum_{TZ=1}^{7} Q_{rad,TZ} \tag{2}$$

2.4. Space cooling

The internal project temperature in all thermally treated TZ (except

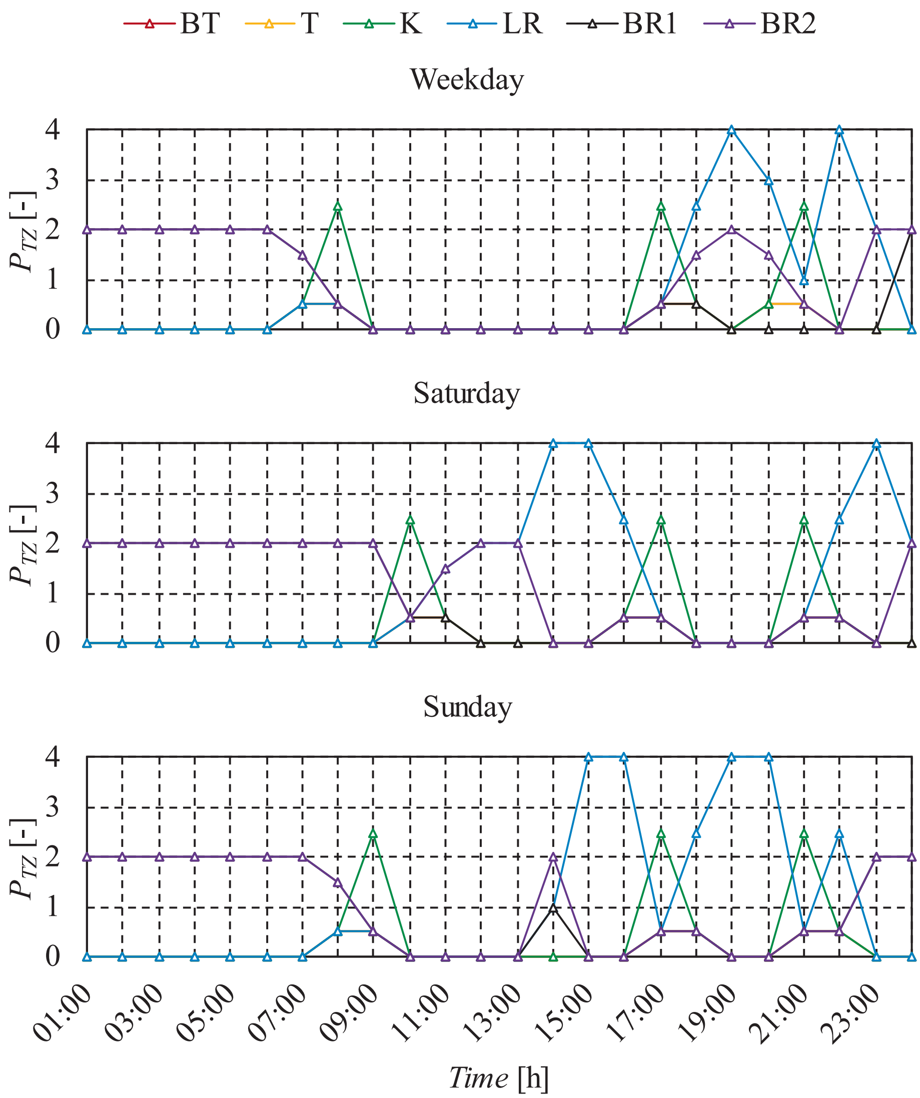


Fig. 2. Simulation scenarios for people occupancy during the year.

for AS) for space cooling is identical and amounts to $t_{in,TZ,cool} = 26$ °C [51,61]. The individual air-conditioner units (Fig. 6) are used for this purpose. The thermal performance of the cooling units is the same for all TZ [62]: $Q_{acu,TZ} = 3500$ W, $COP_{acu,TZ} = 2.61$.

As shown in Fig. 6, an air-conditioning unit consists of internal and external components. The internal component is the evaporator, while the external one is the condenser.

Due to its counter-clockwise operation cycle and affordable market price, this cooling system has become quite popular in Serbia, particularly in recent years, because of the high external temperatures during the summer (over 30 °C).

2.5. Active solar system

One of the conditions for achieving ZRB status is that the electricity consumption for various needs (internal lighting, home appliances and water heating) be compensated (canceled) by own electricity production. For this reason, in Google SketchUp and EnergyPlus software, the south roof of the single-family building is covered with PV panels.

2.6. Passive solar system

Although there are many constructive solutions in practice, the application of pergolas in Serbia is still limited to individual (isolated) cases. Fig. 8 shows the adopted pergolas concept – the wall-roof pergolas, which so far has not been investigated in terms of energy, ecological and economic. As in the case of PV panels, the geometry of this solar element was created in Google SketchUp software.

In front of the south and east facades (external application area, Fig. 8), horizontally placed pergolas simultaneously form the wall and roof of the open terrace. They are made of wooden rectangular boards (the dimensions of one board in cross-section are 10 × 2 cm). The distance between two adjacent boards is 10 cm. The length and number of boards are different depending on their position: east wall (7.3 m, 24 pieces), east roof (7.5 m, 15 pieces), south wall (9.5 m, 24 pieces) and south roof (8 m, 15 pieces). The goal of using pergolas is to reduce the final (electricity) energy consumption for space cooling.

To avoid unnecessary solar shading during the heating season [51], the seasonal (manual) tracking mechanism was applied, following the duration of the heating season in Serbia [47]. Pergolas are working from April 16 to October 14 and are not working between October 15 to April 15. These operating limits are implemented in the EnergyPlus settings.

2.7. Location parameters

The region of Western Serbia consists of 8 districts (Fig. 9) [63]: Kolubara (Valjevo), Mačva (Loznica), Morava, Pomoravlje, Rasina (Kruševac), Raška (Kraljevo), Šumadija (Kragujevac) and Zlatibor

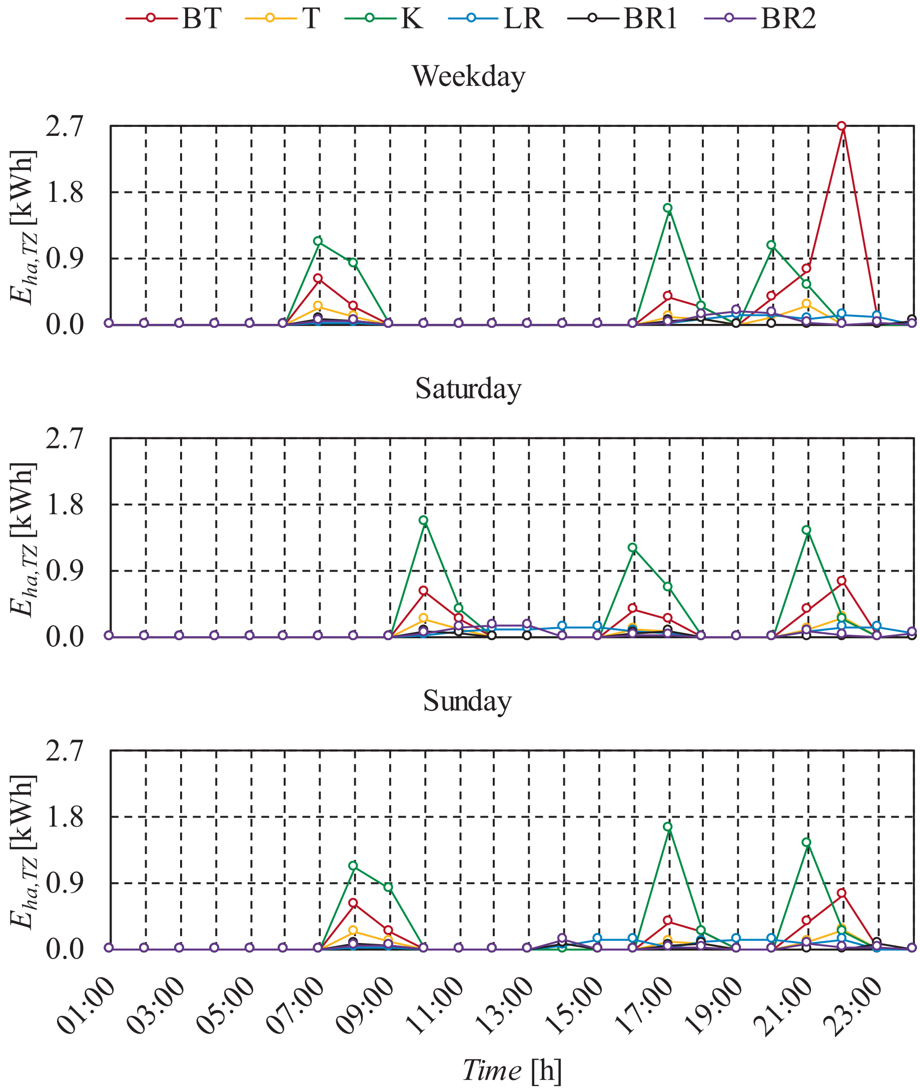


Fig. 3. Simulation scenarios for home appliances during the year.

(Požega, Sjenica, Užice, Zlatibor). Kopaonik is located on the border of two districts: Rasina and Raška. Morava and Pomoravlje were not included in this study, because in [64] there were no corresponding EnergyPlus weather data for the locations in the mentioned districts.

The entire region is located in an area of moderate continental climate. However, some locations (Fig. 9) are located at altitudes of up to 200 m (Loznica, Kragujevac, Kruševac, Valjevo), some in the range from 200 to 500 m (Kraljevo, Požega), and some over 500 m (Kopaonik, Sjenica, Užice and Zlatibor). Taking this criterion into account, it can be concluded that the relief is diverse.

The EnergyPlus weather data of the external temperature t_{out} [°C] (Fig. 10), beam I_{beam} [W/m^2] and diffuse I_{diff} [W/m^2] solar irradiance on the horizontal surface (Fig. 11), wind speed c_{wd} [m/s] and direction a_{wd} [°] (Fig. 12), for all locations from Fig. 9, are shown in next Figures. Samples are presented on an hourly level during the year.

Diagrams in Fig. 10 show that the t_{out} is between −24.05 °C (minimum software value for Kopaonik) and 36.96 °C (maximum software value for Kragujevac).

The region of Western Serbia is suitable for the installation of solar systems, i.e. for thermal and electricity production (Fig. 11). Namely, hourly maximum and average values of the beam component ranged between 838.38 W/m^2 (for Sjenica) and 854.06 W/m^2 (for Kragujevac), that is, between 101.46 W/m^2 (for Kopaonik) and 158.97 W/m^2 (for Kragujevac). Conversely, for the same period, hourly maximum and average values of the diffuse solar irradiance are in the following ranges: 447.94–631.44 W/m^2 and 72.93–81.39 W/m^2. In both cases, diffuse solar irradiance is weakest in Loznica and strongest in Kopaonik.

Maximum wind speed values, except in the case of Sjenica (24.94 m/s) and Zlatibor (18.86 m/s), are less than 11 m/s (Fig. 12). In the case of Sjenica and Zlatibor, these are individual weather cases, because the average annual wind speed does not exceed 3.05 m/s (applies to Kopaonik). The wind mostly comes from the south. In the case of Kopaonik and Zlatibor, the dominant wind is from the southeast direction, that is, from the southwest. Numerous values (Fig. 12) show that the wind potential is extremely small, so Western Serbia is not suitable for the installation of wind turbines – devices that transform the kinetic energy of the wind into electrical energy.

3. Methods

3.1. Simulation scenarios

Scenario S1 (Fig. 13a) describes the classic single-family building model without any solar systems. Scenario S2 (Fig. 13b) describes the same RB equipped with PV panels, i.e. the ZRB concept before external wall-roof pergolas and scenario S3 (Fig. 13c) is dedicated to the ZRB concept with active (PV panels) and passive (external wall-roof pergolas) solar systems.

