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Numerical Simulation of Climate Change Impact on Energy, Environmental and Economic Performances of Small Single-Family Houses Equipped with Trombe Walls and Fixed Horizontal Overhangs

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Abstract: Although the European residential sector has promoted various heating and cooling passive solar systems in many ways, ongoing climate changes affect these construction elements at an annual level. Using the weather files for three years in the recent past (2018, 2021 and 2023), this paper numerically investigates the energy, environmental and economic performance of two small single-family houses equipped with Trombe walls and fixed horizontal overhangs of different depths (0 m, 0.25 m, 0.5 m, 0.75 m and 1 m) for two characteristic European climate zones: continental (Kielce city, Poland) and moderate continental (Kragujevac city, Serbia). Both houses were created in Google SketchUp 8 software using current Statistical data and Rulebooks of energy efficiency, while adopted heating (gas boiler and radiators) and cooling (individual air-conditioning units) active thermo-technical systems were simulated in EnergyPlus 7.1 software using official specific energy, environmental and economic indicators. Compared to the appropriate reference houses—without mentioning passive solar systems—the main results of this study are as follows: (1) higher outdoor air temperatures can reduce final (thermal) energy consumption for heating by 37.74% (for the Kielce climate zone) and 52.49% (for the Kragujevac climate zone); (2) higher outdoor air temperatures can increase final (electricity) energy consumption for cooling between 5.71 and 11.75 times (for Kielce) and 4.36 and 9.81 times (for Kragujevac); (3) percentage savings of primary energy consumption and monetary savings are highest when houses are equipped with Trombe walls and 1 m deep overhangs; and (4) all considered cases of passive solar systems do not contribute to the reduction of greenhouse gas emissions. Since climate change is a consequence of greenhouse gas emissions, priority should be given to environmental indicators in future investigations.

Keywords: climate change; overhang; Poland; Serbia; simulation; single-family house; Trombe wall

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1. Introduction

The Trombe wall (TW), also known as the solar wall concept [1] and the green architectural concept [2], is an interesting massive construction element [3] oriented towards the equator [4] that indirectly accumulates solar energy [5] and then is transmitted to a heated space by convection and radiation [6]. In this way, the final energy consumption for heating (during the winter season) in the building is reduced [7,8]. This makes the TW suitable for use in continental and moderately continental climate regions; thus, the European residential sector is paying a lot of attention to the promotion of this passive solar system.

Unlike the rest of Europe, it seems that Poland [9–15] and Serbia [16–26] do not sufficiently contribute to this topic, although they have enormous potential. Poland is located in a continental climate zone and Serbia is located in a moderately continental climate zone.

The evolution of the TWs was shown in 1967–2022 by Szyszka [9]. In [10], Szyszka et al. presented an overview of the most commonly used solutions of the TW. They also discussed their concept of the modified TW dedicated to the climate conditions of Central Europe. Oltarzewska and Krawczyk realized the review paper of the current state of the TW [11]. They also simulated (using the TRNSYS software) building with the TW for three system variants and four locations with different climatic conditions. One of the paper's main conclusions was that the effectiveness of the TWs depends largely on the climatic conditions and should be considered only as auxiliary support for HVAC systems. The research presented in [12] aimed to determine the influence of glazing parameters on the thermal performance of the TW containing a phase change material. Three glazing types with different heat transfer coefficients and total solar energy transmittance factors were used. The investigation was conducted using numerical and experimental tools. The energy efficiency of an interactive glass wall prototype similar to the TW was presented in [13]. The experiments were conducted in field conditions using a regulated air temperature test chamber. Calculations showed that this construction ensures that heat gains exceed heat losses. The effect of some boundary conditions on an innovative solution of the Thermo-Diode TW was analyzed in [14]. The new TW concept was designed to ensure thermal insulation for the building envelope with simultaneous solar gains. Experimental results showed that the thermal efficiency ranged between 21.58 and 30.30%. Błotny and Nemś proposed a passive solar heating and cooling system in Wrocław, Poland—the TW on the southern facade of a room measuring 4.2 × 5.2 × 2.6 m [15]. They used Ansys Fluent 16.0 to examine the temperature distribution and air circulation for two representative days during the heating and cooling period (16 January and 15 August).

In contrast to the Polish literature, research into the thermal performance of the TW in Serbia is mainly based on various numerical tools. Dragićević and Lamić [16,17] developed a steady-state and one-dimensional mathematical model of the modified TW with forced convection that could operate in four different modes. In [18], three different TW concepts were created, which were simulated in the EnergyPlus software; building with the vertical (classic) TW, building with the inclined TW and building with vertical and inclined TWs. In the third (combined) case, the heating energy consumption was the lowest, but the cooling energy consumption was the highest. Bojić et al. used EnergyPlus software to integrate the TW into the two Mozart house model types [19]: the original Mozart house model (the first one) and the modified Mozart house model (the second one). The three-dimensional numerical CFD model of the TW for temperature field analyses of the characteristic layers was presented in [20]. The indoor air temperatures of a thermally insulated residential building with the unvented TW and a direct passive solar system for different building orientations and TW thicknesses were analyzed (using two software packages: RMSun and InSunTr) in [21]. Numerical simulations (in two software: EnergyPlus and jEplus) on the educational building example showed that the heating energy savings could be 77%. In contrast, maximum cooling energy savings could be 79% if the TW is installed in combination with other passive solar systems [22,23]. The impact of different green roof types on the energy properties of a detached residential building with the TW was presented in [24]. The model of active insulation of buildings using a special form of the TW was proposed numerically (using MATLAB 2022) in [25]. In [26], the traditional Serbian country cottage equipped with the passive TW in the vicinity of the city of Kragujevac was investigated.

However, meteorological measurements around the world during the last decade [27,28] have shown that the global climate picture has worsened, i.e., that climate change is well underway. These changes are particularly noticeable in the European continental (Poland) and moderately continental (Serbia) belts. A clear boundary between the seasons no longer exists. Outside temperatures during winter are higher than before (often exceeding the value of 10 °C), while snow, the main feature of winter, is an increasingly rare phenomenon, especially in Serbia. Summers are getting hotter, with an increasing number of heat waves (according to data from the Republic Hydrometeorological Services of Poland [29] and Serbia [30], the number of such days is over 30 per summer season) [31–34].

Providing thermal comfort in the residential sector, i.e., preventing overheating (regardless of the period of the year) in such meteorological circumstances is challenging, especially in buildings and houses equipped with passive solar heating systems such as TWs. The users of buildings and houses, the national energy and economic sectors and the environment are facing these challenges today with insufficient involvement of the global scientific community (applying to Poland and Serbia). The main scientific contribution of this paper is to indicate to the global scientific community that there is a legitimate threat to the future implementation of heating passive solar systems if the problem is not approached adequately (from different angles)—a topic that has not been explored in the available literature.

This paper numerically investigates the cause-and-effect relationships between (1) climate change, (2) heating (TWs) and cooling (fixed horizontal overhangs, i.e., FHOs) passive solar systems, and (3) heating (gas boiler and radiators) and cooling (individual air-conditioning units) active thermo-technical systems in two small single-family house types during the year, for two dominant climate zones on the European continent: continental and moderate continental. In the first case (for the continental climate zone), the reference house model (without passive solar systems) is located in Kielce and respects Polish current Statistical data and Rulebooks of energy efficiency. In the second case (for the moderate continental climate zone), the Kragujevac reference house model respects Serbian current Statistical data and Rulebooks of energy efficiency. Both house models (with and without passive solar systems) were designed in Google SketchUp software. Weather files for three years in the recent past (2018, 2021 and 2023) were implemented in EnergyPlus software to conduct energy, environmental and ecological (EEE) simulations in all considered scenarios (the influence of the following different FHO depths was also taken into account: 0 m, 0.25 m, 0.5 m, 0.75 m and 1 m). At the end of the paper, diagrams are presented for two limit cases of FHO depths (0 m and 1 m), which can be used to predict the final energy consumption for heating and cooling in single-family houses with similar geometric, structural and thermo-technical characteristics depending on outdoor air temperatures and location parameters (climate zones).

Using the above, the reference house models are described in detail in Section 2. Section 3 is dedicated to the physical-thermal characteristics of the Trombe wall. Used weather files for Kielce (Poland) and Kragujevac (Serbia) during the analyzed period (2018, 2021 and 2023) are described in Section 4. All analyzed cases (simulation scenarios) are defined graphically and textually in Section 5, and energy, environmental and economic indicators are defined in Section 6. Special attention is paid to Section 7 (which presents the results obtained) while concluding remarks are presented in Section 8.

2. Design of the Reference House Models

In this chapter, the Kielce (for Poland) and Kragujevac (for Serbia) reference house models are described (Section 2.1) as follows: orientation of the houses, layouts of rooms, net floor areas and volumes of the houses, window–wall ratios, form factors and thermal properties of the exterior house elements. The heating (gas boiler and radiators) and cooling (individual air-conditioning units) active thermo-technical systems are described in Sections 2.2 and 2.3, respectively.

2.1. Construction Physics

Figure 1 shows the isometric view (Figure 1a) and cross-section with room layout (Figure 1b) of the Kielce initial (reference) house model. The Kragujevac initial (reference) house model with the same views (isometric and cross-section with room layout) is presented in Figure 2.

