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Evaluation of Residential Buildings Savings for Various Envelope Retrofits and Heating Energy Sources: A Simulation Study

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Abstract: The paper considers the issue of the thermal refurbishment of residential buildings built between 10 and 40 years ago in some European countries. It suggests that, while facade retrofitting is the most effective solution for older dwellings, all actions are equally less effective for newer dwellings built in this millennium. According to the current situation, as society shifts away from the use of fossil fuels, this paper presents the expected energy and financial savings that were calculated using one of four different heating sources. The study shows that the efficiency of the additional thermal retrofitting of the structures is low when the building is heated with a heat pump. The addition of thermal insulation to already well-insulated roofs or floors results in minimal savings of approximately 0.15 kWh per square meter of heated floor area per year. The potential advantage of replacing existing windows with new windows in a top thermal quality was shown. After window replacement, the financial benefits could be twice as high in houses heated by district heating compared to houses heated by gas or a heat pump, including an alternative heat pump with photovoltaics.

Keywords: residential building; thermal retrofitting; energy source; energy efficiency

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1. Introduction

Reducing the energy consumption of buildings is a long-term phenomenon. From 2000 to 2019, thanks to the better availability of thermal insulation, but also thanks to legislative changes, the EU's energy consumption for heating buildings has reduced by more than 28% [1]. In recent years, the attention of experts has been drawn more to the final goal, which is to reduce CO_2 emissions [2]. Given that, in the European Union, the residential sector has a marked stake in buildings (approximately 75% of the floor area of buildings represent family and apartment buildings [3]), it is really logical to focus more attention here, rather than on schools, hospitals, hotels and other building types. In the strategies to reduce CO_2 emissions by 2050, there is the expectation of reducing the energy consumption of existing buildings [4] in addition to new buildings. This may take place gradually or by so-called deep renovation, in which all building envelope structures are deeply retrofitted [5]. The proposal to establish an EU-wide repository of deep renovation packages for residential buildings has been made [6]. While there are numerous examples of successful deep renovation projects [7,8], the massive transformation of all existing buildings into buildings with nearly zero energy demand (nZEB) has not been observed. The reasons for this are well-known and have been extensively described, including economic, legislative, technological, and other factors [9]. Most of the articles retrieved discussed economic barriers [10]. The term 'economic barriers' refers primarily to extra costs compared to conventional buildings [11]. Some authors have specifically addressed barriers to delivering low- or zero-carbon buildings in high-density cities. They argue that there are still gaps in considering the entire supply chain and location impact [12]. Heffernan's questionnaires show that economic factors are the second most significant barriers following the skills and knowledge barriers [13]. Current studies have indicated that the global cost of initial investment and life cycle costs are more important factors for investors when deciding, rather than energy consumption during the operation of the building [14]. Therefore, in the long-term strategy of residential buildings' thermal retrofitting in Slovakia, it is assumed that most buildings will undergo only light (40–50%) or medium (45%) modernization in the coming years [15].

The thermal balance of buildings, referring to their losses and gains, has significantly changed in recent years. This is due to the fact that solar and internal thermal gains have a larger share in well-insulated buildings [16,17]. Additionally, the use of renewable sources also has an increasing impact on the hourly time step calculation method of heating and cooling energy needs [18,19]. According to EN ISO 52016-1 [20], it is therefore possible to evaluate the buildings under the dynamic method with an hourly time step. Energy performance experts agree that if several corrections or corrective factors are introduced, the original monthly calculation method loses transparency and robustness [21]. The more dynamic technologies and processes that are included in the calculation, the less transparent the monthly method becomes. Conversely, in these conditions, the hourly method is more transparent [22]. A dynamic hourly step simulation is often considered a suitable approach for calculation, provided that sufficient information for all input data is available (including operating conditions and their variations). More precisely, climate data are also generally advantageous [23,24]. For instance, the thermal capacity of building structures is not constant over time and may vary depending on the climatic conditions (e.g., cold vs. transitional periods) and building user behavior. Evidence of this is the simulation study conducted in the Danish climate, where the modulation of temperature within a comfortable range and the use of heat storage has saved 25 kWh/m^2 [25]. According to the results of three-dimensional analysis, i.e., focusing on energy, economy, and environmental aspects in Polish climatic conditions, the most advantageous variant is the use of the glycol–water heat pump supported by photovoltaic institutions [26].