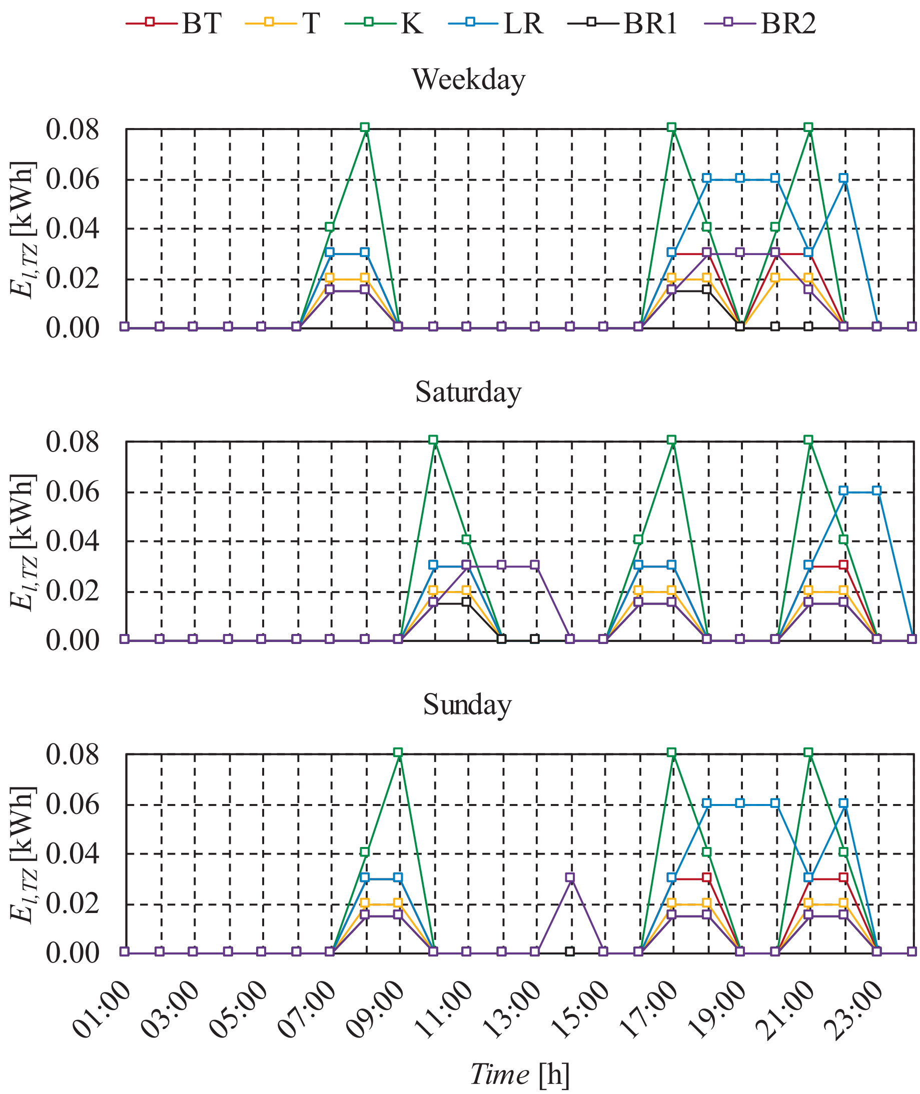


Fig. 4. Simulation scenarios for internal lighting during the year.

Table 4
Simulation settings for home appliances and internal lighting [52].

TZ	AS	BR1	BR2	BT	H	K	LR	T
$Q_{ha,TZ}$ [W]	–	250	200	4900	–	3000	150	1000
$Q_{l,TZ}$ [W]	–	30	30	60	–	80	60	40

Legend: $Q_{ha,TZ}$ [W] – Power of the home appliances in the thermal zone and $Q_{l,TZ}$ [W] – Power of the internal lighting in the thermal zone.

Energy, environmental and economic indicators were used in numerical analyses for each single-family building model (Fig. 13), to examine, depending on location parameters (10 different locations in the Western Serbia region), the possibilities of reaching the status of ZenRBs, ZemRBs and ZcRBs. This Section will also describe the payback periods in the case of using solar systems in the S2 (PV panels) and S3 (PV panels and wall-roof pergolas) scenarios.

3.2. Energy indicators

Annual useful $E_{use,heat}$ [kWh], final $E_{fin,heat}$ [kWh] and primary $E_{pry,heat}$ [kWh] energy consumption for space heating, in the single-family building (Fig. 13), is determined using Eqs. (3)–(5) [51,60].

$$E_{use,heat} = \sum_{TZ=1}^{7} E_{rad,TZ} \tag{3}$$

$$E_{fin,heat} = \frac{E_{use,heat}}{\eta_{pb}\eta_{pn}\eta_{rs}} \tag{4}$$

$$E_{pry,heat} = R_{pb}E_{fin,heat} \tag{5}$$

where [51]: $E_{rad,TZ}$ [kWh] is the annual useful energy consumption in the thermal zone for space heating, η_{pb} [–] is the efficiency of the pellet boiler ($\eta_{pb} = 0.85$), η_{pn} [–] is the efficiency of the pipe network ($\eta_{pn} = 0.98$), η_{rs} [–] is the efficiency of the regulation system ($\eta_{rs} = 0.92$) and R_{pb} [–] is the primary energy conversion factor of the pellet boiler ($R_{pb} = 0.1$).

Annual useful $E_{use,cool}$ [kWh], final $E_{fin,cool}$ [kWh] and primary $E_{pry,cool}$ [kWh] energy consumption for space cooling, in the same residential building (Fig. 13), is determined using Eqs. (6)–(8) [51,60].

$$E_{use,cool} = \sum_{TZ=1}^{7} E_{acu,TZ} \tag{6}$$

$$E_{fin,cool} = \frac{E_{use,cool}}{COP_{acu}} \tag{7}$$

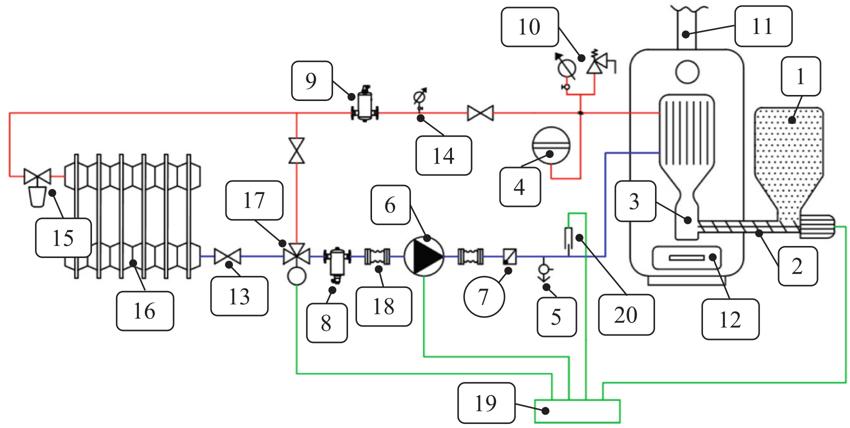


Fig. 5. Central heating system with pellet boiler and radiators [59]. Legend: 1 – Pellet tank, 2 – Pellet screw conveyor, 3 – Combustion chamber, 4 – Expansion vessel, 5 – Filling and draining tap, 6 – Circulation pump, 7 – Check valve, 8 – Dirt trap, 9 – Air vent, 10 – Safety valve, 11 – Chimney, 12 – Ash removal system, 13 – Valve, 14 – Manometer, 15 – Radiator valve with thermostatic head, 16 – Radiator, 17 – Three-way valve, 18 – Noise absorber, 19 – Controller and 20 – Termometer.

Table 5
Internal project temperatures for space heating [51].

TZ	AS*	BR1	BR2	BT	H	K	LR	T
$t_{in,TZ,heat}$ [°C]	–	20	20	24	20	20	20	24

* AS is the unheated TZ.

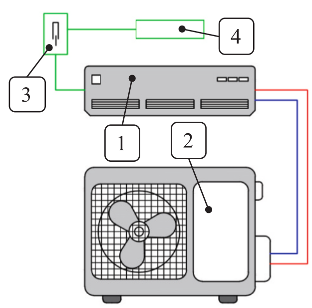


Fig. 6. Cooling system with Individual air-conditioner units. Legend: 1 – Evaporator, 2 – Condenser, 3 – Termometer and 4 – Controller.

$$E_{pry,cool} = R_{el} E_{fin,cool} \tag{8}$$

where [51]: $E_{acu,TZ}$ [kWh] is the annual useful energy consumption in the thermal zone for space cooling, COP_{acu} [–] is the coefficient of performance of the air-conditioner units (COP_{acu}=$COP_{acu,TZ}$) and R_{el} [–] is the primary energy conversion factor of electricity ($R_{el} = 2.5$).

Annual final energy consumption for home appliances $E_{fin,ha}$ [kWh] Eq. (9), internal lighting $E_{fin,l}$ [kWh] Eq. (10), water heating $E_{fin,wh}$ [kWh] Eq. (11) and annual final energy production from PV panels $E_{fin,PV}$ [kWh] Eq. (12), in the single-family building (Fig. 13), are recpetively [51,60].

$$E_{fin,ha} = \sum_{TZ=1}^{6} E_{ha,TZ} \tag{9}$$

$$E_{fin,l} = \sum_{TZ=1}^{6} E_{l,TZ} \tag{10}$$

$$E_{fin,wh} = \sum_{TZ=1}^{3} E_{wh,TZ} \tag{11}$$

$$E_{fin,PV} = A_{PV} F_{PV} I_{PV} \eta_{PV} \eta_{inv} \tag{12}$$

where [51,52,56,61]: $E_{ha,TZ}$ [kWh] is the annual final energy consumption in the thermal zone for home appliances, $E_{l,TZ}$ [kWh] is the annual final energy consumption in the thermal zone for internal lighting, $E_{wh,TZ}$ [kWh] is the annual final energy consumption in the thermal zone for water heating, F_{PV} [–] is the fraction of the photovoltaic panels with active surface area ($F_{PV} = 0.85$), I_{PV} [kWh/m^2] is the total (beam, diffuse and reflected) incoming solar radiation on the photovoltaic panels, η_{PV} [–] is the efficiency of the photovoltaic panels ($\eta_{PV} = 0.2$) and η_{inv} [–] is the efficiency of the inverter ($\eta_{inv} = 0.85$).

Based on Eqs. (9)–(12), annual final $E_{fin,otn}$ [kWh] Eq. (13) and primary $E_{pry,otn}$ [kWh] Eq. (14) energy consumption for "other needs" in the single-family building can be determined [51,52,56,61].

$$E_{fin,otn} = E_{fin,ha} + E_{fin,l} + E_{fin,wh} - E_{fin,PV} \tag{13}$$

$$E_{pry,otn} = R_{el} E_{fin,otn} \tag{14}$$

Since Eqs. (7) and (13) define the same energy source (electricity), a new quantity is introduced that unites them. In question is $E_{fin,el}$ [kWh] Eq. (15) [51,52,56,61].

$$E_{fin,el} = E_{fin,cool} + E_{fin,otn} \tag{15}$$

Regardless of the energy source, they can be viewed together if reduced to their primary form $E_{pry,tot}$ [kWh], as shown in Eq. (16) [51,52,56,61].

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

The main purpose of PV panels is to minimize the annual final energy consumption, i.e. electricity, for space cooling and "other needs" in the single-family building Eqs. (13) and (15) – without PV panels, reaching ZRB status is not possible. In practice, several cases can occur (Fig. 14), all depending on the occupancy needs and the performance of the PV

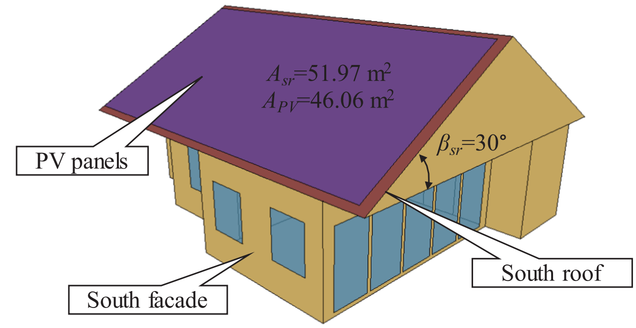


Fig. 7. Single-family building equipped with photovoltaic panels. Legend: A_{PV} [m^2] – Area of the photovoltaic panels, A_{sr} [m^2] – Area of the south roof and β_{sr} [°C] – Inclination angle of the south roof to the horizontal plane.

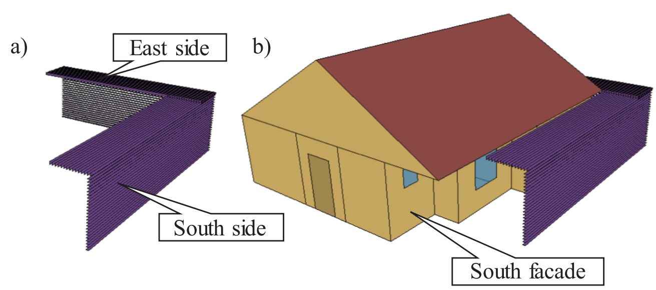


Fig. 8. Single-family building equipped with wall-roof pergolas: a) Isometric view and b) Practical application.

panels.

In the first case (Fig. 14a), electricity production is sufficient to satisfy all the needs. In the second case (Fig. 14b), electricity production requirements are somewhat higher, the PV solar system is not able to provide a sufficient amount, so a part is compensated from the grid. In the third case (Fig. 14c), more electricity is produced than is needed, so the surplus is delivered to the grid. This part can be used later, in a working regime described in the case (Fig. 14b). In the fourth case (Fig. 14d), all electricity production is directly delivered to the grid (for example, when the single-family building is empty).