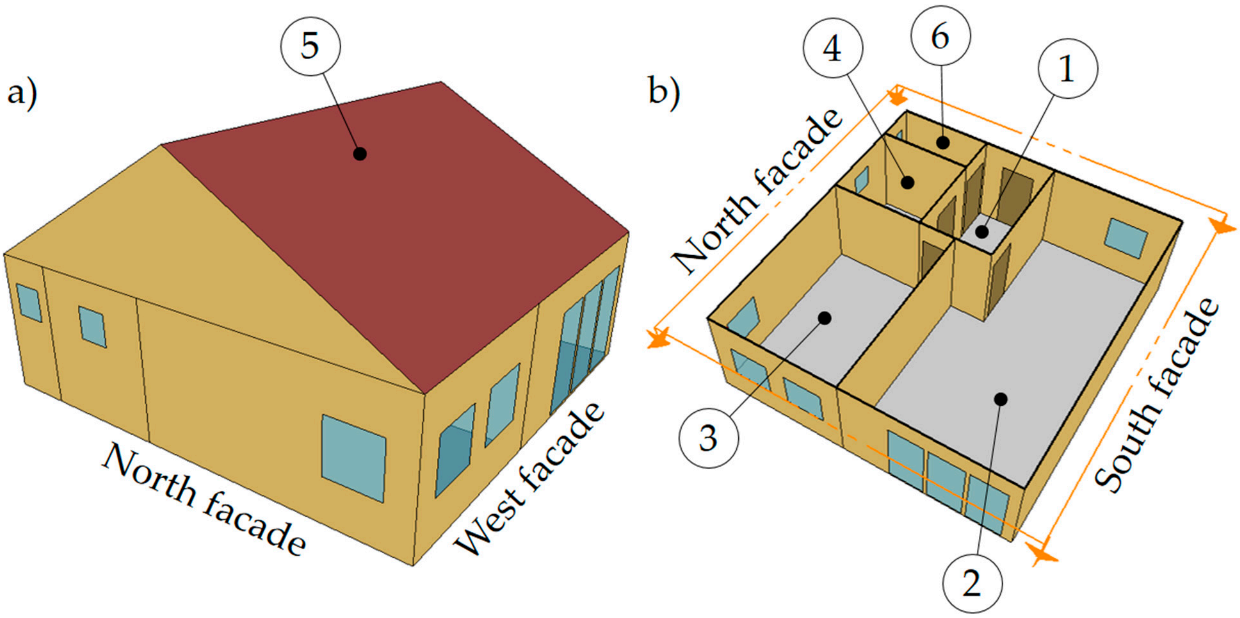

Figure 1. Isometric view (**a**) and characteristic horizontal section with room layout (**b**) of the Kielce (Poland) reference small single-family house model. TZ1—hall 1, TZ2—multifunctional room (living room, kitchen, dining room, bedroom), TZ3—children's room, TZ4—bathroom, TZ5—attic space, TZ6—storage room.

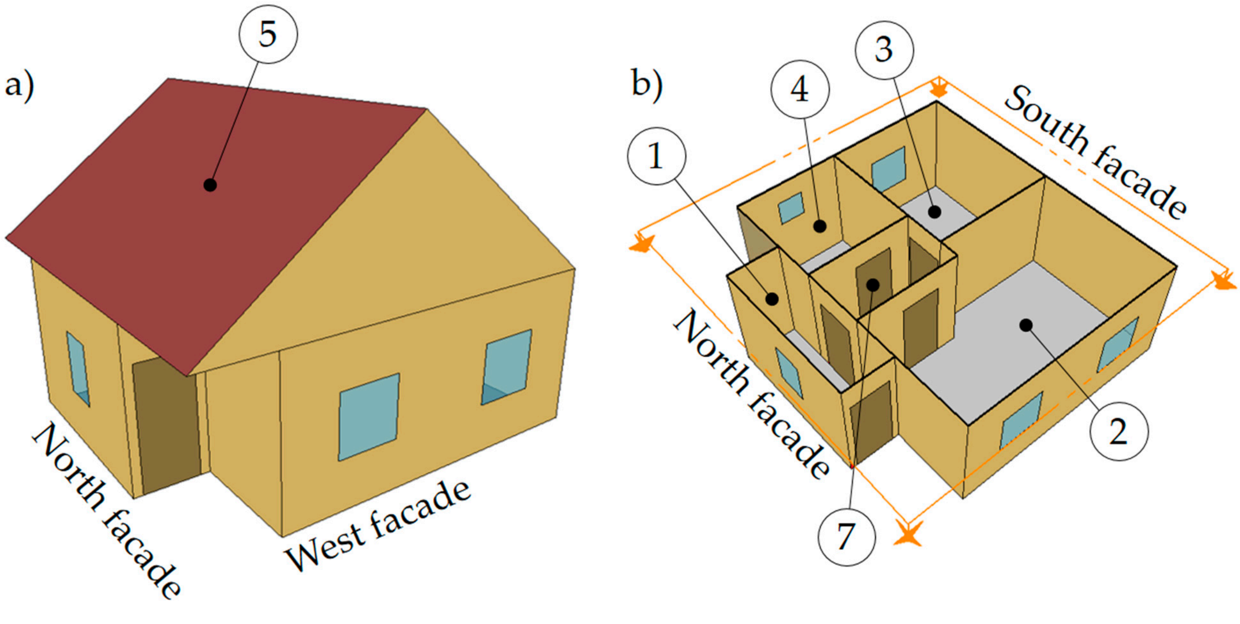

Figure 2. Isometric view (**a**) and characteristic horizontal section with room layout (**b**) of the Kragujevac (Serbia) reference small single-family house model. TZ1—hall 1, TZ2—multifunctional room (living room, kitchen, dining room, bedroom), TZ3—children's room, TZ4—bathroom, TZ5—attic space, TZ7—hall 2.

Figures 1 and 2 show that the houses are small in dimensions and intended for the permanent residence of a family of four—the small single-family houses. The entrance doors are oriented to the east (Figure 1) and the west (Figure 2). The design of the houses was chosen following the valid Statistical data and Typology buildings in Poland [35] and Serbia [36].

The total net floor area of the Kielce house is 134.36 m^2 (the ground floor and attic space are the same: 67.18 m^2 each). There are five thermal zones (TZs) on the ground floor (Figure 1b). The net floor areas A [m^2] and volumes V [m^3] of all TZ (six of them) are presented in Table 1. The total window area is 11.77 m^2; therefore, the window (with door)–wall ratio is 0.125. The form factor is 0.98 m^{-1}. The adopted number of air changes for TZs is 0.5 h^{-1} (for TZ1, TZ3, TZ5 and TZ6) and 1.5 h^{-1} (for TZ2 and TZ4).

Table 1. The net floor areas and volumes of all thermal zones in the analyzed small reference single-family house models.

Ordinal Number	TZ	Mark	A [m^2]		V [m^3]	
			Kielce (Poland)	Kragujevac (Serbia)	Kielce (Poland)	Kragujevac (Serbia)
TZ1	Hall 1	H1	6.84	4.32	17.78	11.23
TZ2	Multifunctional room	MR	34.18	18	88.87	46.80
TZ3	Children's room	CR	17.61	10.5	45.77	27.30
TZ4	Bathroom	BT	5.8	6.25	15.08	16.25
5TZ	Attic space	AS	67.18	46.9	81.93	60.97
6TZ	Storage room	SR	2.75	-	7.15	-
TZ7	Hall 2	H2	-	3.75	-	9.75
Σ			134.36	89.72	256.58	172.3

The total net floor area of the Kragujevac house is 89.72 m^2 (ground floor is 42.82 m^2, attic space is 46.9 m^2, Table 1). The total window area in this case is 5.86 m^2; thus, the window–wall ratio is 0.071. The form factor is 1.13 m^{-1}. The adopted number of air changes for TZs is 0.5 h^{-1} (for TZ1, TZ3, TZ5 and TZ7) and 1.5 h^{-1} (for TZ2 and TZ4).

The created Kielce and Kragujevac houses also follow Polish [37] and Serbian [38] Rulebooks of energy efficiency, respectively. For each exterior house element (Table 2), the maximum allowed U_{max} [W/(m^{2}K)] values were adopted to satisfy the mentioned documents.

Table 2. Maximum allowed U_{max} values for the analyzed small reference single-family house models.

Exterior House Element	Mark	U_{max} [W/(m^{2}K)]	
		Kielce (Poland [37])	Kragujevac (Serbia [38])
Floor	F	0.25	0.3
Wall	W	0.2	
Slope roof	SR	0.3	
Window	WW	0.9	1.5
Door	D		1.6
Intermediate floor construction	IFC	-	0.2

2.2. Heating System

Only three TZs were subjected to heating in both houses (rooms where most of the day was spent): TZ2, TZ3 and TZ4. On the other side, TZ1, TZ5, TZ6 (Kielce house) and TZ7 (Kragujevac house) were temporary rooms without longer stays during the day.

The heat generator in the central heating system was a gas boiler. The produced heat energy was delivered with hot water to radiators located in heated rooms (TZ2, TZ3 and TZ4). This heating system was implemented in both houses with the aim that the temperature (during the year) in the treated rooms does not fall below 20 °C (in TZ2 and TZ3) and 24 °C (in TZ4).

2.3. Cooling System

As in the case of heating, the same rooms were subjected to cooling: TZ2, TZ3 and TZ4. Classic individual air-conditioned units (cooling power and coefficient of performance are Q_{cool} = 3500 W and COP = 2.61, respectively) formed the cooling system. The control system (temperature in thermally treated rooms) was set to maintain the desired temperature (below 26 °C) during the year.