A list of the nomenclature used throughout this paper is provided in Table 1 as follows.

Table 1. List of nomenclature used in this paper.

Abbreviation	Referred to
nZEB	Nearly Zero Energy Demand Building
TMY	Test Meteorological Year
RB1	Residential Building Built in 1976
RB2	Residential Building Built in 1983
RB3	Residential Building Built in 2015
U-value	Heat Transfer Coefficient Value
SHGC	Solar Heat Gain Coefficient
RU	Heat Recovery Unit
COP	Coefficient of Heat Pump Performance
CHP	Combined Heat and Power System
PV	Photovoltaic Power System

The challenges mentioned above, such as applying an hourly time step, considering the variable thermal capacity of building structures, and accounting for increased heat gains, require more accurate calculations of thermal retrofitting effectiveness. Furthermore, it is essential to evaluate effectiveness objectively, considering the heat source as a factor in financial decision making. With this background, this paper utilized a unique combination of well-established steady-state input values and a progressive energy simulation tool to develop its calculations. The formulation of the most reliable conclusions on energy efficiency in retrofitting residential buildings can be achieved through this approach.

2. Materials and Methods

The main steps for the research can be seen in the flowchart in Figure 1. Firstly, we conducted an analysis of the boundary conditions such as climate conditions and internal heat gains. Representative samples of buildings with suitable structural properties were selected. The level of thermal retrofitting was then defined. Heating demand calculations were carried out, followed by calculations of the energy demand by source. An analysis was conducted on the energy and financial savings resulting from the retrofitting process.

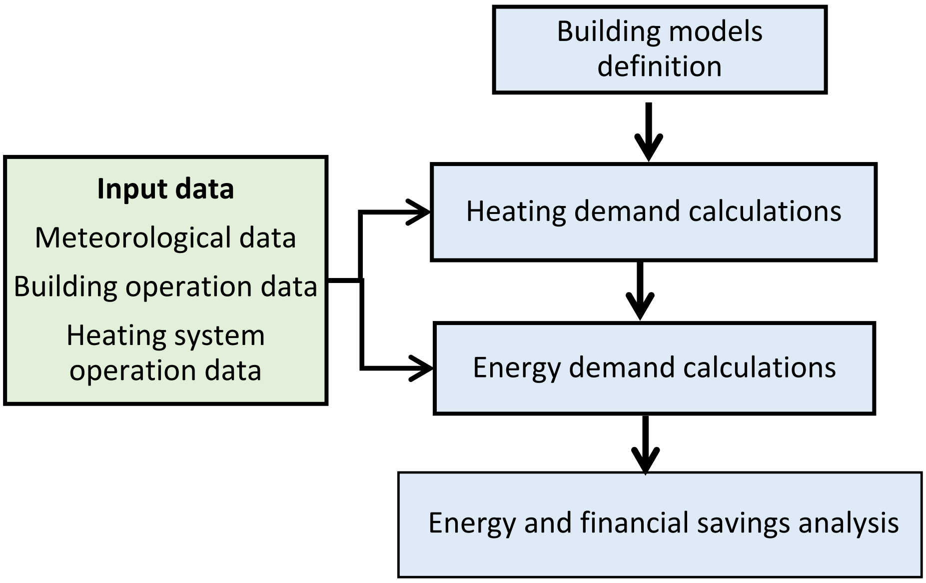
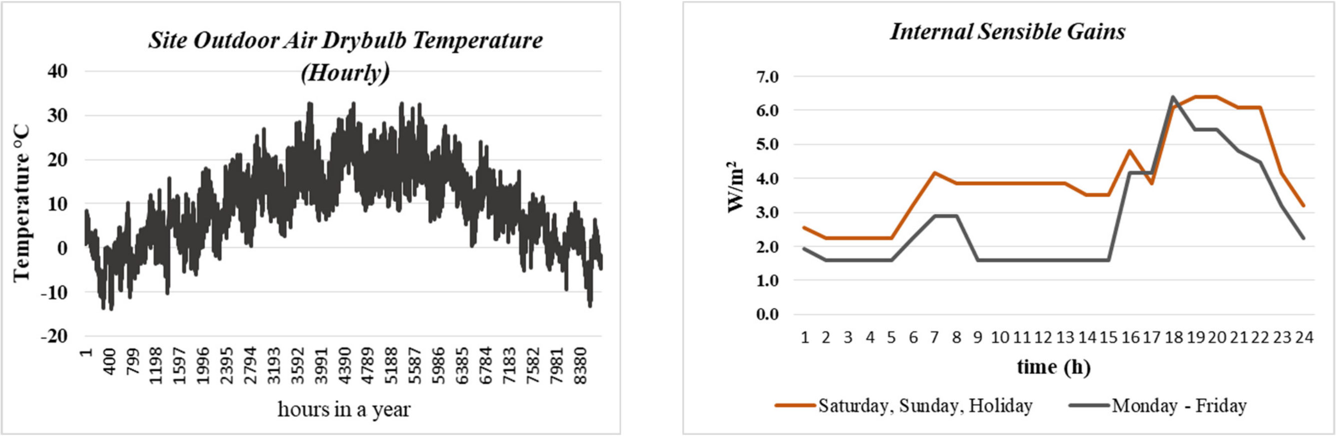