3.3. Ecological indicators

Environmental indicators are primarily viewed through the CO_2 footprint (greenhouse gas). Annual CO_2 emission for space heating $m_{CO2,heat}$ [kg] Eq. (17), space cooling $m_{CO2,cool}$ [kg] Eq. (18) and "other needs" $m_{CO2,otn}$ [kg] Eq. (19), in the single-family building, are [51].

$$m_{CO2,heat} = g_{pb}E_{pry,heat} \tag{17}$$

$$m_{CO2,cool} = g_{el}E_{pry,cool} \tag{18}$$

$$m_{CO2,otn} = g_{el}E_{pry,otn} \tag{19}$$

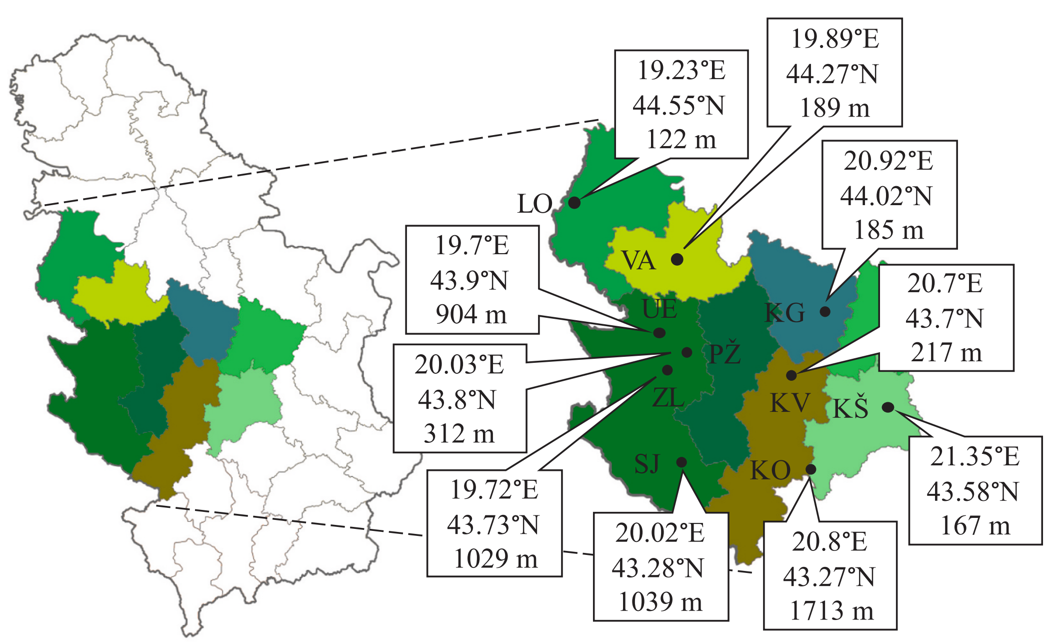


Fig. 9. Western Serbia region. Legend: KO – Kopaonik, KG – Kragujevac, KV – Kraljevo, KŠ – Kruševac, LO – Loznica, PŽ – Požega, SJ – Sjenica, UE – Užice, VA – Valjevo and ZL – Zlatibor.

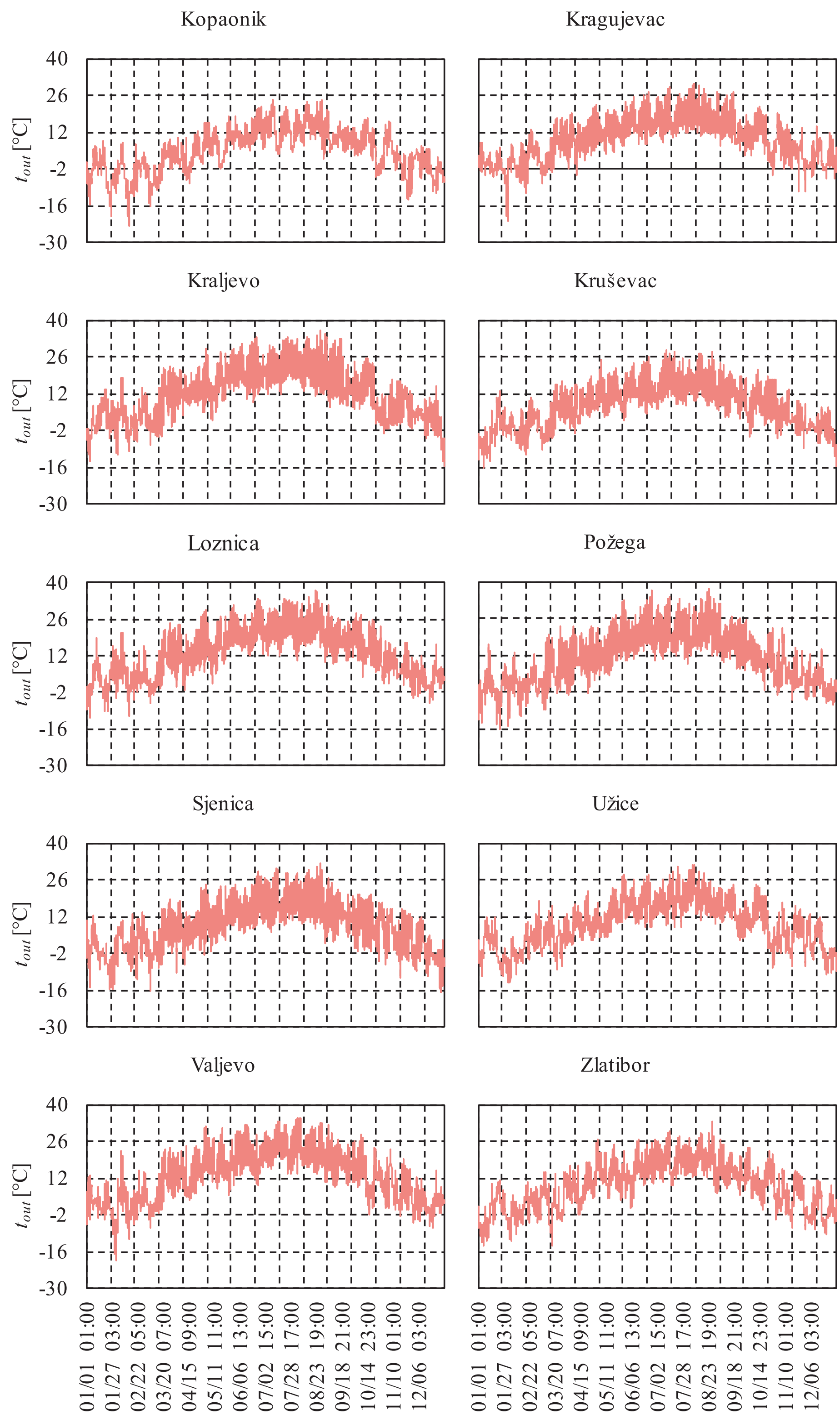


Fig. 10. Hourly external temperature in the Western Serbia region during the year.

where [51]: g_{pb} [kg/kWh] is the specific CO_2 emission for pellet (zero-emission) and g_{el} [kg/kWh] is the specific CO_2 emission for electricity ($g_{el} = 0.53$ kg/kWh).

Total annual CO_2 emission $m_{CO2,tot}$ [kg] Eq. (20), in the single-family building, can be calculated as the sum of the Eqs. (17)–(19).

$$m_{CO2,tot} = m_{CO2,heat} + m_{CO2,cool} + m_{CO2,otn} \tag{20}$$

3.4. Economic indicators

Annual pellet cost M_{pb} [€], in the single-family building, can be determined by Eq. (21).

$$M_{pb} = C_{pb}\frac{E_{fin,heat}}{J_{pb}} \tag{21}$$

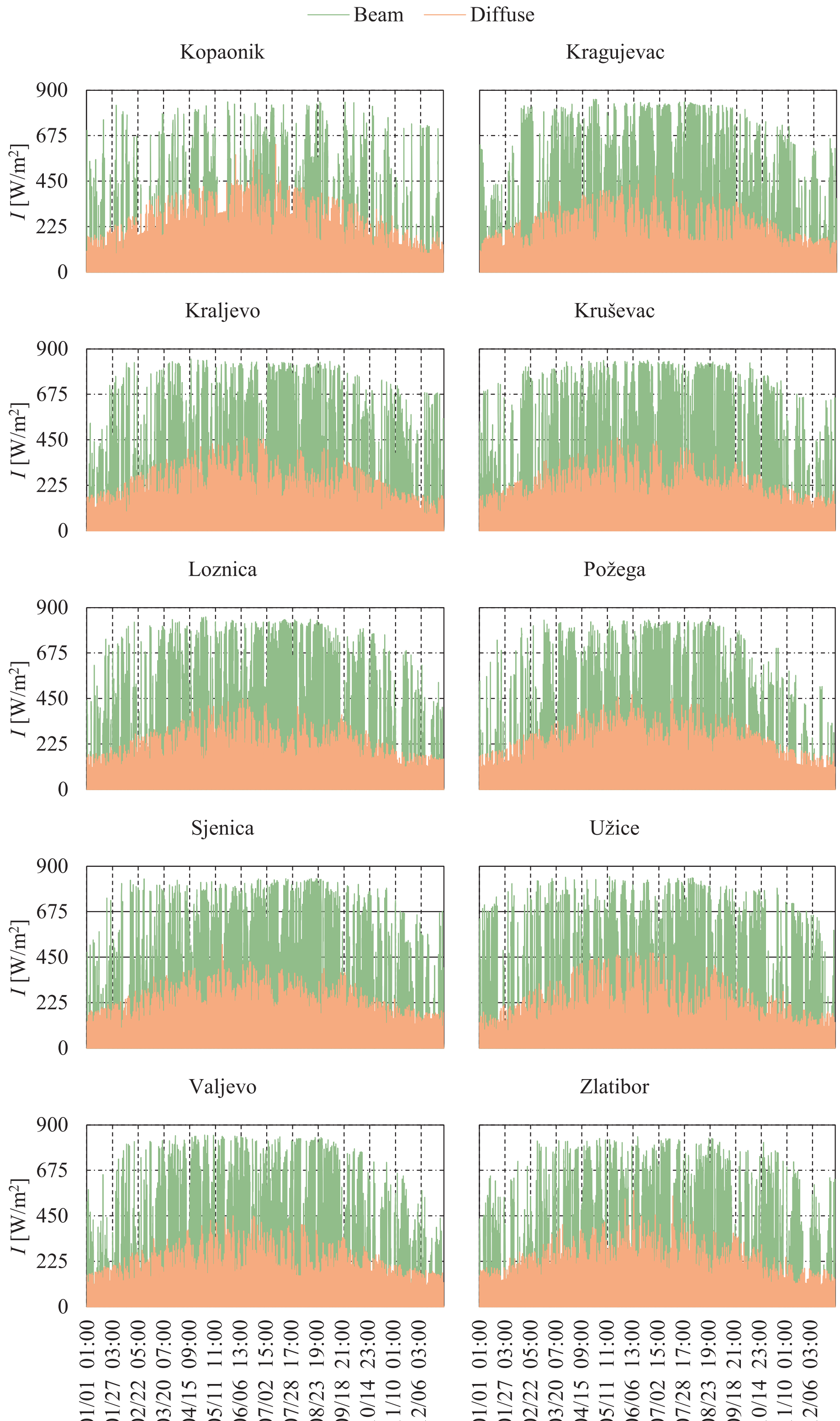


Fig. 11. Hourly beam and diffuse solar irradiance on the horizontal surface for locations in the Western Serbia region during the year.

where: C_{pb} [€/t] is the specific price of the pellet ($C_{pb} = 269$ €/t [66]) and J_{pb} [kWh/t] is the specific calorific value of the pellet ($J_{pb} = 5000$ kWh/t [67]).