3. Design of the Trombe Wall

In the next phase of the paper, the southern facade walls (Figures 1 and 2, Table 1) were replaced by the TWs. Figure 3 shows the Kielce small single-family house before (Figure 3a) and after (Figure 3b) the implementation of the TW. The same principle was applied to the Kragujevac small single-family house (Figure 4a shows the reference model while Figure 4b shows the advanced model).

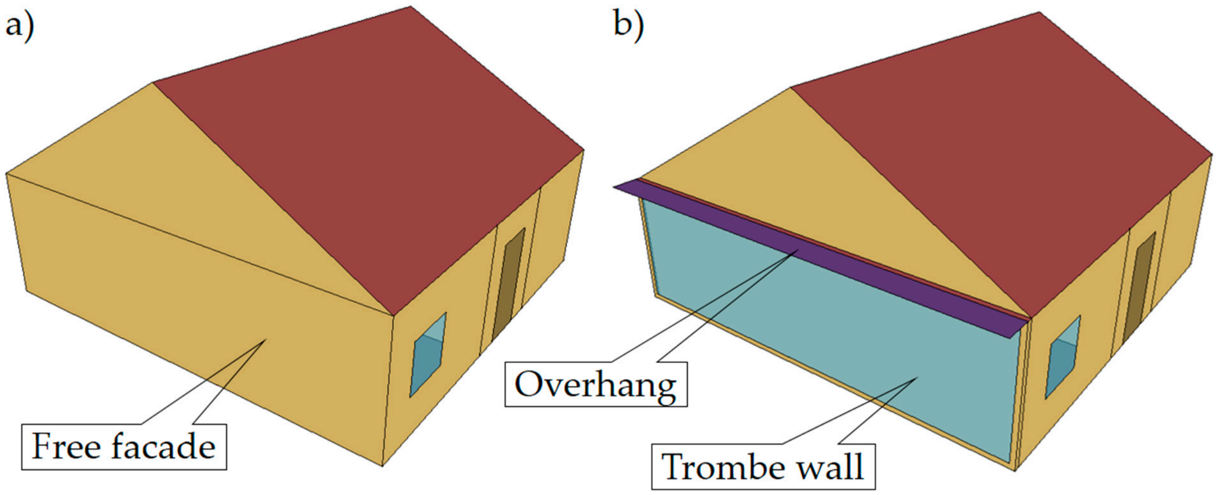

Figure 3. The Kielce small single-family house model before (**a**) and after (**b**) the implementation of the passive solar systems (Trombe wall and fixed horizontal overhang).

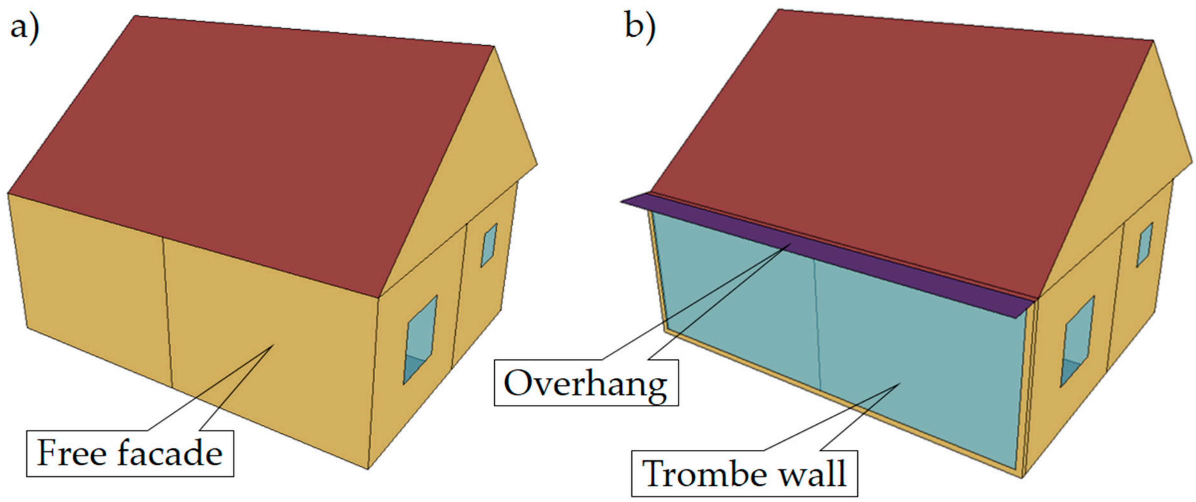

Figure 4. The Kragujevac small single-family house model before (**a**) and after (**b**) the implementation of the passive solar systems (Trombe wall and fixed horizontal overhang).

In the case of the Kielce house, the TW covers only one room, i.e., TZ2 (Figure 3). In the case of the Kragujevac house, the TW covers two rooms, i.e., TZ2 and TZ3 (Figure 4). Figures 3 and 4 also show the FHOs placed above the TWs along the south facade. Their fundamental role is to reduce the heat load of the analyzed houses during the summer season. The geometric and thermal characteristics of all layers in the TW construction (glazing, air layer, selective coating and massive wall) are shown in Table 3.

Table 3. The geometrical and thermal performance of the Trombe wall [39].

Description	Mark	Unit	Layer			
			Glazing	Air Layer	Selective Coating	Massive Wall
Thickness	δ	[m]	0.003	0.1	0.0016	0.4
Thermal conductivity	λ	[W/(mK)]	0.9	-	393	1.73
Density	ρ	[kg/m^3]	-	-	8907	2242
Specific heat	c_p	[J/(kgK)]	-	-	370	837
Solar transmittance	*ST*	[-]	0.899	-	-	-
Solar reflectance	*SR*	[-]	0.079	-	-	-
Absorptance	α	[-]	-	-	0.94	0.65
Emissivity	ε	[-]	-		0.06	0.9

4. Location Parameters

Figure 5 shows three main monthly meteorological data during the analyzed period (2018, 2021 and 2023) for two adopted locations: Kielce and Kragujevac.

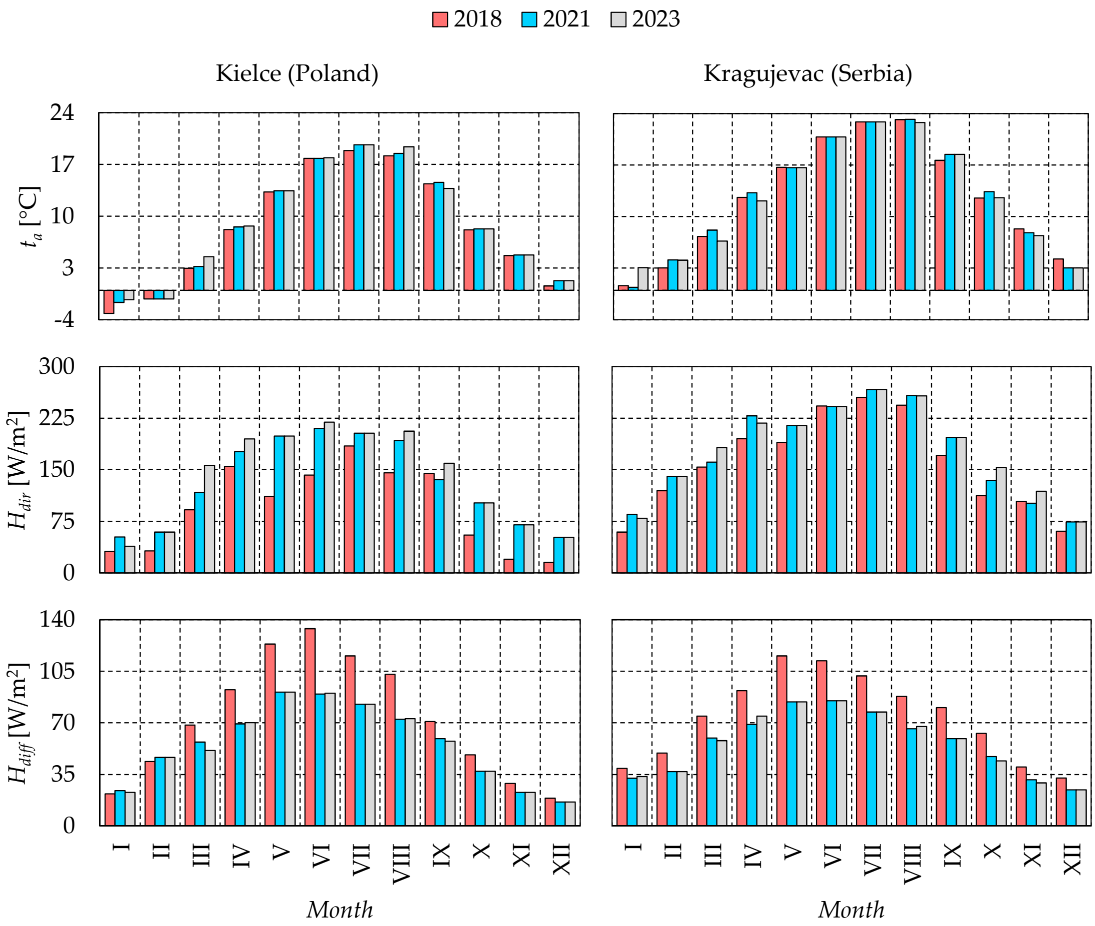

Figure 5. Monthly weather files for Kielce (Poland—continental climate zone) and Kragujevac (Serbia—moderate continental climate zone) during 2018, 2021 and 2023.

The first meteorological data is outdoor air temperature t_a [°C], the second is direct solar radiation on a horizontal surface H_{dir} [W/m^2], while the third is diffuse solar radiation on a horizontal surface H_{diff} [W/m^2] (Figure 5).