Figure 1. Overall methodology of the calculation procedure.

2.1. Boundary Conditions

To meet the research goals, the first step was to determine the appropriate climate conditions for hourly calculation. This involved selecting a suitable test reference year that coincided with the already used climatic parameters according to the local standard for monthly calculations. Figure 2a illustrates the annual course of the hourly air dry-bulb temperature values used in the calculation. Secondly, the task involves creating hourly divided typical building usage profiles, linked to established profiles from the monthly time step. In the process of creating profiles for use, written records and questionnaires are advantageous. They can also be used to create detailed schedules and help with the creation of standardized user input data for several types of buildings. When this gap in inputs is reduced, dynamic simulations become more accurate [27]. The internal heat gain profiles of residential buildings reflect their operation. The schedule is typically divided into two types: for a weekday working day (from Monday to Friday) and a day off (Saturday, Sunday, and holiday), as shown in Figure 2b. The values are related to the floor space and are based on the requirements of the Slovak technical standard. Specifically, the sensible internal gains during the heating period were 4 $W/(m^2 \cdot h)$ on average. The daily profile of sensible internal heat gains for residential buildings was based on a maximum occupancy of 30 m^2 per person and a maximum power output of 2.33 W per m^2 from appliances. The profiles shown in Figure 2b also consider current research findings on occupancy tracking in residential dwellings [28], as well as observed hourly electricity consumption in European households [29].



(**a**) (**b**)

Figure 2. Inputs for heating demand calculation: (**a**) internal sensible heating gains for workdays and weekends; (**b**) outdoor air dry-bulb temperature from Bratislava Test Meteorological Year (TMY).

2.2. Building Models

For the purpose of processing in this study, three computing models of residential buildings were prepared. They differ in the construction date and, therefore, the potential for energy savings after retrofitting. This scope reflects the need for a larger-scale study, encompassing different building geometries and varying levels of current thermal protection. The first two apartments were built in the 1970s and 1980s, while the third is more recent (Figure 3). Residential buildings constructed during the 1970s and 1980s comprise 50% of all apartment buildings in Slovakia.