According to the data available in [68], electricity price $M_{el,m}$ [€], on montly level, in Serbia, for a single-tariff meter moves, in the following way: for green zone (up to 350 kWh, $C_{gz,el} = 0.077$ €/kWh Eq. (22)), for blue zone (351–1600 kWh, $C_{bz,el} = 0.116$ €/kWh Eq. (23)) and for red zone (over 1600 kWh, $C_{rz,el} = 0.233$ €/kWh Eq. (24)).

$$M_{gz,el,m} = C_{gz,el}E_{fin,el} + D_{el} \tag{22}$$

$$M_{bz,el,m} = C_{gz,el}350 + C_{bz,el}\left(E_{fin,el} - 350\right) + D_{el} \tag{23}$$

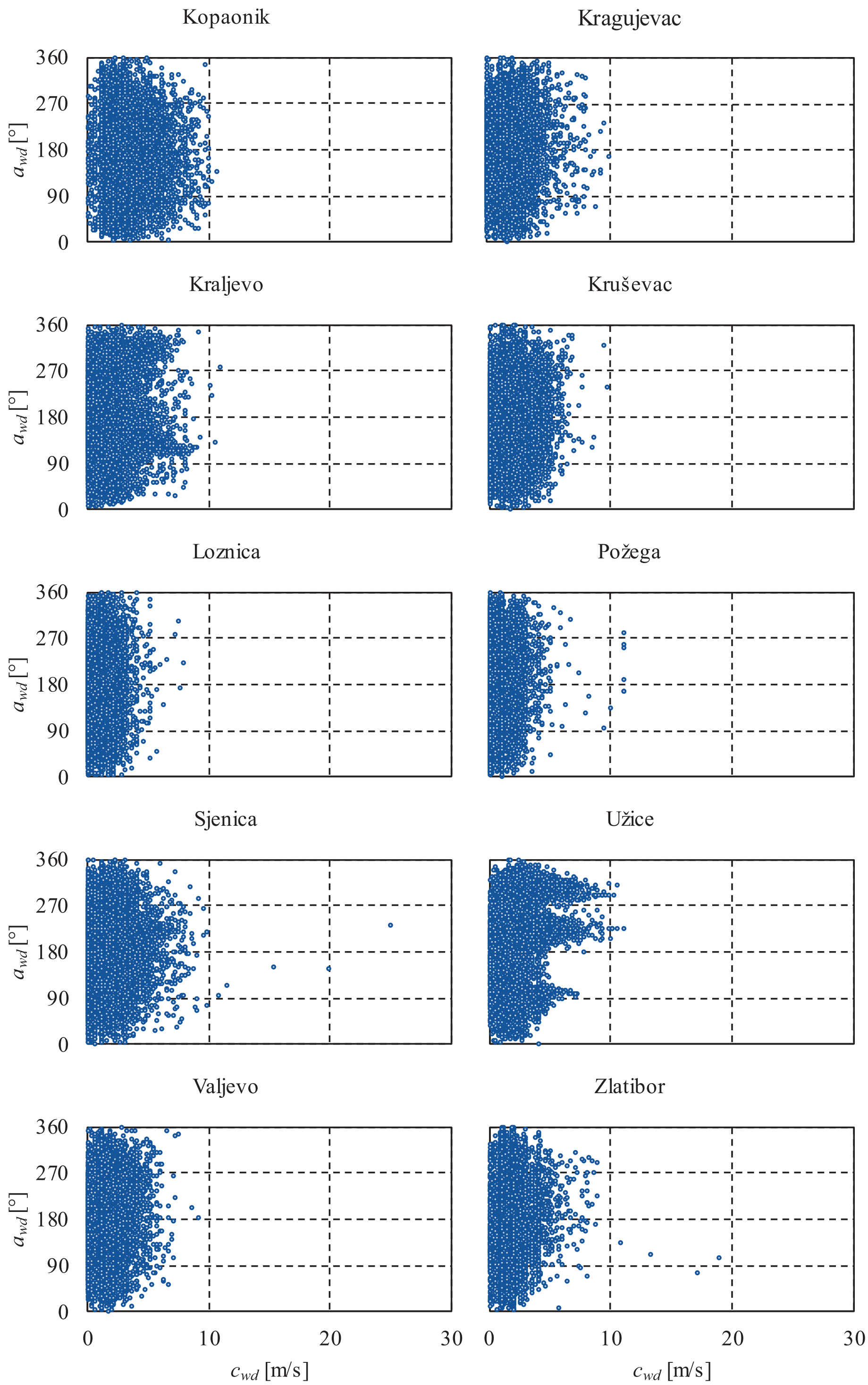


Fig. 12. Hourly wind speed and direction in the Western Serbia region during the year.

$$M_{rz,el,m} = C_{gz,el}350 + C_{bz,el}1250 + C_{rz,el}\left(E_{fin,el} - 1600\right) + D_{el} \tag{24}$$

where D_{el} [€] is the depreciation price of the electricity distribution.

Value D_{el} takes into account approved power, price for access to the electricity distribution, price for the improvement of energy efficiency, price for the incentive of privileged producers and price for other elements [69].

In this case, annual electricity cost M_{el} [€], in the single-family building, is given by Eq. (25).

$$M_{el} = \sum_{m=1}^{12} M_{el,m} \tag{25}$$

In the end, total annual costs M_{tot} [€] Eq. (26), for all needs in the single-family building, is the sum of the M_{pb} and M_{el} values.

$$M_{tot} = M_{pb} + M_{el} \tag{26}$$

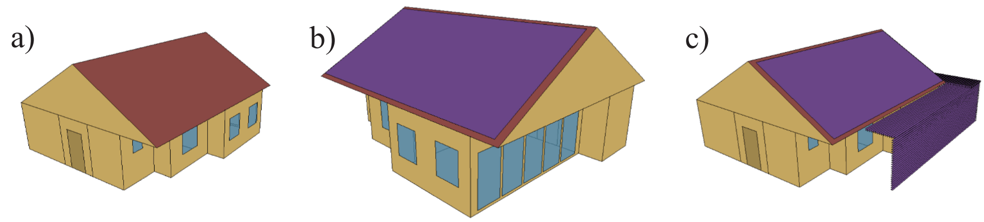


Fig. 13. Simulation scenarios: a) Single-family building without solar systems (Scenario S1), b) Single-family building with photovoltaic panels (Scenario S2) and c) Single-family building with photovoltaic panels and wall-roof pergolas (Scenario S3).

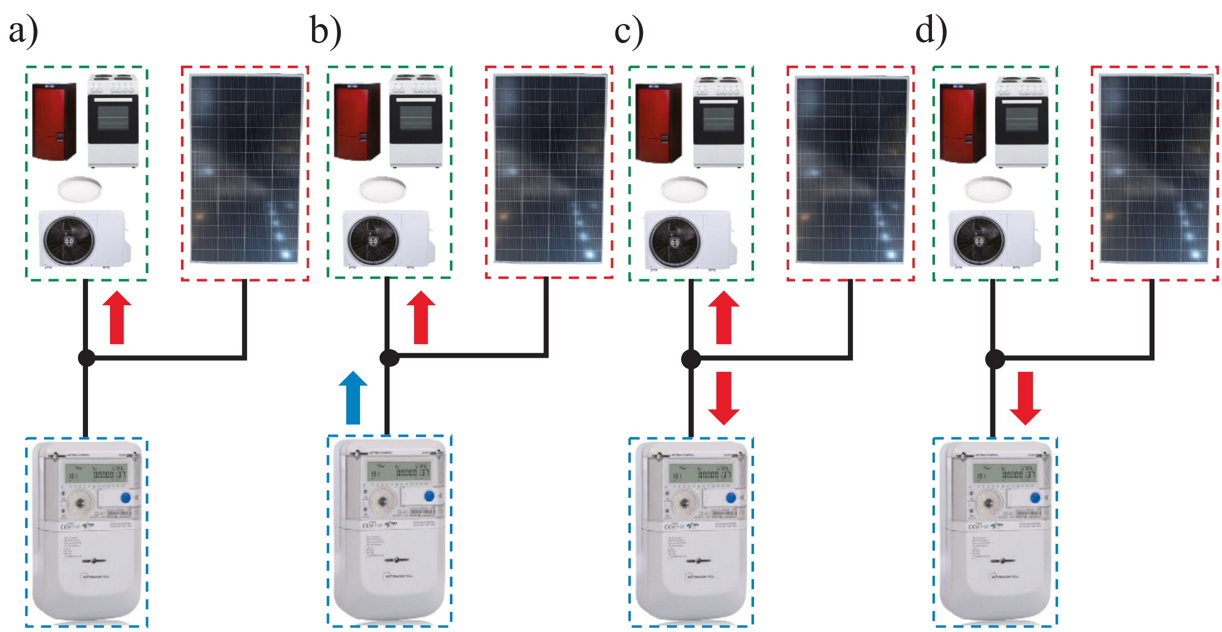


Fig. 14. Working principle of the on-grid photovoltaic panels [65]: a) Total electricity production, b) Partial electricity production, c) Partial electricity surplus and (d) Total electricity surplus.

3.5. Payback period

Payback period *PB* [a] generally depends on the investment and maintenance costs (on the one hand) and the financial savings (costs before and after implementation of energy efficiency measures) achieved on an annual basis (on the other hand).

In the case of scenario S2, investments of X_{PV} [€] refer to the implementation of PV panels in Eq. (27).

$$PB_{PV} = \frac{X_{PV}}{M_{tot,bef} - M_{tot,PV}} \tag{27}$$

where: PB_{PV} [a] is the payback period for the implementation of the photovoltaic panels, $M_{tot,bef}$ [€/a] is the annual costs before implementation of the photovoltaic panels and $M_{tot,PV}$ [€/a] is the annual costs after implementation of the photovoltaic panels.

In the case of scenario S3, investments increase in relation to costs in Eq. (27) for the costs of installing external wall-roof pergolas X_{perg} [€] Eq. (28).

$$PB_{PV,perg} = \frac{X_{PV} + X_{perg}}{M_{tot,bef} - M_{tot,PV,pegr}} \tag{28}$$

where: $PB_{PV,per}$ [a] is the payback period for the implementation of the photovoltaic panels and external wall-roof pergolas and $M_{tot,PV,perg}$ [€/a] is the annual costs after implementation of the photovoltaic panels and external wall-roof pergolas.

4. Results

4.1. Electricity consumption and production for "other needs"

Fig. 15 shows annual electricity consumption for home appliances, internal lighting and water heating and production from PV panels in the single-family building. For the same residential building, the monthly structure of electricity consumption is shown in Fig. 16, while the monthly structure of electricity production is shown in Fig. 17.

Electricity consumption, for all building models (scenario S1, scenario S2, scenario S3), for all adopted locations in the Western Serbia region (10 of them) is the same ($E_{fin,ha} + E_{fin,l} + E_{fin,wh} = 6787.84$ kWh, Fig. 15), while electricity production depends on the meteorological data (Figs. 11 and 15). The percentage redistribution of this expenditure was carried out as follows (Fig. 15): 6.21 % is used for internal lighting needs, 30.41 % for water heater needs, while most (63.38 %) of the electricity is allocated for home appliances. The most unsuitable location for installing PV panels is Kopaonik ($E_{fin,PV} = 9421.41$ kWh), while electricity production is above $E_{fin,PV} = 11500$ kWh for Kragujevac ($E_{fin,PV} = 11803.27$ kWh), Kruševac ($E_{fin,PV} = 11695.1$ kWh) and Sjenica ($E_{fin,PV} = 11651.84$ kWh).

Fig. 16 shows that $E_{fin,ha,m}$ does not exceed of more than 389.38 kWh, $E_{fin,l,m}$ does not exceed 38.07 kWh and $E_{fin,wh,m}$ does not exceed the value of 186 kWh. Fig. 15 also shows two dips (discontinuities) in electricity consumption. The first in February (family is going on winter vacation) and the second in July and August (family is going on summer vacation).

Electricity production varies from month to month in all locations

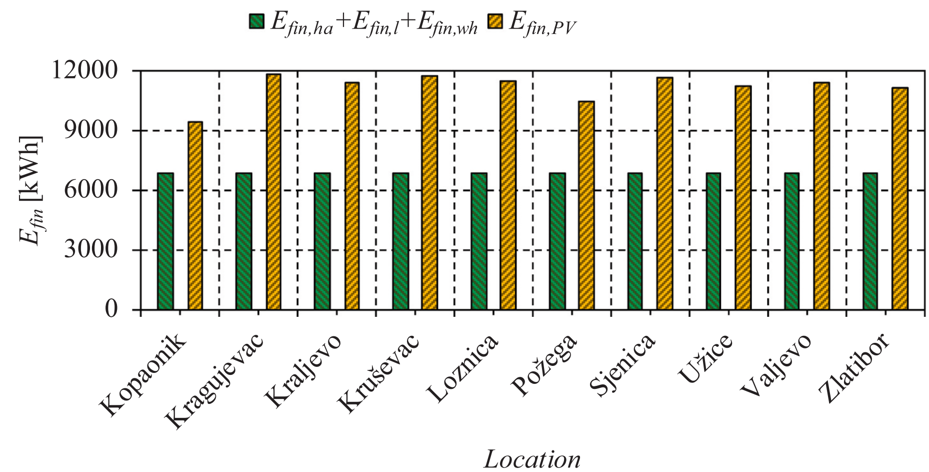


Fig. 15. Annual electricity consumption and production for "other needs" in the Western Serbia region.