The first observation that can be made from Figure 5 is that the average monthly values of t_a and H_{dir} are higher for Kragujevac (time zone is +1 h, latitude is 44.15°N, longitude is 21.03°E and elevation is 185 m [40]) during the analyzed period (2018, 2021 and 2023), which is in accordance with the climatic characteristics of the observed locations. Unlike t_a and H_{dir}, H_{diff} values vary from year to year, so during some months the diffuse solar radiation is higher for Kielce city (same time zone, latitude is 50.81°N, longitude is 20.69°E and elevation is 261 m [40]).

According to data available in [41], the average temperature of the Earth's surface today is about 1.2 °C warmer than it was in the late 1800s. The rate of climate change surged alarmingly between 2011 and 2020 because this period was the warmest [42]. That trend continues today, and this is proven by the values of t_a for Kielce and Kragujevac (Figure 5). The Kielce climate picture shows that the annual average values of t_a in 2021 and 2023 are higher by 0.37 °C and 0.53 °C, compared to the same values in 2018. The temperature profile of Kragujevac is somewhat better, because the annual average temperature in 2021 increased by 0.19 °C, and in 2023 by 0.06 °C compared to 2018. Direct solar radiation also recorded growth in 2021 and 2023 compared to 2018. In Kielce's case, it was 36.71 W/m^2 in 2021 and 44.33 W/m^2 in 2023. In Kragujevac's case, it was 16.2 W/m^2 in 2021 and 19.63 W/m^2 in 2023.

All specified data indicate that the planet is still not going in the right direction. If nothing is done, some policies and studies point to up to 3.1 °C of warming by the end of the century [41]. The consequences of climate change will be a series of negative effects that will not bypass the residential sectors either.

5. Simulation Scenarios

Figure 6 shows all analyzed cases, taking into account the following variables: (a) two small single-family house models (Kielce and Kragujevac), (b) two heating and passive systems (only active and active with passive), (c) three different years (2018, 2021 and 2023), (d) five depths of the FHO (0 m, 0.25 m, 0.5 m, 0.75 m and 1 m) and (e) two climate zones (Poland—continental climate zone, and Serbia—moderate continental climate zone).

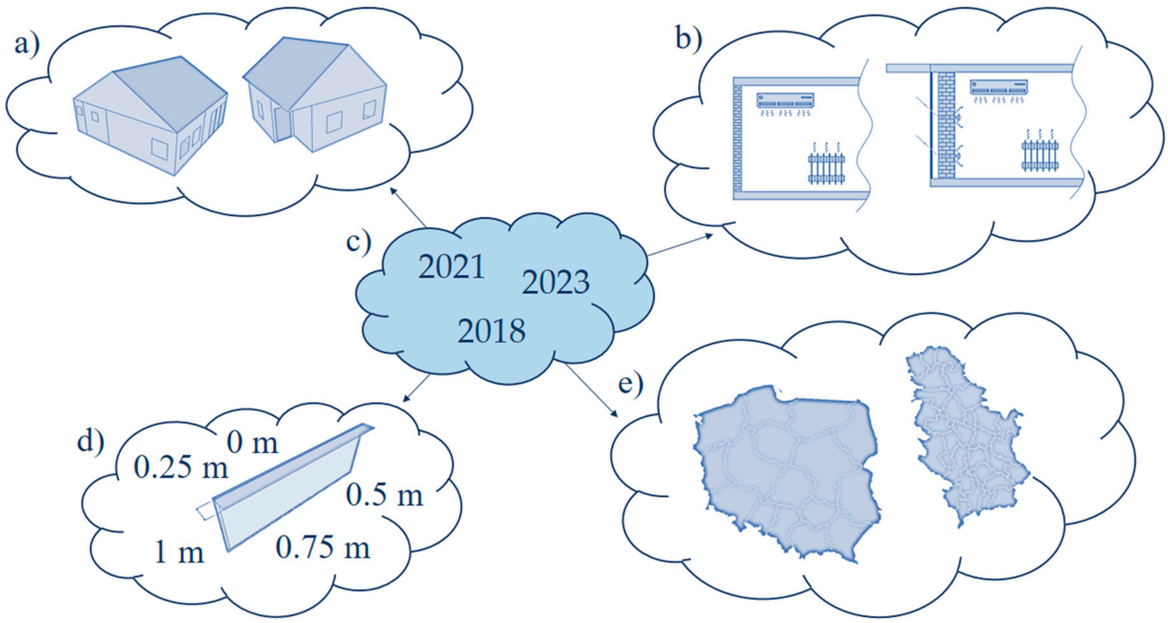

Figure 6. All considered simulation cases.

6. Energy, Environmental and Economic Flows

Annual final energy consumption for heating (thermal) $E_{fin,heat}$ [kWh/a] (Equation (1)) and cooling (electricity) $E_{fin,cool}$ [kWh/a] (Equation (2)), in all simulation scenarios (Figure 6), are determined in the following way (Figure 7):

$$E_{fin,heat} = \frac{E_{use,heat}}{\eta_r \eta_{rs} \eta_{pn} \eta_{gb}} \quad (1)$$

$$E_{fin,cool} = \frac{E_{use,cool}}{COP} \quad (2)$$

where (Table 4): $E_{use,heat}$ [kWh/a] is the annual useful energy consumption for heating; η_r [-] is the radiator efficiency; η_{rs} [-] is the regulatory system efficiency; η_{pn} [-] is the pipe network efficiency; η_{gb} [-] is the gas boiler efficiency; $E_{use,cool}$ [kWh/a] is the annual useful energy consumption for cooling; and COP [-] is the coefficient of performance of the air-conditioning unit.

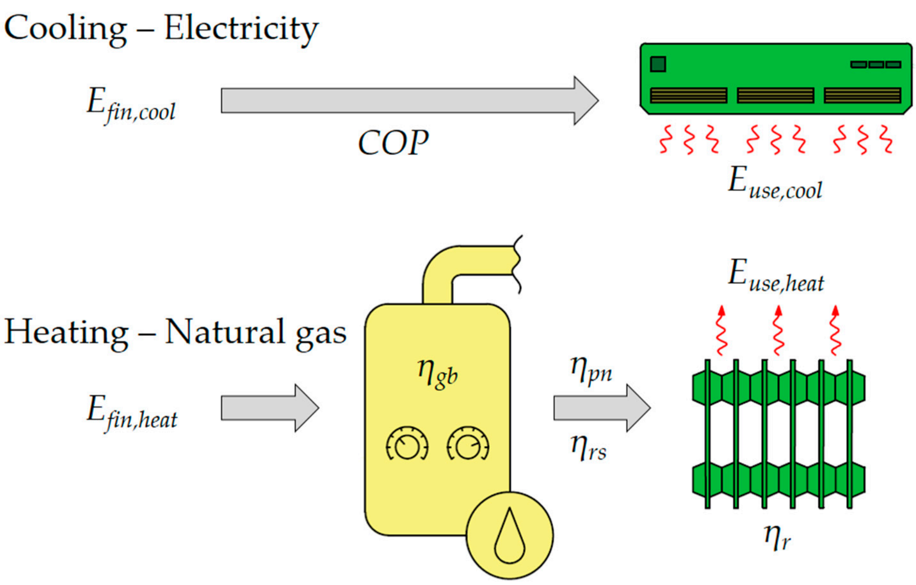

Figure 7. Energy transformations in the analyzed small reference single-family house models.

Table 4. Specific energy, environmental and economic indicators.

Mark	Unit	Kielce (Poland)	Kragujevac (Serbia)
η_r	[-]	0.98 [37,38]	
η_{rs}		0.95 [37,38]	
η_{pn}		0.98 [37,38]	
η_{gb}		0.87 [37,38]	
COP		2.61 [37,38]	
R_{ng}		1.1 [37,38]	
R_{el}		2.32 [43]	2.5 [38]
e_{ng}	[kg/m^3]	2.2 [44]	1.9 [38]
e_{el}	[kg/kWh]	0.758 [45]	0.53 [39]
h_{ng}	[kWh/m^3]	10.5 [46]	9.24 [47]
p_{ng}	[€/m^3]	0.95 [48]	0.49 [49]
p_{el}	[€/kWh]	0.24 [50]	0.052 [51]

The annual primary energy consumption for heating $E_{pry,heat}$ [kWh/a] (Equation (3)) and cooling $E_{pry,cool}$ [kWh/a] (Equation (4)) are as follows:

$$E_{pry,heat} = R_{ng} E_{fin,heat} \tag{3}$$

$$E_{pry,cool} = R_{el} E_{fin,cool} \tag{4}$$

where (Table 4): R_{ng} [-] is the primary energy factor for natural gas and R_{el} [-] is the primary energy factor for electricity.

Annual greenhouse emissions for heating $m_{CO2,heat}$ [kg/a] (Equation (5)) and cooling $m_{CO2,cool}$ [kg/a] (Equation (6)) are as follows:

$$m_{CO2,heat} = e_{ng} \frac{E_{pry,heat}}{h_{ng}} \tag{5}$$

$$m_{CO2,cool} = e_{el} E_{pry,cool} \tag{6}$$

where (Table 4): e_{ng} [kg/m^3] is the specific CO_2 emission for natural gas, h_{ng} [kWh/m^3] is the specific natural gas heat capacity and e_{el} [kg/kWh] is the specific CO_2 emission for electricity.