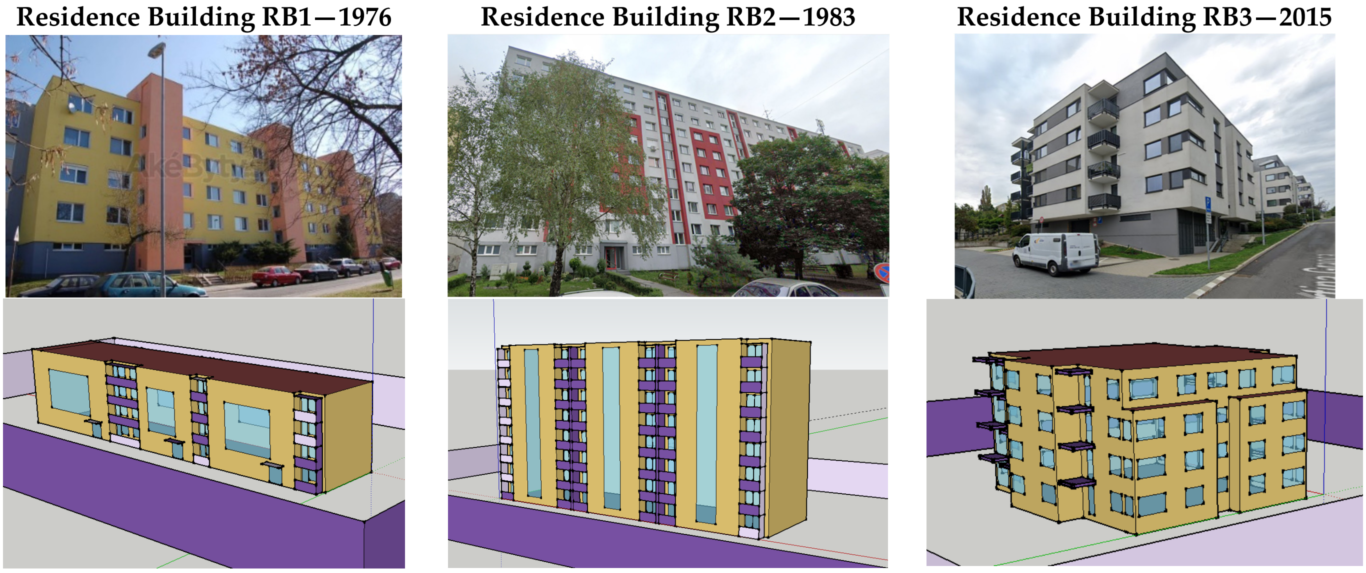


Figure 3. Views on reviewed existing buildings and their simulation models below.

The first representative is the 4-storey apartment building, constructed in 1976 using reinforced concrete panels (Figure 3). Its geometric characteristics are presented in Table 2. The original lightweight concrete cladding was made with ceramsite, and the flat roof is a reinforced concrete slab with a thermal insulation made from cinder and aerated concrete panels. The ceiling above the lowest technical floor (without heating) lacked thermal insulation. The window structures consist of wooden frames with double clear pane fenestration.

Table 2. Summary table of buildings' characteristics.

Residence Building RB1		
Parameter	*Value*	*Units*
Conditioned space floor area	2330.7	m^2
Energy demand before modernization	133.2	$kWh/(m^2 \cdot a)$
External walls U-value	1.49	$W/(m^2 \cdot K)$
Roof U-value	1.0	$W/(m^2 \cdot K)$
Floor U-value	1.75	$W/(m^2 \cdot K)$
Window U-value without shading system	2.7	$W/(m^2 \cdot K)$
Window with shading system SHGC	45	%
Window/floor area	16.3	%
Infiltration	0.68	1/h
Residence Building RB2		
Parameter	*Value*	*Units*
Conditioned space floor area	4228.4	m^2
Energy demand before modernization	90.1	$kWh/(m^2 \cdot a)$
External walls U-value	1.0	$W/(m^2 \cdot K)$
Roof U-value	0.6	$W/(m^2 \cdot K)$
Floor U-value	1.88	$W/(m^2 \cdot K)$
Window U-value without shading system	2.7	$W/(m^2 \cdot K)$
Window with shading system SHGC	45	%
Window/floor area	15.4	%
Infiltration	0.79	1/h
Residence Building RB3		
Parameter	*Value*	*Units*
Conditioned space floor area	1750.0	m^2
Energy demand before modernization	42.9	$kWh/(m^2 \cdot a)$
External walls U-value	0.32	$W/(m^2 \cdot K)$
Roof U-value	0.2	$W/(m^2 \cdot K)$
Floor U-value	0.61	$W/(m^2 \cdot K)$
Window U-value without shading system	1.4	$W/(m^2 \cdot K)$
Window with shading system SHGC	40	%
Window/floor area	21.1	%
Infiltration	0.5	1/h