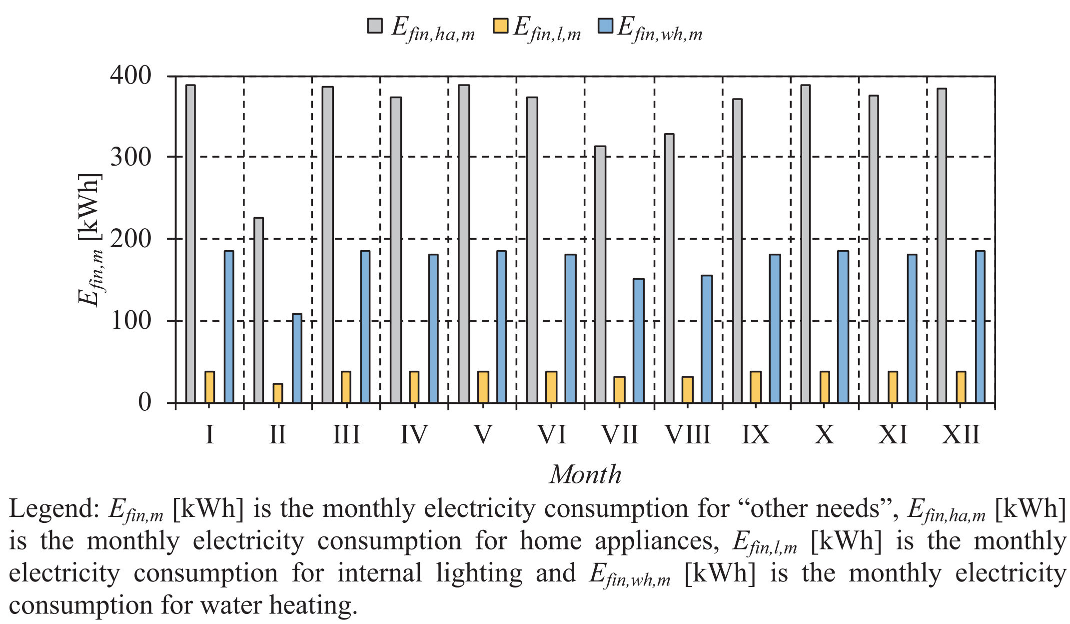


Fig. 16. Monthly electricity consumption for home appliances, internal lighting and water heating. Legend: $E_{fin,m}$ [kWh] is the monthly electricity consumption for "other needs", $E_{fin,ha,m}$ [kWh] is the monthly electricity consumption for home appliances, $E_{fin,l,m}$ [kWh] is the monthly electricity consumption for internal lighting and $E_{fin,wh,m}$ [kWh] is the monthly electricity consumption for water heating.

(Fig. 17). If the monthly values were to be compared with each other, the production is lower in the following locations: January (338.74 kWh, Požega), February (476.88 kWh, Kopaonik), March (700.86 kWh, Kopaonik), April (933.50 kWh, Kopaonik), May (1030.68 kWh, Kopaonik), June (1127.66 kWh, Kopaonik), July (1211.69 kWh, Kopaonik), August (1205.66 kWh, Kopaonik), September (875.94 kWh, Kopaonik), October (605.20 kWh, Požega), November (401.97 kWh, Požega) and December (227.38 kWh, Požega). On the other side, monthly production is highest in the following locations: January (531.75 kWh, Užice), February (665.28 kWh, Kragujevac), March (1011.08 kWh, Kragujevac), April (1226.21 kWh, Valjevo), May (1354.55 kWh, Sjenica), June (1413.29 kWh, Kragujevac), July (1494.83 kWh, Loznica), August (1403.50 kWh, Kragujevac), September (1102.58 kWh, Kruševac), October (864.83 kWh, Zlatibor), November (612.38 kWh, Kraljevo) and December (458.33 kWh, Užice).

4.2. Energy consumption for space heating and cooling

Annual useful, final and primary energy consumption for space heating (Fig. 18) and cooling (Fig. 19), depending on simulation scenario and location parameters, are shown in the next diagrams.

As can be seen from Fig. 18, regardless of scenario simulation, the adopted limit value $E_{use,heat} = 6000$ kWh is exceeded only for Kopaonik (range between 6000–8000 kWh). In all other cases (for the remaining 9 locations), this value is within the limits of 3000–6000 kWh, regardless of whether the terrain is mountainous, hilly or flat (Fig. 9). However, by introducing additional division criteria, locations can be sorted into the following two subgroups: $3000 < E_{use,heat} < 4500$ kWh (Kragujevac, Kraljevo, Kruševac, Loznica and Valjevo) and $4500 < E_{use,heat} < 6000$ kWh (for Požega, Sjenica, Užice and Zlatibor). It is interesting that according to the adopted indicator ($E_{use,heat}$), Požega (with an altitude of 312 m and $t_{avg,out} = 10.31$ °C, Fig. 10) is not in the group of hilly or plain locations, but mountain locations. The reason is the I_{beam} curve (Fig. 11), which shows that annual average beam solar irradiance on the horizontal surface is 15.9 % weaker than Sjenica, 14.55 % weaker than Užice and 9.96 % weaker than Zlatibor. The lower yield of the I_{beam} values reduces solar thermal gains in the building, which must be compensated by annual energy useful consumption for space heating. Regardless of

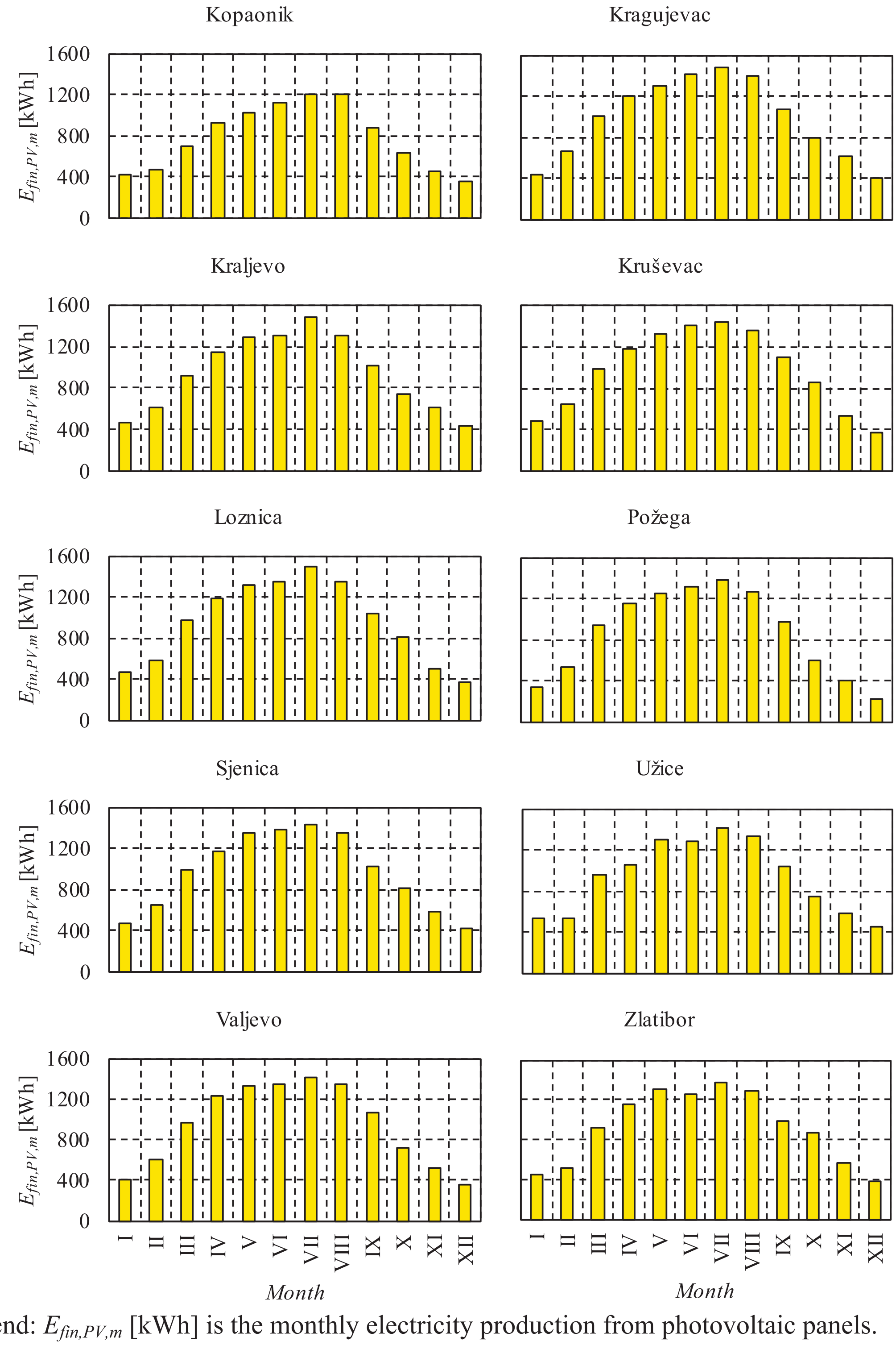


Fig. 17. Monthly electricity production from photovoltaic panels in the Western Serbia region. Legend: $E_{fin,PV,m}$ [kWh] is the monthly electricity production from photovoltaic panels.

the location, annual useful energy consumption for space heating is the lowest in scenario S1 because solar shading is minimal. By installing PV panels (scenario S2), the southern roof is in constant shade, due to which the annual useful energy consumption for space heating increases slightly in the range between 1.07 % (Požega) and 1.62 % (Sjenica). Seasonal use of the external wall-roof pergolas (from April 16 to October 14, scenario S3) additionally negatively affects on $E_{use,heat}$ – especially in the so-called transitional periods (Fig. 20). Compared results from scenario S3 with results from scenario S2, it can be concluded that the $E_{use,heat}$ values increase by (Fig. 18): 8.36 % (Kopaonik), 5.55 % (Kragujevac), 5.6 % (Kraljevo), 5 % (Kruševac), 4.79 % (Loznica), 5.17 % (Požega), 7.46 % (Sjenica), 6.86 % (Užice), 5.61 % (Valjevo) and 6.28 % (Zlatibor).

Due to losses in the chain of energy transformations, which are reflected in the performance of the central heating system (Fig. 5), consumption $E_{fin,heat}$ can be divided into three groups: 3000–6000 kWh

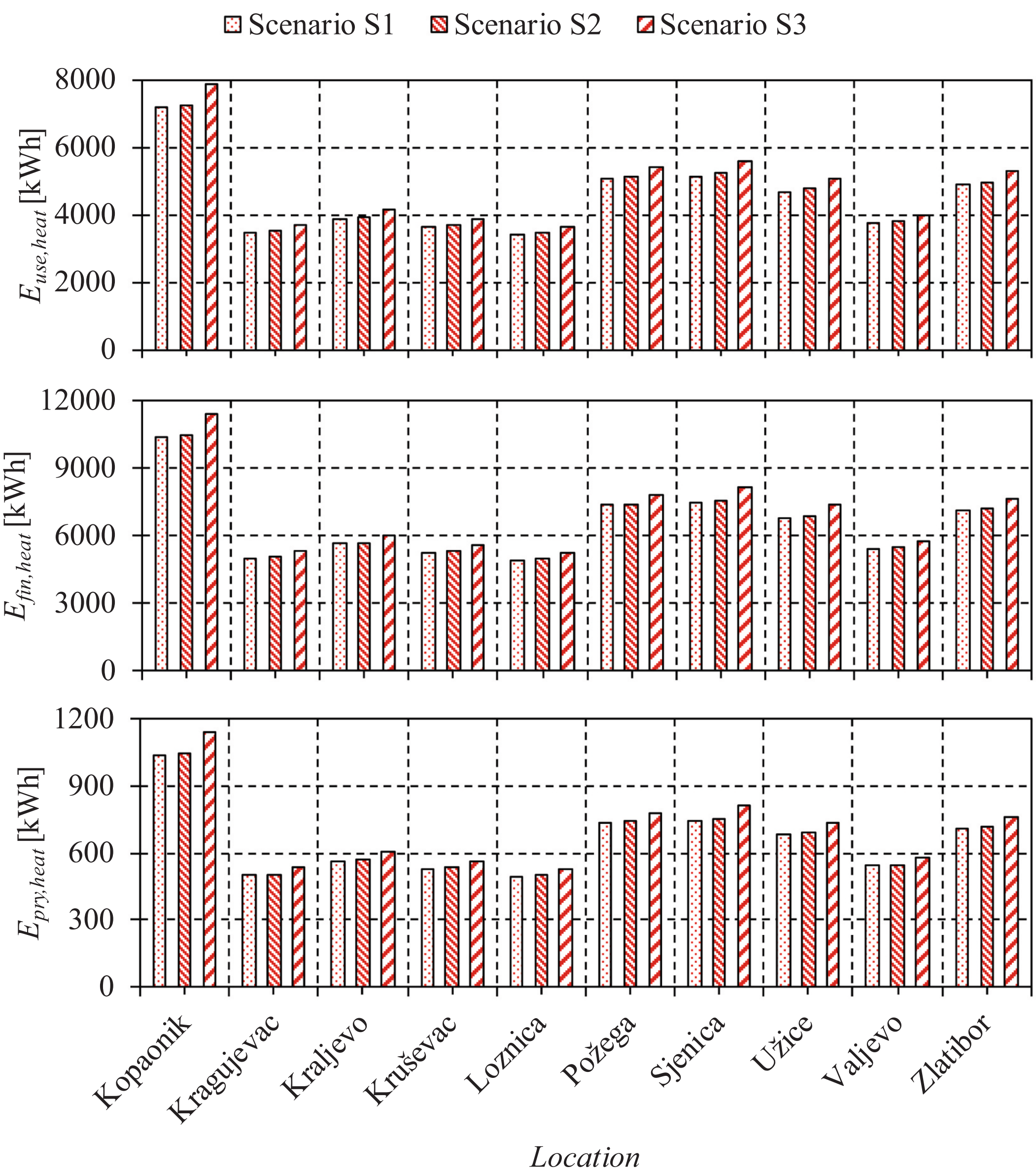


Fig. 18. Annual energy consumption for space heating in the Western Serbia region depending on the simulation scenario.