At the end, annual monetary costs for heating P_{heat} [€/a] (Equation (7)) and cooling P_{cool} [€/a] (Equation (8)) are as follows:

$$P_{heat} = p_{ng} \frac{E_{fin,heat}}{h_{ng}} \tag{7}$$

$$P_{cool} = p_{el} E_{fin,cool} \tag{8}$$

where (Table 4): p_{ng} [€/m^3] is the specific monetary cost for natural gas and p_{el} [€/kWh] is the specific monetary cost for electricity.

7. Results and Discussion

Table 5 presents annual energy (useful, final and primary) consumption, CO_2 emission and monetary costs in the Kielce (Figures 1 and 3a) and Kragujevac (Figures 2 and 4a) reference house models in 2018. In the rest of the analyzed cases, i.e., simulation scenarios (Figure 6), all EEE indicators will be compared to these results.

Table 5. Annual energy consumption, CO_2 emission and monetary costs for the analyzed small reference single-family house models in 2018.

		Kielce (Poland)		Kragujevac (Serbia)	
Mark	**Unit**	**Heating**	**Cooling**	**Heating**	**Cooling**
A_{tot}	[m^2]	134.36		89.72	
A_{net}	[m^2]	57.59		34.75	
E_{use}	[kWh/a]	10606.85	288.01	5057.22	468.6
E_{fin}	[kWh/a]	13362.62	110.35	6371.14	179.54
E_{pry}	[kWh/a]	14698.88	256.01	7008.25	448.85
m_{CO2}	[kg/a]	3079.77	194.06	1441.09	237.89
P	[€/a]	1209	26.48	337.86	9.34

Note: A_{tot} [m^2] is the total net floor area and A_{net} [m^2] is the net (thermally treated) floor area.

As can be seen in Table 5, annual useful energy consumption for heating in the Kielce reference house is 2.1 times higher than in the Kragujevac reference house. On the other hand, annual useful energy consumption for cooling in the Kragujevac reference house is 1.63 times higher than in the Kielce reference house. These results show that climatic conditions greatly influence the energy behavior of the analyzed houses. Since both houses are thermally insulated (Table 2), the annual specific energy consumption for heating $E_{fin,heat}/A_{tot}$ them is less than 100 kWh/m^2/a; in the first case (for the continental climate zone) it is 99.45 kWh/m^2/a, while in the second case (for the moderate continental climate zone) it is 71.01 kWh/m^2/a. The low U values, the low window-to-wall ratios (0.125 and 0.071, Section 2.1) and the absence of transparent elements (windows) on the southern facade walls (Figures 1–4) are indicative of a low heat load during the cooling season. The total (heating and cooling) annual primary energy consumption is 14954.89 kWh/a (Kielce reference house) and 7457.1 kWh/a (Kragujevac reference house), respectively. The total annual CO_2 emission is 48.72% lower in the Kragujevac reference house, while the total annual costs in Kragujevac are 3.56 times lower.

Figure 8 shows the structure of useful energy consumption for heating $E_{use,heat}$ [kWh/a] and cooling $E_{use,cool}$ [kWh/a] in the Kielce and Kragujevac houses with the TWs, depending on the climatic conditions and the depth of the FHOs.

Regardless of the used weather files (simulated years) and the climate areas (continental or moderate continental), annual energy consumption $E_{use,heat}$ is the lowest in the house with the TW and without the FHO, while the it is largest in the house with the TW and the FHO at a depth of 1 m. In the case of $E_{use,cool}$, the opposite effect occurs; the highest annual consumption was recorded in the house with the TW and the FHO at a depth of 1 m, while the lowest annual consumption was recorded in the house with the TW and without the FHO. By comparing $E_{use,heat}$ (both for Kielce and Kragujevac) from 2021 and 2023 with $E_{use,heat}$ in 2018 (Figure 6), it is clear that it is much lower, and the reason is climate change, i.e., growth of outdoor air temperatures in 2021 and 2023.

Based on numerical simulations of the thermal behavior of the Kielce advanced house, the main results are (Figure 8): $E_{use,heat}$ is the highest (8873.88 kWh/a) during 2018 when the TW is used in combination with the FHO (1 m deep); $E_{use,heat}$ is the lowest (6604.09 kWh/a) during 2023 when using the TW without the FHO (1 m deep); $E_{use,cool}$ is the largest (3384.8 kWh/a) during 2023 when the TW is used without the FHO in front of the southern facade wall; and $E_{use,cool}$ is the smallest (1644.61 kWh/a) during 2022 when the FHO depth of 1 m is installed in front of the TW. By using the FHO (from 0 m to 1 m), annual useful energy consumption for heating can increase by 5.64% (in 2018), 7.78% (in 2021) and 6.55% (in 2023). On the other hand, by using shading elements (the FHOs), there are benefits in terms of reducing annual useful energy consumption for cooling, by 46.32% (in 2018), 47.49% (in 2021) and 46.96% (in 2023).

Unlike the Kielce advanced house (where the annual useful energy consumption for heating is higher than the annual useful energy consumption for cooling in all cases), in the case of the Kragujevac advanced house, the annual useful energy consumption for heating is lower than the annual useful energy consumption for cooling until the depth of the overburden reaches 0.75 m (Figure 8). For the analyzed location with a moderate continental climate, the following main results during the year can be observed: $E_{use,heat,max}$ = 3002.24 kWh/a (overhang depth of 1 m, in 2018), $E_{use,heat,min}$ = 2402.77 kWh/a (no overhang, in 2021), $E_{use,cool,max}$ = 4595.58 kWh/a (no overhang, in 2018) and $E_{use,cool,min}$ = 2042.87 kWh/a (overhang depth of 1 m, in 2021). Depending on the FHO depths, the useful energy consumption for heating can increase by over 12% (12.27% in 2018, 13.17% in 2021 and 12.77% in 2023), while the useful energy consumption for cooling can decrease by over 47% (47.35% in 2018, 48.36% in 2021 and 47.88% in 2023).

When taking into account the appropriate specific indicators that describe the efficiency of thermo-technical systems (Table 4), it is clear that the annual final energy consumption for heating $E_{fin,heat}$ [kWh/a] will be higher than the annual useful energy consumption for heating (Figure 9). For the same reason (COP = 2.61, Table 4), the annual final energy consumption for cooling $E_{fin,cool}$ [kWh/a] will be lower than the annual useful energy consumption for heating.

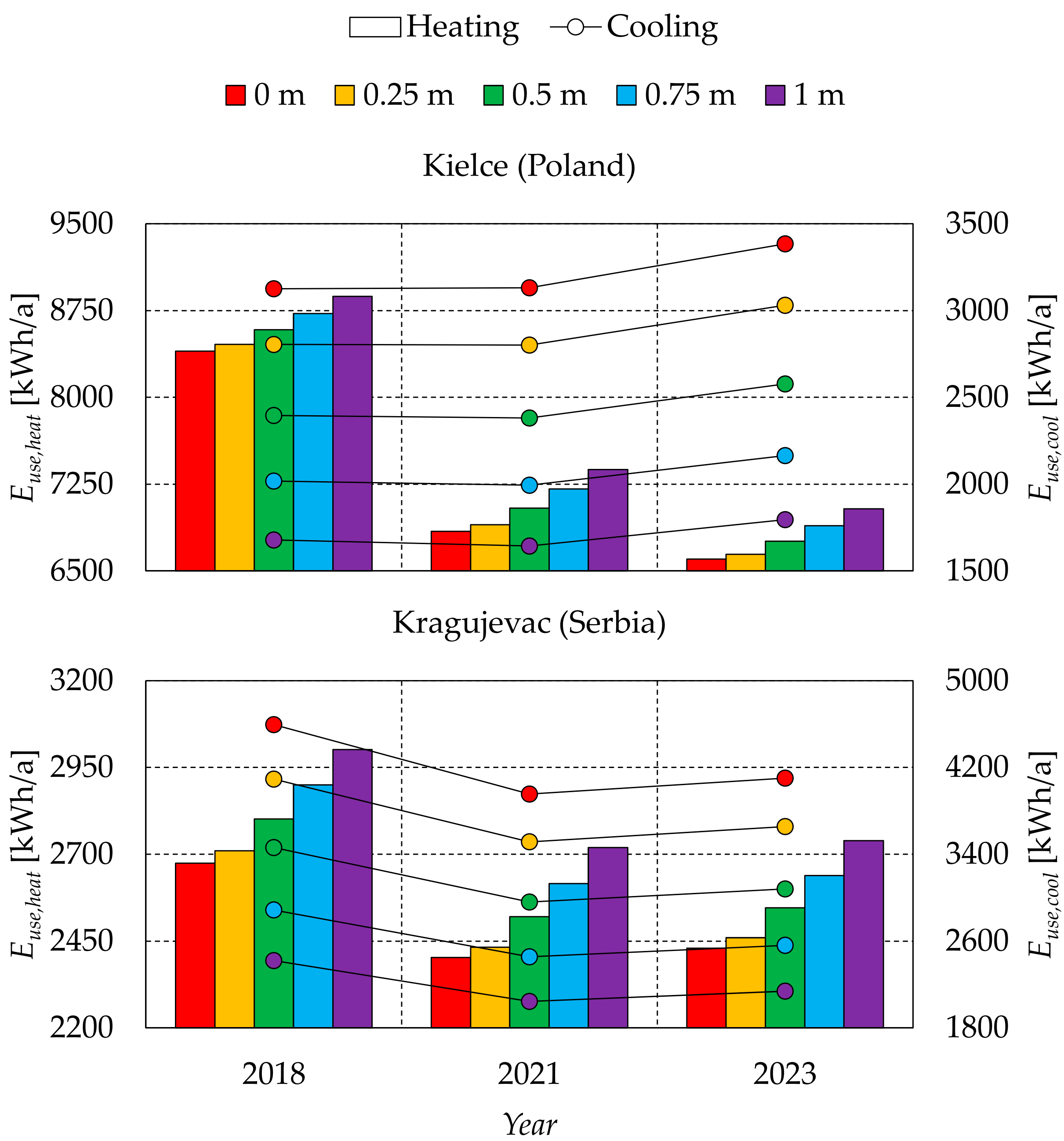

Figure 8. Annual useful energy consumption for heating and cooling in the analyzed small advanced single-family house models.

The maximum and minimum values of the annual final energy consumption for heating (11,179.4 kWh/a and 8319.9 kWh/a) and cooling (1296.86 kWh/a and 630.12 kWh/a) in the Kielce advanced house can be seen in Figure 9. The same figure shows the maximum and minimum values of the annual final energy consumption for heating (3782.25 kWh/a and 3027.04 kWh/a) and cooling (1760.76 kWh/a and 782.71 kWh/a) in the Kragujevac advanced house. The maximum and minimum values are achieved in the same circumstances, as it was in the case of annual useful energy consumption (Figure 8).

Figure 10 shows one more energy indicator, i.e., the annual primary energy consumption for heating $E_{pry,heat}$ [kWh/a] and cooling $E_{pry,cool}$ [kWh/a] in the Kielce and Kragujevac advanced houses with the TW and different depths of the FHOs (0 m, 0.25 m, 0.5 m, 0.75 m and 1 m), depending on simulation years (2018, 2021 and 2023).

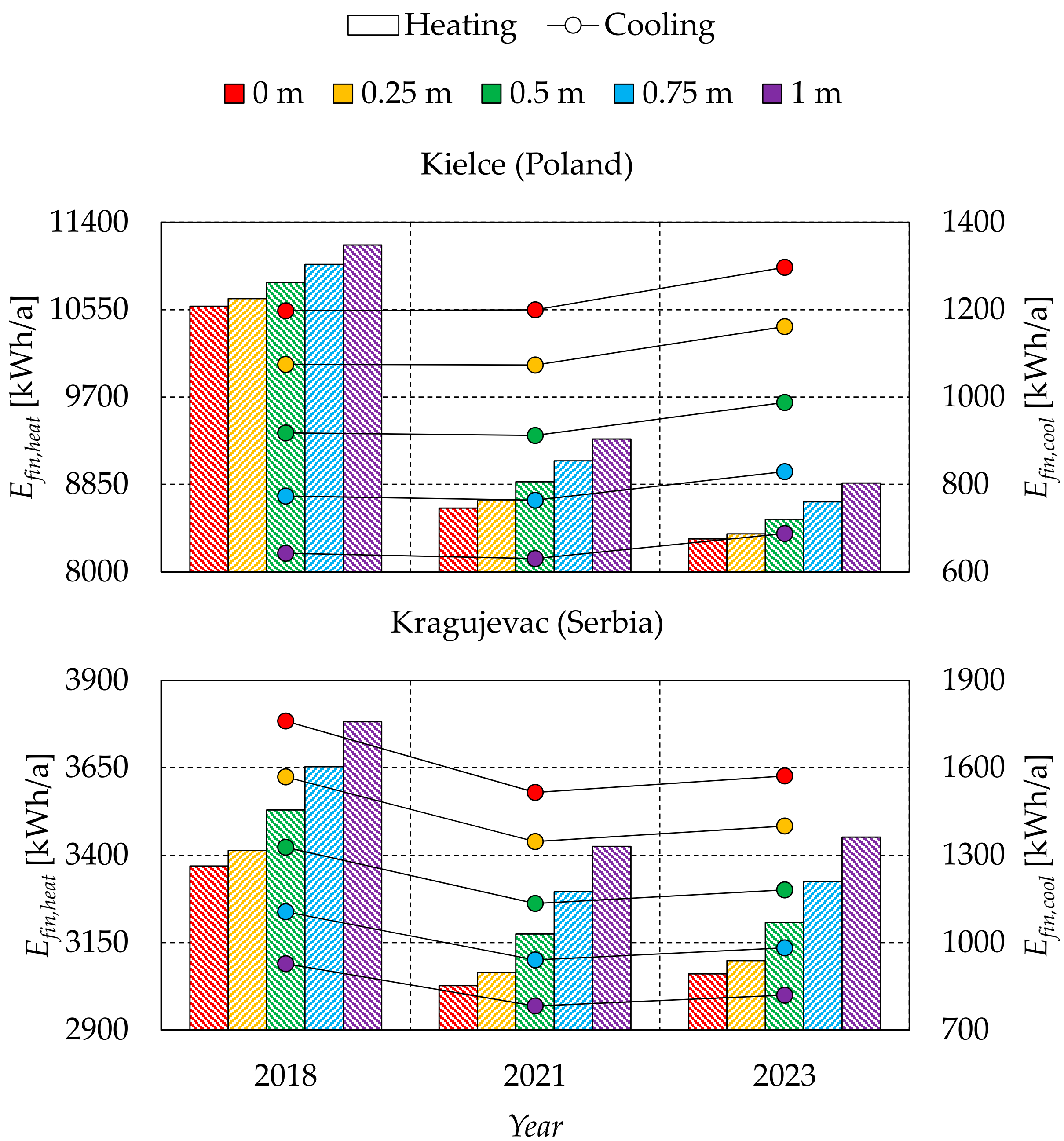

Figure 9. Annual final energy consumption for heating and cooling in the analyzed small advanced single-family house models.

The total (heating and cooling) annual primary energy consumption $E_{pry,heat}$+$E_{pry,cool}$ in the Kielce advanced house (for all cases) is between 11,347.33 kWh/a (in 2023) and 14,419.7 kWh/a (in 2018). In relation to the house with the TW and without FHO, the highest savings (21.31%) are achieved in 2023 in the house with the TW and 1 m deep FHO. Compared to the reference house model (Table 5), a positive score is achieved in all simulation combinations. The smallest positive effects (3.58%) are characteristic of the house without FHO in 2018. The biggest positive effects can be achieved in the already mentioned case, with a slightly better result (24.12%).

In the Kragujevac advanced house, the total annual primary energy consumption is smaller than the Kielce advanced house and ranges between 5724.93 kWh/a (in 2021) and 8107.53 kWh/a (in 2018). If the reference model (Table 5) is now compared with the advanced models, it can be noted that there are cases where the annual total primary energy consumption does not decrease in the advanced models, but increases, and these are in the following cases: the advanced house with the TW and without overhang during 2018 (−8.72%) and the advanced house with the TW and 0.25 m deep FHO during the same year (−2.94%). In relation to the reference model, the largest savings (23.23%) are possible when the reference model house is equipped with the following elements: (1) the TW and (2) 1 m deep FHO (Figure 10).

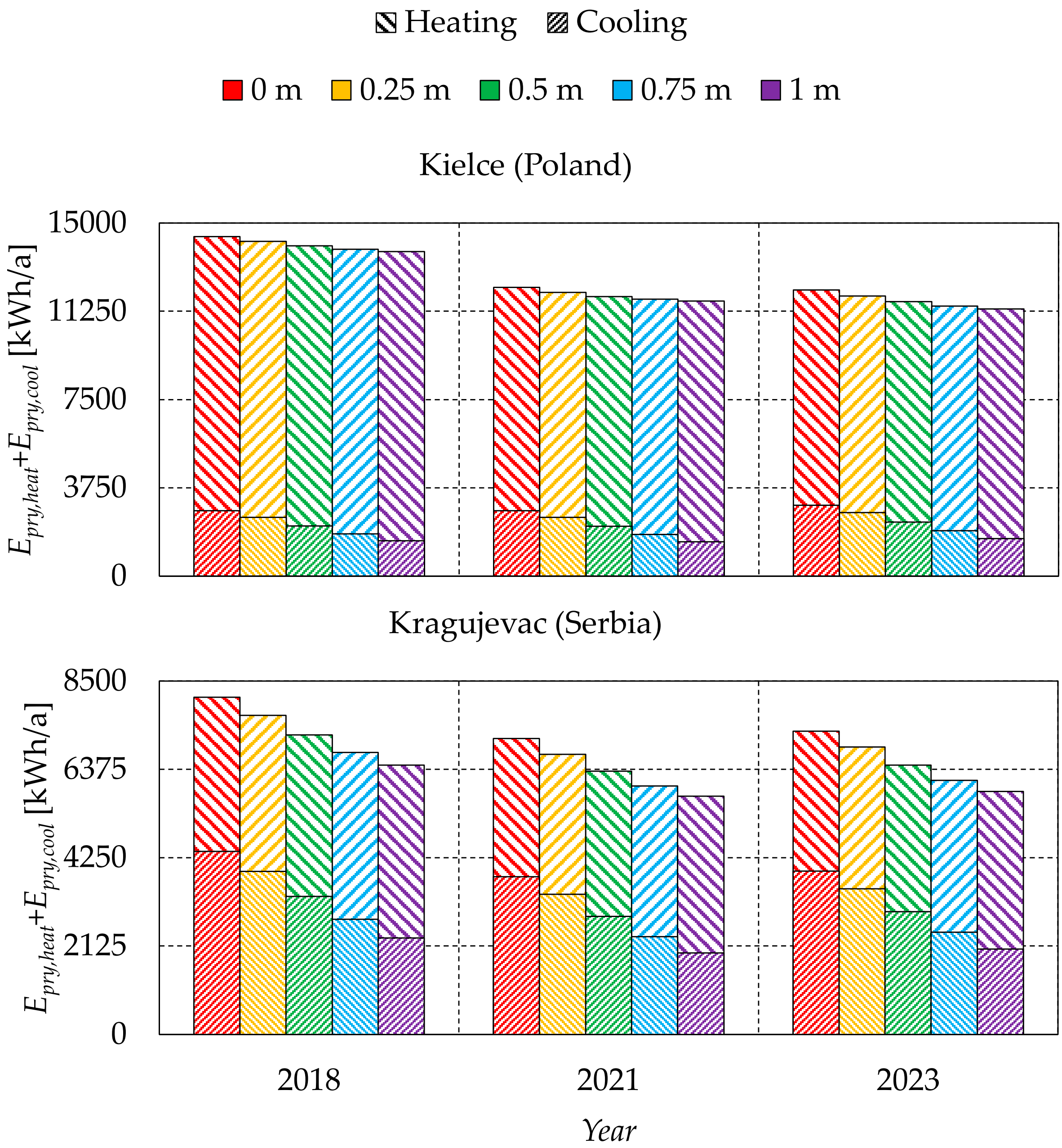

Figure 10. Annual primary energy consumption for heating and cooling in the analyzed small advanced single-family house models.