(Kragujevac, Kruševac, Loznica and Valjevo), 6000–9000 kWh (Požega, Sjenica, Užice and Zlatibor) and 9000–12000 kWh (Kopaonik). Kraljevo is specific in that it is simultaneously in two groups: together with Kragujevac ($E_{fin,heat}$ = 5632.59 kWh in scenario S1 and $E_{fin,heat}$ = 5704.36 kWh in scenario S2) or together with Požega ($E_{heat,fin}$ = 6023.77 kWh is scenario S3).

According to $E_{fin,heat}$ and R_{pb} values, consumption $E_{pry,heat}$ is the lowest in the case of Loznica ($E_{pry,heat}$ = 494.02 kWh in S1, $E_{pry,heat}$ = 500.69 kWh in S2 and $E_{pry,heat}$ = 524.68 kWh in S3), and the highest for Kopaonik ($E_{pry,heat}$ = 1037.78 kWh in S1, $E_{pry,heat}$ = 1049.76 kWh in S2 and $E_{pry,heat}$ = 1137.56 kWh in S3).

The simulation results (Fig. 19) showed that the locations can be divided into two large groups in the case of cooling ($E_{use,cool}$), analogous to the size of $E_{use,heat}$: <3000 kWh /a (Kopaonik and Sjenica) and 3000–6000 kWh /a (Kragujevac, Kraljevo, Kruševac, Loznica and Valjevo). The diagram also shows that PV panels and pergolas (scenario S3) can also affect the (positive) rank of the RB, i.e. on its transfer from a group with a higher to a group with a lower consumption $E_{use,cool}$: Požega, Užice and Zlatibor. Regardless of the location of the locations, $E_{use,cool}$ is reduced after implementation PV panels and pergolas in percentage terms as follows (Fig. 19): 31.95 % (Kopaonik), 30.66 % (Kragujevac), 31.94 % (Kraljevo), 30.23 % (Kruševac), 29.6 % (Loznica), 27.2 % (Požega), 31.05 % (Sjenica), 36.57 % (Užice), 29.95 % (Valjevo) and 34.65 % (Zlatibor). The pergolas benefits during the adopted period (from April 16 to October 14) are of great importance (in energy terms) to the end user, in this case, the residents of a single-family building. Fig. 19 is interesting in another sense. Namely, the used weather files of a more recent date (for the analyzed locations) show that in the future attention cannot be devoted only to the heating season (from April 15 to October 15), as has been the case in Serbia so far. The moderately continental climate has become much more sensitive, so it is also the cooling season, i.e. summer season, has become much more demanding in terms of energy. The best evidence of this is the situations in which $E_{use,cool} > E_{use,heat}$: Kragujevac, Kraljevo, Kruševac, Loznica and Valjevo. However, this condition is fulfilled only when the building in the mentioned locations is without pergolas (Fig. 19). This clearly shows that the adaptation of the building sector to climate change in the future cannot be imagined without the application of cooling passive solar systems.

A more detailed analysis (on a monthly level) of $E_{use,heat,m}$ [kWh] and

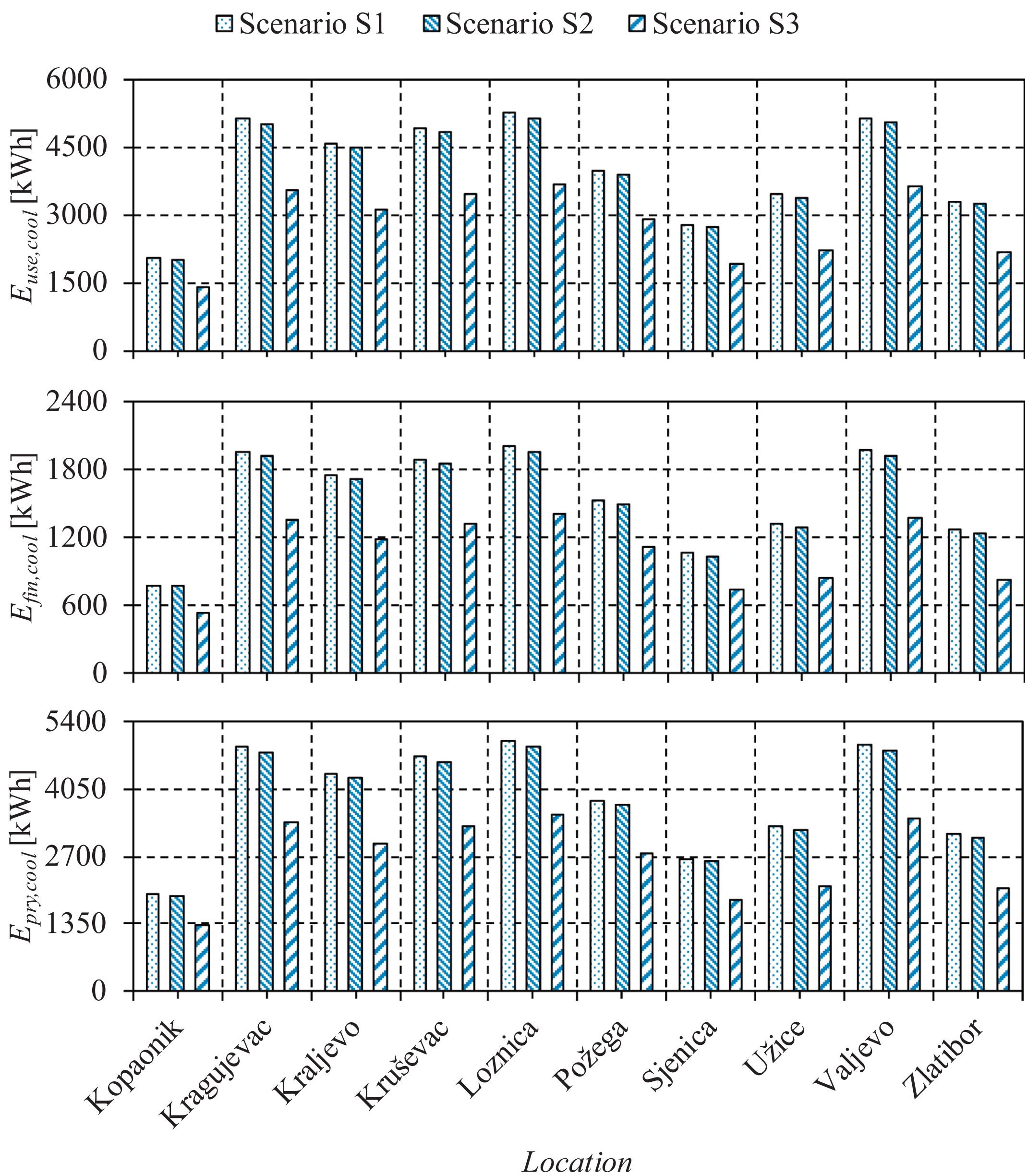


Fig. 19. Annual energy consumption for space cooling in the Western Serbia region depending on the simulation scenario.

$E_{use,cool,m}$ [kWh] values, in the simulation scenarios S2 and S3, is shown in Fig. 20.

The simulation results (Fig. 20) for RB without pergolas (scenario S2) showed that monthly heating and cooling transition periods (at the same time $E_{use,heat,m} > 100$ kWh and $E_{use,cool,m} > 100$ kWh) are different from location to location: Kopaonik (May, September and October), Kragujevac and Kraljevo (March, April, October and November), Kruševac (March and November), Loznica (March, April and November), Požega (March, April and October), Sjenica and Užice (April, May and October), Valjevo (March, October and November) and Zlatibor (April and October).

The transition period can be extended for RBs with pergolas (scenario S3) due to the additional investment in $E_{use,heat,m}$ (Fig. 20): Kopaonik (for June), Kruševac (for April and October), Loznica (for November) and Sjenica (for September). It can also be shortened due to reduced $E_{use,cool,m}$ (Fig. 20): Kraljevo (without November).

The biggest monthly $E_{use,heat,m}$ rise values, due to the use of a passive solar system (scenario S3), for all analyzed locations are in October: for 38.77 kWh (Loznica) and for 171.84 kWh (Kopaonik). The biggest monthly $E_{use,cool,m}$ drop values are, for some locations in June (Kragujevac, Kraljevo, Kruševac, Loznica, Užice and Valjevo), for some in July (Kopaonik) and for others in August (Požega, Sjenica and Zlatibor). This monthly decrease is within the following limits: for 192.71 kWh (Kopaonik) and for 300.92 kWh (Kraljevo).

In total energy balance ($E_{use,heat} + E_{use,cool}$), the pergolas benefits (scenario S3), on the annual basis, can be expressed as a percentage in the following way (Fig. 20): 0.11 % (Kopaonik), 14.84 % (Kragujevac), 13.58 % (Kraljevo), 13.99 % (Kruševac), 14.72 % (Loznica), 7.98 % (Požega), 5.1 % (Sjenica), 10.65 % (Užice), 13.76 % (Valjevo) and 9.21 % (Zlatibor). From the above, it can be concluded that the percentage savings for towns at a lower altitude are greater than 10 %.

4.3. Zero residential building status

The following diagrams (Figs. 21–24) show the research results for ZRB concepts in a wider administrative territorial area (for 10 locations in the region of Western Serbia), for the single-family building with PV panels (scenario S2) and the single-family building with PV panels and

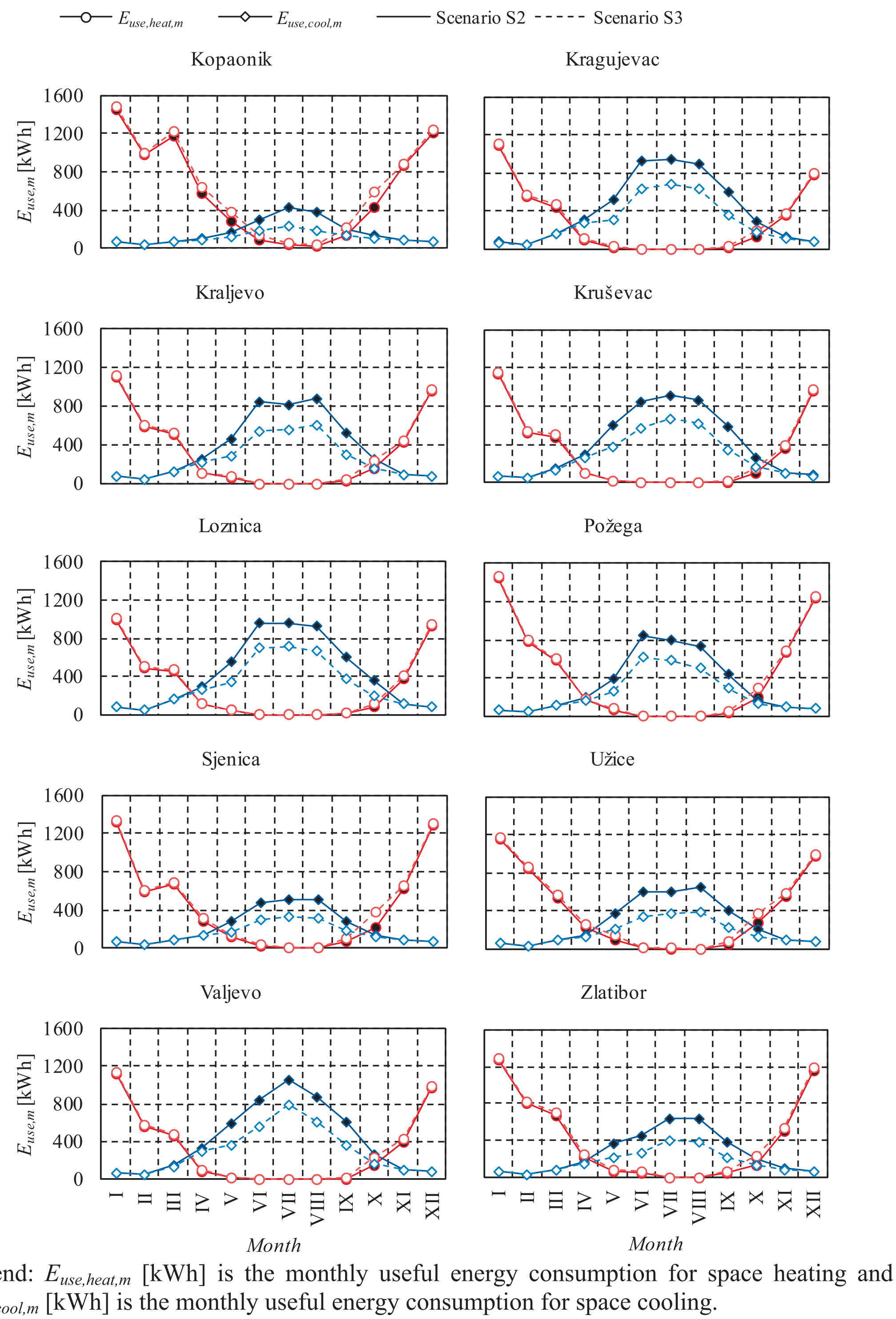


Fig. 20. Monthly useful energy consumption for space heating and cooling in the Western Serbia region depending on the simulation scenario. Legend: $E_{use,heat,m}$ [kWh] is the monthly useful energy consumption for space heating and $E_{use,cool,m}$ [kWh] is the monthly useful energy consumption for space cooling.

external wall-roof pergolas (scenario S3): ZenRB concept (Figs. 21 and 22), ZemRB concept (Fig. 23), and ZcRB concept (Fig. 24). The single-family building from scenario S1 is not included because it does not have the ZRB potential.