The next figure (Figure 11) shows the emission of greenhouse gases, which, from an ecological aspect, describes the performances of the analyzed houses equipped with active and passive heating and cooling systems.

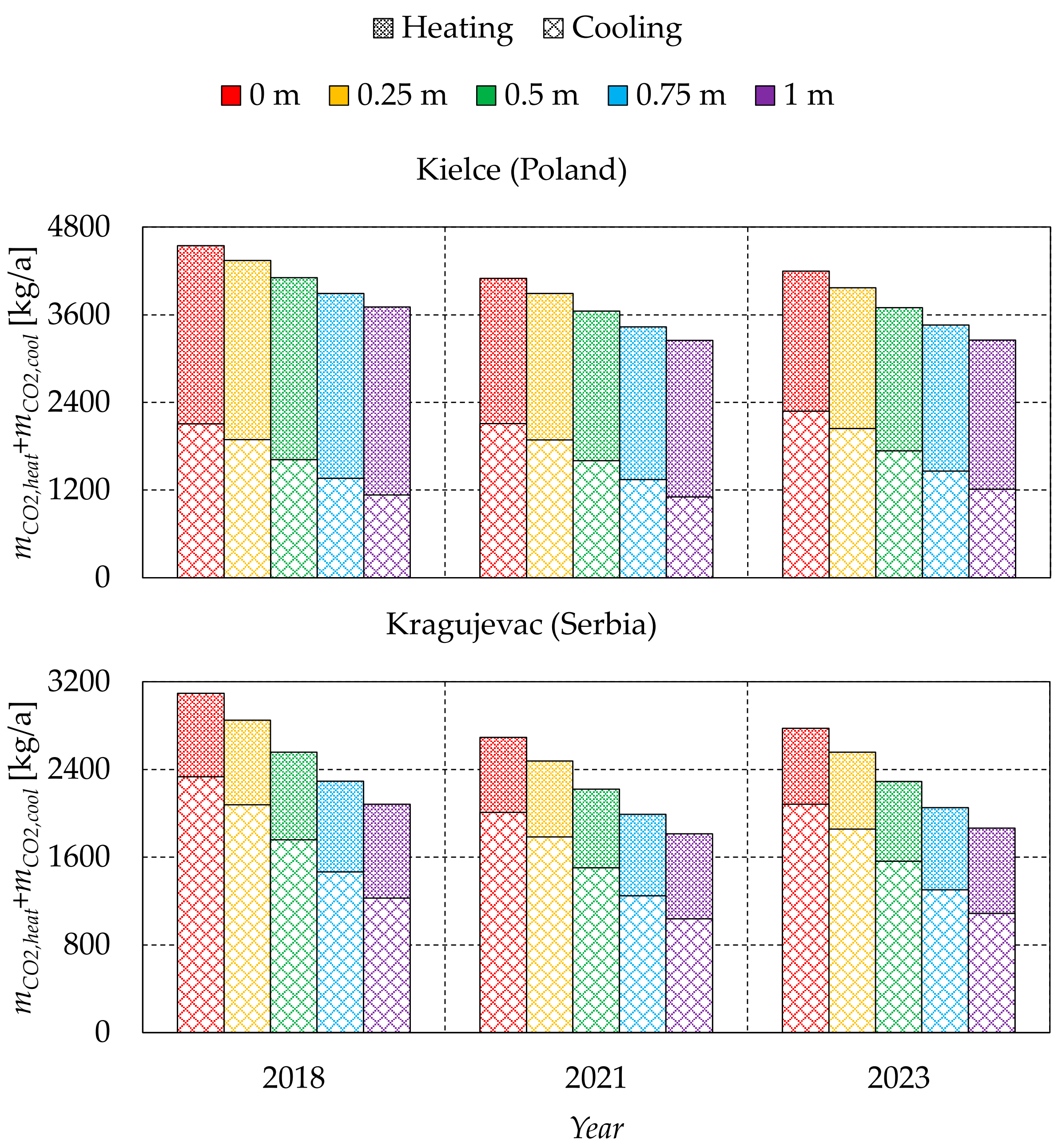

Figure 11. Annual greenhouse emissions for heating and cooling from the analyzed small advanced single-family house models.

Since h_{ng}, e_{ng} and e_{el} values are not the same for Poland and Serbia (Table 5), CO_2 emissions from the analyzed houses could not be the same either (Figure 11). The lowest annual CO_2 emissions in the Kielce (3249.49 kg/a) and Kragujevac (1811.93 kg/a) advanced single-family houses are in 2021 when the FHO depth is 1 m.

The structure of the CO_2 emissions is also not the same. The annual share of electricity (for cooling) in the total amount of CO_2 emissions for the different Kielce houses (depending on the simulation scenario, Figure 6) is as follows: from 30.5% (when the overhang depth is 1 m) to 46.34% (when there is no overhang) in 2018; from 34.1% (for 1 m) to 51.51% (without overhang) in 2021; and from 37.19% (1 m) to 54.32% (0 m) in 2023.

The share of electricity for the Kragujevac advanced house is much higher (Figure 11); from 58.94% (when the overhang depth is 1 m) to 75.38% (when there is no overhang) in 2018; from 57.24% (for 1 m) to 74.57% (without overhang) in 2021; and from 58.16% (1 m) to 75.05% (0 m) in 2023.

By comparing the reference (Table 5) with the advanced houses (Figure 11), it can be seen that passive solar systems do not contribute to the annual reduction of CO_2 emissions. More precisely, positive trends in the case of the Kielce house can be realized only if the depth of the overhangs are 1 m—in 2021 for 0.74% and in 2023 for 0.64%. Passive solar systems installed in the Kragujevac house, in all analyzed cases, negatively contribute to the reduction of CO_2 emissions. In other words, it is higher in every analyzed case; in some cases (without overhang) it is over 60%.

Following the simulation scenario (Figure 6), economic indicators are also analyzed in the following figure (Figure 12), which shows the necessary annual financial investments for working the heating P_{heat} [€/a] and cooling P_{cool} [€/a] systems.