The first criterion ($E_{fin,el}$) shows that the annual electricity production from the solar system is greater than the annual electricity consumption, i.e. $E_{fin,el} < 0$ kWh /a, both in scenarios S2 and S3 (Fig. 21). This means that ZenRB status can be reached without problems in both cases. The only difference is the amount of electricity produced, which is delivered to the grid. In the first case (scenario S2), the annual surplus of electricity amounts from 1864.61 kWh to 3826.59 kWh, while in the second case (scenario S3) it amounts from 2100.68 kWh to 4130.49 kWh (Fig. 21). In both cases, the lowest value refers to Kopaonik and the highest to Sjenica. By comparing the percentages of electricity produced for the same location, the greatest benefits from scenario S3 can be realized in Valjevo (17.25 %), followed by Loznica (16.83 %) and Kraljevo (15.55 %).

And according to $E_{pry,tot}$ criterion, ZenB status is reached in both

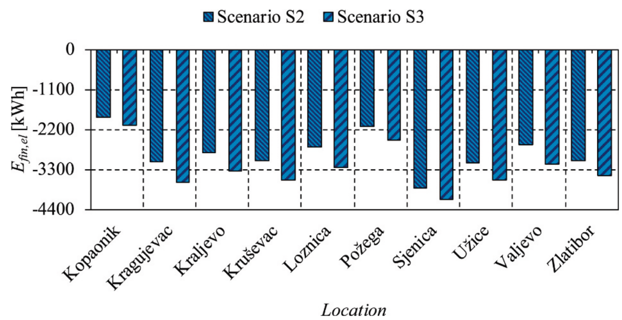


Fig. 21. Relation between total annual electricity consumption and ZenRB status in the Western Serbia region depending on the simulation scenario.

scenarios (Fig. 22). Now numerous values are even more on the side of single-family building – due to coefficients R_{pb} and R_{el}. Kopaonik (3611.77 kWh – scenario S2 and 4114.14 kWh – scenario S3) and Sjenica (8810.34 kWh – scenario S2 and 9513.68 kWh – scenario S1) continue to occupy the same positions, as locations that are the most unfavorable and the most favorable for the application of the mentioned method.

Environmental indicators (total annual CO_2 emission) are also on the side of ZemRB concept (Fig. 23). The amount of CO_2 emission (heating, cooling, etc.) is also a negative value in all cases. As in the case of using the previous two indicators, Kopaonik and Sjenica keep the same positions.

Unlike the energy and environmental indicators, simulation results showed that the economic indicator is not a function of ZcRB concept (Fig. 24) – due to the adopted system for space heating and cooling. Taking into account the price of pellets and electricity, monetary costs vary, depending on location and climatic conditions.

Before installing pergolas (scenario S2), M_{tot} values are as follows (Fig. 24): 1012.21 € (Kopaonik), 756.21 € (Kragujevac), 784.83 € (Kraljevo), 769.43 € (Kruševac), 755.81 € (Loznica), 861.60 € (Požega), 843.89 € (Sjenica), 832.50 € (Užice), 780.09 € (Valjevo) and 836.58 € (Zlatibor). After installing pergolas (scenario S3), M_{tot} values are (Fig. 24): 1047.96 € (Kopaonik), 745.06 (Kragujevac), 777.39 € (Kraljevo), 758.71 € (Kruševac), 743.27 € (Loznica), 864.80 € (Požega), 860.64 € (Sjenica), 836.95 € (Užice), 770.86 € (Valjevo) and 842.26 (Zlatibor). Based on the economic analysis, the monetary costs are the highest in the case of Koplaonik, Požega and Sjenica.

From Fig. 25 it can also be noticed that the costs M_{tot} in scenario S3 (compared to scenario S2) have a slightly increasing trend for locations such as Kopaonik, Požega, Sjenica, Užice and Zlatibor. A slightly decreasing trend is characterized by Kragujevac, Kraljevo, Kruševac, Loznica and Valjevo. In the first case, it is about locations with more sensitive meteorological conditions during the heating season, while in

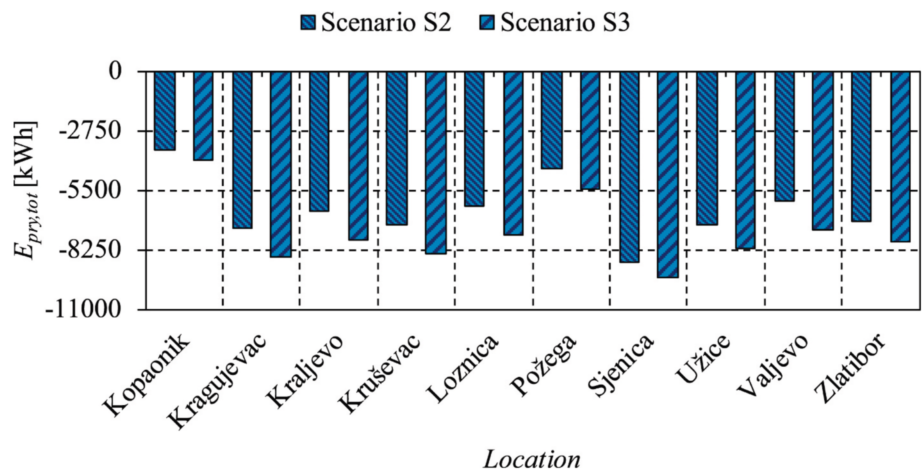


Fig. 22. Relation between total annual primary energy consumption and ZenRB status in the Western Serbia region depending on the simulation scenario.

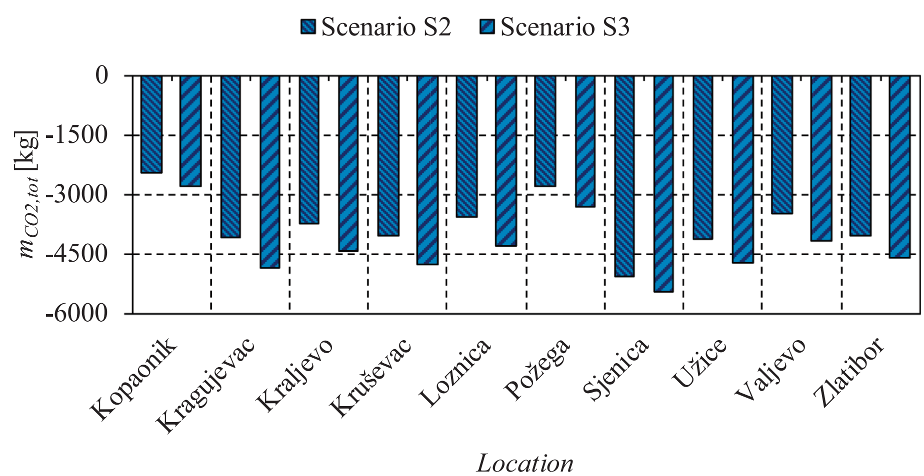


Fig. 23. Relation between total annual CO_2 emission and ZemRB status in the Western Serbia region depending on the simulation scenario.

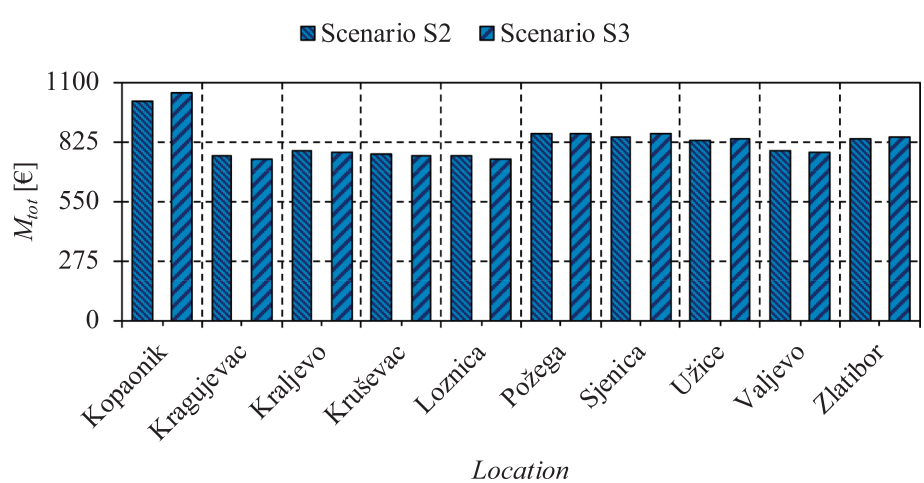


Fig. 24. Relation between total annual money cost and the potential to achieve ZcRB status (not achieved due to pellet and electricity costs) in the Western Serbia region depending on the simulation scenario.

the second case, it is about locations with more sensitive meteorological conditions during the cooling season.

4.4. Energy-ecological-economic optimization

Energy, environmental and economic analyses, carried out on the specific building model (single-family building), showed that ZRB status is influenced by many factors: location, meteorological conditions,

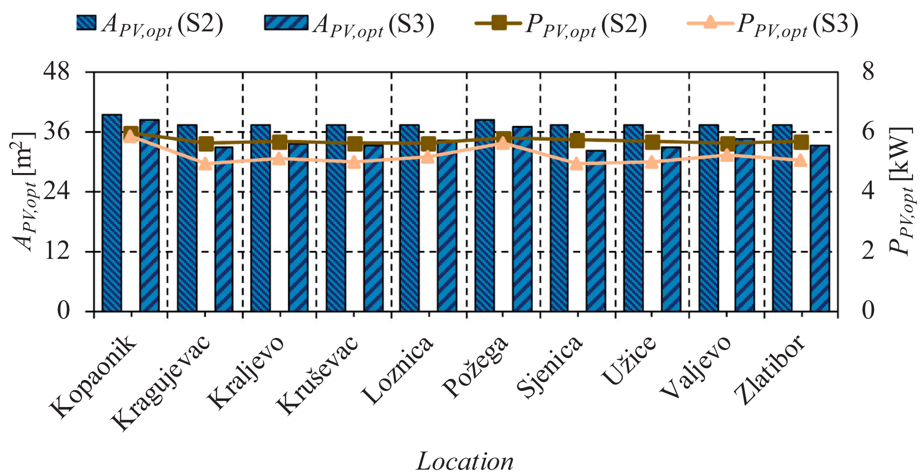


Fig. 25. Optimal area of photovoltaic panels and capacities of solar power plants in the Western Serbia region depending on the simulation scenario.

thermo-technical systems and occupancy schedules.

Energy (Figs. 21 and 22) and ecological (Fig. 23) indicators showed that there is space to reduce A_{PV} = 46.06 m^2 (Fig. 7), without endangering ZenRB status or ZemRB status. The following diagram (Fig. 25) shows the optimal area of PV panels $A_{PV,opt}$ [m^2] for scenarios S2 and S3 depending on location parameters. The same diagram shows the required (optimal) capacities of solar power plants $P_{PV,opt}$ [kW], corresponding to the values of $A_{PV,opt}$.

Optimal area of PV panels $A_{PV,op}$ is determined so that the indicators $E_{fin,el}$, $E_{pry,tot}$ and $m_{CO2,tot}$ do not threaten the energy and environmental ZRB status. Optimization results in scenario S2 are respectively (Fig. 25): 39.15 m^2 (Kopaonik), 37.31 m^2 (Kragujevac, Kraljevo, Kruševac, Loznica, Sjenica, Užice, Valjevo, Zlatibor) and 38.23 m^2 (Požega). In scenario S3, $A_{PV,opt}$ is between 32.24 m^2 (Sjenica) and 38.23 m^2 (Kopaonik). This means that the benefits of using the external wall-roof pergolas are the largest (A_{PV} is smaller by 5.07 m^2) and the smallest (A_{PV} is smaller by 0.92 m^2) in the case of the mentioned locations.

Depending on the location parameters, capacities of solar power plants on the south roof of the single-family building in scenarios S2 and S3 range between 5.61–5.97 kW and 4.93–5.83 kW, respectively (Fig. 25). The maximum capacity values in both cases are characteristic of single-family buildings located in Kopaonik, while the minimum capacity values refer to Valjevo (scenario S2) and Kragujevac (scenario S3).

Taking into account the optimal area and the installed power of PV panels (solar power plants), investment (about €850/kW installed power [70]) costs with (about €850/kW installed power [70]), subsidies for the implementation mentioned acive solar system (50 % of investment costs are covered by local self-government [71]), the price of pellets (space heating) and electricity (space cooling, home appliances, internal lighting, water heating) before (scenario S1) and after (scenario S2) the implementation of energy efficiency measures, in according to Eq. (27), it is estimated that the payback period (Fig. 26) could be between 3.3 years (for Kragujevac) and 4.35 years (for Kopaonik). The payback period in scenario S3 is longer mainly because of the investment in wooden boards (X_{perg} = 3010.35 € – where one wooden board measuring 10 × 2 cm is 3.16 €/m [72]), which are used to make external wall-roof pergolas (Fig. 26). In scenario S3, it turns out that Valjevo has the most favorable climatic conditions and the shortest repayment period, which is 7.84 years.

4.5. Results validation

To validate numerical results, the next table (Table 6) compares some indicators of the present study with previous experimental and numerical studies in the available literature.

In the first case, the Serbian Rulebook on Energy Efficiency for New Buildings prescribes the permitted consumption $e_{fin,heat}$ = 33 kWh/m^2 during the heating season to meet the minimum conditions for reaching "C" energy class. Except for RB on Kopaonik, in all other cases, this consumption is around this limit (Fig. 18). Đorđević et al. have shown in [73] that buildings can consume $e_{fin,heat}$ = 75 kWh/m^2, while ODYSSEE-MURE [74] states a value of $e_{fin,heat}$ = 80 kWh/m^2. The value of the $e_{fin,heat}$ for European residential sector can reach up to 200 kWh/m^2 in some

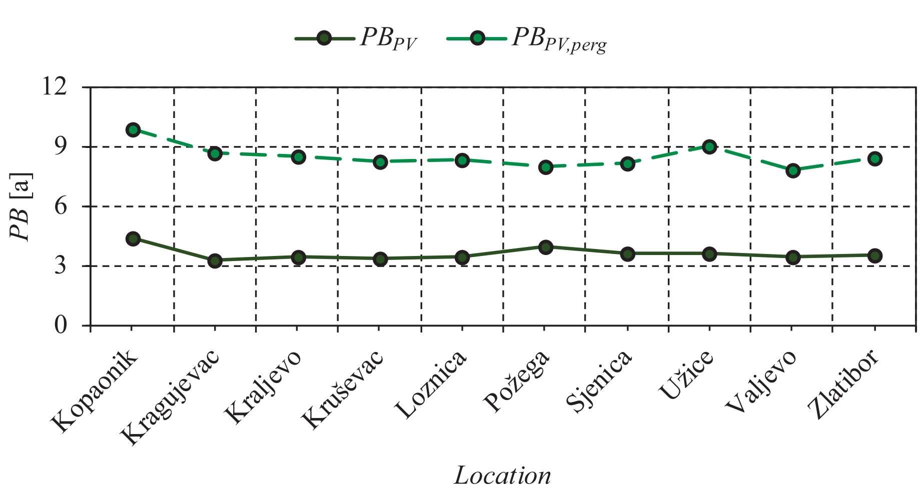


Fig. 26. Payback period in the Western Serbia region depending on the simulation scenario.

Table 6
Results validation.

Indicator	$e_{fin,heat}$ [kWh/m^2]	$e_{fin,cool}$ [kWh/m^2]	$e_{fin,PV}$ [kWh]	$S_{fin,cool,perg}$ [%]
Present study	30.88–64.86	4.89–12.53	204.55–256.26	27.2–36.57
Other sources	33 kWh/m^2 [51] 75 kWh/m^2 [73] 80 kWh/m^2 [74]	10.3 kWh/m^2 [75] 7 kWh/m^2 [76]	188 kWh [77], 220–300 kWh [78]	>30 % [79] 3.2–28.97 % [80] >50 % [81]

Legend: $e_{fin,heat}$ [kWh/m^2] – Specific final energy consumption for space heating, $e_{fin,cool}$ [kWh/m^2] – Specific final energy consumption for space cooling, $e_{fin,PV}$ [kWh/m^2] – Specific final energy production from photovoltaic panels and $S_{fin,cool,perg}$ [%] – Percentage savings of the final energy consumption for space cooling for the external pergolas.

cases.

EUROTAT showed that in 2022, the share of final energy consumption for space cooling is about 0.6 % [82]. The agreement with these data shows the results obtained by Behmane and Pakere in [75], as well as by Werner in [76]. The present study, in some cases, shows slightly lower, and in others slightly higher, cooling requirements.

The same conclusions can be drawn in the case of pergolas as well, because the numerical results of the present study ($S_{fin,cool,perg}$ = 27.2–36.57 %) are within the framework (also numerical investigations) defined by Alothman et al. in [79], that is, Shahdan et al. in [80]. The first showed that the percentage energy savings can be up to 30 %, and the second that they are between 3.2 % and 28.97 %.

5. Discussion with study limitations

The numerical results showed that with the combined application of biomass (space heating), air-to-air heat pump (space cooling), smart electic systems (home appliances, internal lighting and water heating), active (PV panels) and passive (external wall-roof pergolas) solar systems, in compliance with the Rulebook on Energy Efficiency for New Buildings of Serbia and responsible occupancy schedules, in the single-family building, a zero footprint (ZRB status) is achieved for all adopted locations (10 of them) in the Western Serbia region, according to two criteria: the first is ZenRB status, and the second is ZemRB status.

In contrast to the previous two criteria for reaching the ZRB status, the numerical results also showed that the ZcRB status cannot be achieved (the negative side of the proposed strategy) precisely because of the use of different types of thermo-technical systems. The monetary costs allocated for space heating and electricity are over 700 € per year in the most favorable case. In general, it is very difficult to reach ZRB status according to economic criteria. For such a thing to be possible, it is necessary to replace the existing heat energy generator with a geothermal heat pump and the radiators with floor heating panels – for example. Heat recovery systems can also be a good choice.

It should be emphasized that the ZemRB status was achieved because only the CO_2 footprint was used. Other criteria (NO_x footprint, CO_2 footprint in the chain of energy transformations of pellet production, negative effects of transport, etc.) were not taken into consideration. The reason is the absence of legal frameworks for defining the limit values of the mentioned sensitive points in the current Rulebook on Energy Efficiency for New Buildings of Serbia [52]. In other words, Rulebook application is limited to CO_2 emissions only.

The numerical study was conducted based on four simulation scenarios (weekdays, Saturday, Sunday and holidays) of schedule occupancy to meet the needs of an average family of four. It should be noted that, in real circumstances, the behavior of tenants can be very unstable and unpredictable, wich can significantly impact energy consumption and potentially alter the ZRB balance. It is clear that without responsible national-level policies and responsible tenant behavior, applying any energy efficiency concept, especially in the residential building sector, is pointless.

Pergolas (and similar shading building elements) can be an interesting and attractive design solution with a wider energy spectrum of use, due to their contribution to reducing final energy consumption for space cooling. In the present study, external wall-roof pergolas were applied based on an on–off operation mode, so that they are active during the cooling season and inactive during the heating season. Fixed pergolas are not recommended for moderate continental climate areas because all four seasons are expressed. Thus, the benefits realized during one half of the year would be canceled during the second half of the year. Pergolas based on an automatic tracking mechanism with small rotation steps and appropriate sensors that would balance between solar gains, solar shading, heat losses and daylight would contribute even more to their wider commercial application.

Currently, the Serbian Rulebook on the Close Conditions for the Distribution and Use of Funds for the Implementation of Energy Efficiency Measures [48] is not supportive of passive solar systems, which is one reason they are not more widely used. In other words, potential users avoid them due to potentially high initial costs. If subsidies of 50 % (similar to those offered for other energy efficiency measures) were included, it would provide a positive incentive for citizens of Serbia. Conversely, high initial expenses could be mitigated, and the maintenance period shortened, if pergolas are constructed from scrap materials from other sectors, such as waste wood of suitable quality, recycled materials, and similar solutions.

6. Conclusion and future research directions

This paper analyzed the impact of bioclimatic external wall-roof pergolas (cooling passive solar system) on the energy, ecological and economic performance of the ZRB status in the narrow territorial area of Serbia with a moderate continental climate, more precisely within the region of Western Serbia.

The research subject was the single-family building equipped with renewable energy heating, cooling and other (PV panels, home appliances, internal lighting and water heating) thermo-technical systems. The residential building was created in compliance with the principles of energy efficiency in carpentry, as defined by law. The proposed ZRB concept was numerically (with Google SketchUp and EnergyPlus) analyzed and tested, using weather data for 10 locations (towns) in the mentioned administrative area. Location parameters (such as altitude and microclimate) of all locations are different.

The initial results showed that the ZenRB and ZecRB status can be realized in every location, both in the case without external wall-roof pergolas and in the case with them. It should be emphasized that there are locations that are more suitable for the application of presented concept in terms of energy, ecology and economy, and that the contribution from the use of pergolas, in the general case, is not negligible.

Total annual useful energy consumption (space heating and cooling together) in the case of the single-family building model (only with photovoltaic panels) was within the following limits: 7922.84 kWh (Sjenica) and 9247.43 kWh (Kopaonik). By using pergolas, reducing this consumption can be close to 15 %, which was shown in two cases: Kragujevac and Loznica. Although it has been observed that the use of pergolas can increase the annual final energy consumption for heating by a little more than 8 % (only in the case of Kopaonik), the benefits during the cooling season are much greater. In other words, annual final energy consumption for cooling can be reduced between 25.3 % (Požega) and 35.26 % (Užice). The simulations showed that the Western Serbia region is extremely suitable for the application of solar systems, without which the targeted ZRB status could not even make sense. Following the used weather files and for the adopted roof slope, the most suitable location for the application of photovoltaic panels is Kragujevac (with annual electricity production of 11803.27 kWh). On an annual basis, when A_{PV} is 46.05 m^2, 4130.49 kWh of electricity can be fed into the grid network. This results in a reduction of annual primary energy consumption (by 9513.68 kWh) and CO_2 emissions (by 5472.89 kg). If the solar systems were optimized according to the single-family building needs, the PV panels area would fall within the following ranges: 37.31–39.15 m^2 (without pergolas) and 32.24–38.23 m^2 (with pergolas). In the first case, the payback period ranges between 3.3–4.35 years, that is, 7.84–9.87 years.

The decarbonization of the European building sector, which currently accounts for about 40 % of energy consumption and 34 % of greenhouse gas emissions (data from 2022), represents one of the key challenges in the near future. ZBs (ZenBs, ZemBs, and ZcBs), through the implementation of advanced energy efficiency systems and RES, provide a significant attempt to reduce this impact. However, to achieve the established targets by 2030, it is important to adopt a multidisciplinary approach that optimizes energy efficiency and integrates appropriate technologies. Use of passive solar systems, such as pergolas and other shading elements, should be more widely implemented, particularly in European areas with continental, moderately continental, and Mediterranean climates. These elements can reduce final energy consumption for cooling during the summer months, thus contributing to the achievement of the established goals. Of course, then need to take into account all the specificities that the selected location brings with it.

Given that the main task of the present paper was the presentation of the ZRB concept, which has not been explored in the literature so far, future directions of research, to further improve and develop this topic, should be focused on the "critical links in the chain" related to the correct selection of location parameters (climatic regions) and thermo-technical systems, more efficient and effective control and management of thermo-technical systems, the influence of the schedule of occupancy, etc.

CRediT authorship contribution statement

Aleksandar Nešović: Writing – review & editing, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aleksandar Radaković:** Writing – original draft, Visualization, Software, Investigation, Data curation, Conceptualization. **Dragan Cvetković:** Validation, Software, Resources, Data curation, Project administration, Supervision. **Robert Kowalik:** Project administration, Investigation, Conceptualization, Formal analysis, Methodology, Writing – original draft. **Igor Saveljić:** Supervision, Resources, Data curation, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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