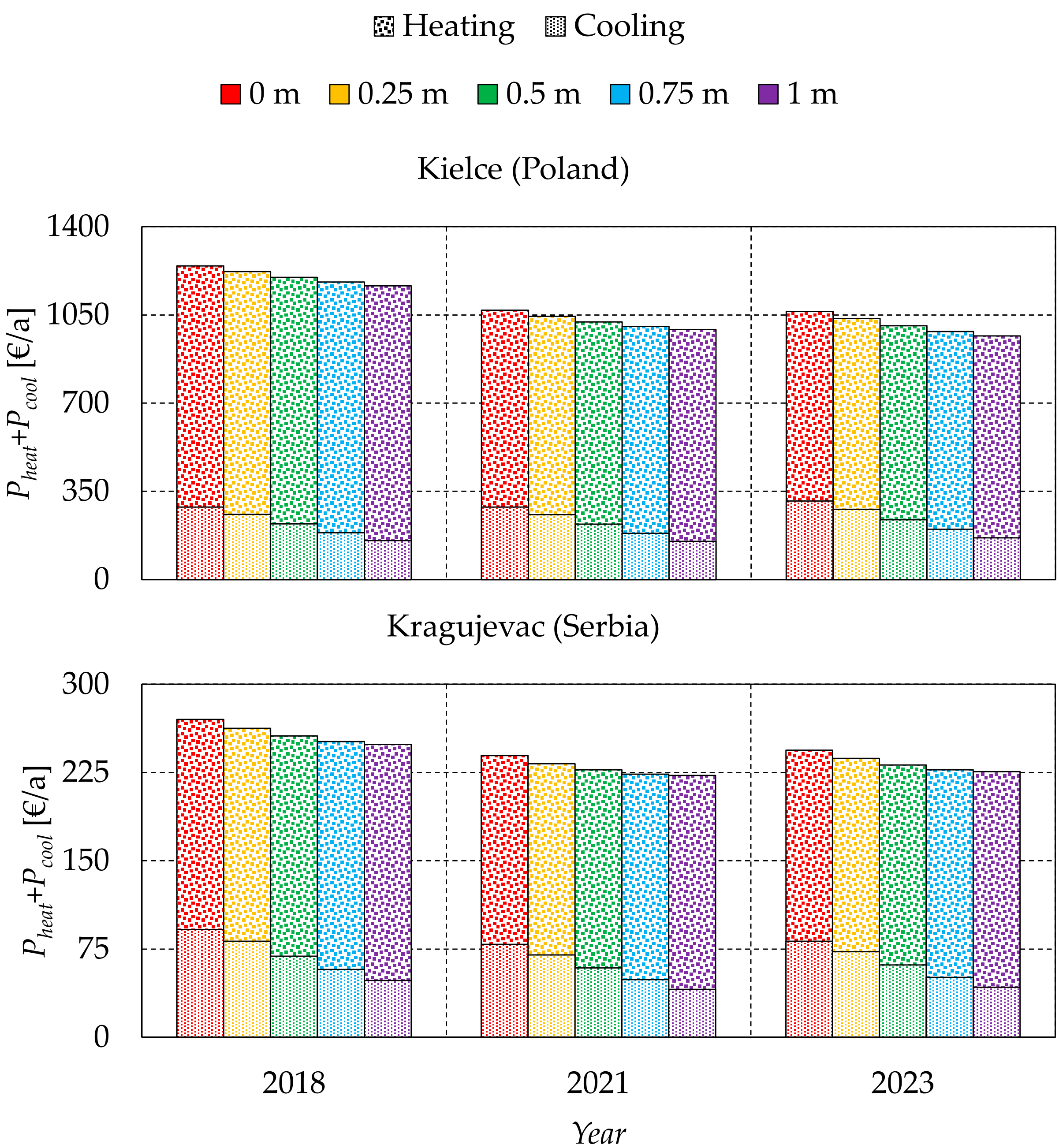

Figure 12. Annual monetary expenses for heating and cooling in the analyzed small advanced single-family house models.

From the current prices of electricity and natural gas (Table 5) compared to the Kielce reference house (1235.48 €/a), annual monetary savings of up to 21.72% (967.16 €/a) can be achieved (for the Kielce advanced model). In the case of the Serbian house, the largest annual savings are 35.96% (from 347.20 €/a for the reference model to 222.36 €/a for the advanced house; TW+1 m FHO). In the Kielce advanced house, the total annual monetary expenses are between 967.16 €/a (2023) and 1244.93 €/a (2018). On the other hand, in the Kragujevac advanced house, the total annual monetary expenses are between 222.36 €/a (2021) and 270.21 €/a (2018).

The linear functional dependence between the monthly final energy consumption (for heating and cooling) and the average monthly outdoor air temperatures is shown in Figure 13.

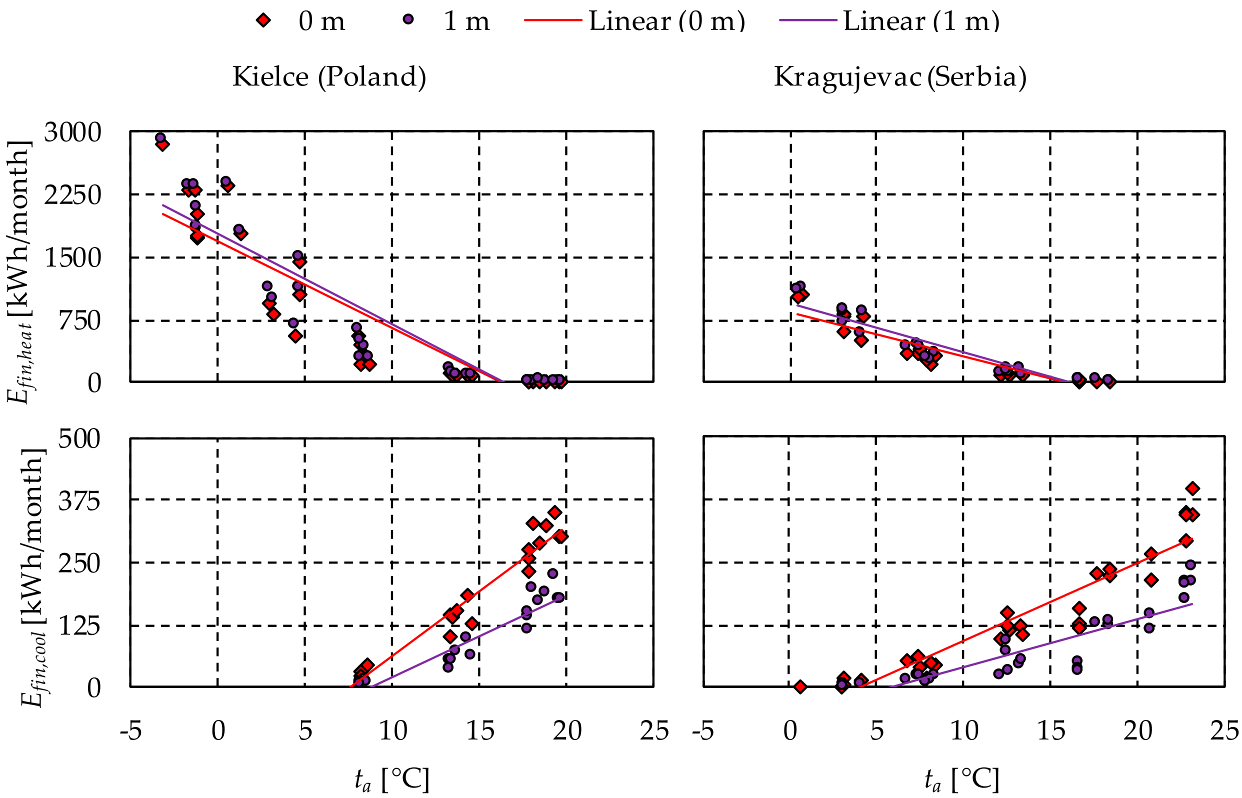

Figure 13. The linear functional dependence between the monthly final energy consumption (for heating and cooling) and the average monthly outdoor air temperatures for the analyzed small advanced single-family house models.

Linear functions were created for both locations (Kielce and Kragujevac) based on a three-year sample (2018, 2021 and 2023), and for two borderline cases: no overhang and 1 m of overhang depth. The equations describing the created lines are shown in Table 6.

From Figure 13, the following phenomena can be observed:

- The heating functional line (0 m) is below the heating functional line (1 m).
- The cooling functional line (0 m) is above the cooling functional line (1 m).
- The functional lines (0 m and 1 m) are approximately parallel to each other in the case of heating, regardless of the location, with a positive slope towards the ordinate axis.
- Functional lines (0 m and 1 m) in the cooling case are characterized by different inclination angles towards the ordinate axis, where the slope is negative.

Equations in Table 6 can be used to predict various scenarios (primarily neutral, i.e., realistic, then optimistic and pessimistic.) in line with climate change. Based on the obtained results, further EEE analysis can be carried out with satisfactory accuracy. They can also be used for other locations with similar meteorological data (continental and moderate continental regions) and houses with similar geometric characteristics and (active and passive) heating and cooling systems.

Table 6. Mathematical interpretation of the linear functional dependence between the monthly final energy consumption (for heating and cooling) and the average monthly outdoor air temperatures for the analyzed small advanced single-family house models.

Heating	Kielce	0 m	$E_{fin,heat} = -104.31t_a + 1690$	(9)
		1 m	$E_{fin,heat} = -108.41t_a + 1776.7$	(10)
	Kragujevac	0 m	$E_{fin,heat} = -53.41t_a + 848.77$	(11)
		1 m	$E_{fin,heat} = -57.73t_a + 933.66$	(12)
Cooling	Kielce	0 m	$E_{fin,cool} = 26.05t_a - 197.04$	(13)
		1 m	$E_{fin,cool} = 16.43t_a - 142.56$	(14)
	Kragujevac	0 m	$E_{fin,cool} = 15.42t_a - 60.398$	(15)
		1 m	$E_{fin,cool} = 9.69t_a - 56.25$	(16)

8. Conclusions

In this paper, the subjects of research were two small single-family houses. One was located in a continental climate zone (Kielce city in Poland), while the other was located in a moderate continental climate zone (Kragujevac city in Serbia). The reference design of the Kielce house was created following the Statistical data and Typology buildings and Rulebook of energy efficiency in Poland. The reference Kragujevac house was created following the Statistical data and Typology buildings and Rulebook of energy efficiency in Serbia. After that, both houses were improved with the passive systems: heating (the Trombe walls) and cooling (the overhangs with different depths: 0 m, 0.25 m, 0.5 m, 0.75 m and 1 m). The goal of the paper was to numerically investigate the energy, environmental and economic performance of the mentioned houses (with different combinations of active and passive heating and cooling systems) taking into account current climate changes, i.e., weather files for three different years (2018—reference year, 2021 and 2023).

The results showed that in all analyzed cases the annual useful and final energy consumption for heating in the Kragujevac house case was lower than in the Polish house case and the useful and final energy consumption for cooling was higher. Total annual primary energy consumption (for heating and cooling) was higher in the Polish house than in the Serbian house. The same applied to greenhouse gas emissions and their monetary costs. Based on the simulations conducted, it can also be concluded that a greater depth of the overhangs affects the increase in heating energy (on the one hand) and the decrease in cooling energy (on the other hand).

Comparing 2021 and 2023 with 2018, it is clear that climate change has a positive effect on the one hand because it is reducing energy consumption for heating during the heating season. On the other hand, climate change has a negative effect because of increasing energy consumption for cooling during the cooling season. In the overall energy–economic balance, current climate effects have a positive impact on the annual primary energy consumption and economic costs in both analyzed houses (with a slight downward trend). The environmental indicators are also characterized by a slight downward trend with climate change, but not enough to realize the benefits of using passive heating and cooling systems. If the number of warm days increases, a deterioration in energy and economic indicators can be expected, in addition to environmental ones.

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