The second building is a slightly newer 9-storey apartment building (Figure 3), constructed in 1983 using concrete panels. Table 1 shows its geometric characteristics. In its original condition, external walls were made of aerated concrete (thickness is 300 mm); the flat roof was constructed using reinforced concrete with thin thermal insulation made of foam polystyrene. The ceiling above the lowest technical floor (without heating) lacked thermal insulation. The windows were identical to those in the first building.

The third building is a modern 5-storey apartment complex with contemporary architecture. It features a larger area of windows and a more complex shape (Figure 3). Among the reviewed buildings, the original building structures have the best thermal resistance. The geometric characteristics of the buildings are presented in Table 1. In its original condition, the perimeter walls were made of 300 mm thick Porotherm company brick; the flat roof was made of reinforced concrete with 170 mm thick foam polystyrene thermal insulation. The ceiling above the non-heated technical floor was made of concrete with 50 mm thick foam polystyrene thermal insulation. The windows and doors were made of plastic profiles with low-emission double glazing of good quality. Table 2 presents a summary of the parameters of the building.

The above mentioned test models were processed using the EnergyPlus version 9.6 [30], which belongs to the group of numerical methods using response factors. The software matches supply and demand based on successive iteration substitution following Gauss–Seidel updating.

The computing models consist of one zone for the entire building. This decision was made to prioritize checking the specification of boundary conditions for an hourly time step and verifying the usability of defined inputs, such as schedules and climate data, rather than creating a highly detailed model. Similarly, some window openings were merged into one larger object because of the model simplification. The modeled heat loss in the basement was considered as a loss to the ambient environment with a temperature that is the midpoint between the interior temperature (20 °C) and the exterior air temperature.

2.3. Variations of Structure Thermal Retrofit

The energy performance, measured as the heating energy demand in kWh/(m^2·a), of 3 reference buildings was simulated using 4 sets of 3 variants of partial structure insulation on the entire building envelope (Table 3). In addition to the original condition (marked as VA), thermal insulation was considered on the exterior walls (variant VB1, VB2, and VB3), roof structures (variant VC1, VC2, and VC3), floor structures above the technical floor (variant VD1 VD2, and VD3), and replacement of windows (variant VE1, VE2, and VE3). The thermal quality of insulated structures was considered according to specific levels of thermal protection in accordance with the current STN 73 0540-2/Z1 + Z2: 2019 [31] as follows: low-energy level, ultra-low-energy level, and nZEB level. Forced ventilation with a heat recovery unit (RU) was deemed necessary in all variants except the original condition.

Table 3. Different treatment methods of residential buildings in 12 variants: additional thermal insulation on exterior walls VB1–VB3, on roof VC1–VC3, on floor VD1–VD3, and windows replacement VE1–VE3.

Residence Building RB1	**VB1**	**VB2**	**VB3**	**VC1**	**VC2**	**VC3**	**VD1**	**VD2**	**VD3**	**VE1**	**VE2**	**VE3**
External walls insulation	160 mm	200 mm	250 mm	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.
Roof insulation	initial s.	initial s.	initial s.	200 mm	250 mm	320 mm	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.
Floor insulation	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	60 mm	100 mm	140 mm	initial s.	initial s.	initial s.
Windows replacement	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	Triple U = 1.0	Triple U = 0.85	Triple U = 0.65
Ventilation	Mechanical ventilation with heat recovery unit—flow rate 1680 m^3/h, efficiency 78.4%											
Residence Building RB2	**VB1**	**VB2**	**VB3**	**VC1**	**VC2**	**VC3**	**VD1**	**VD2**	**VD3**	**VE1**	**VE2**	**VE3**
External walls insulation	150 mm	200 mm	250 mm	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.
Roof insulation	initial s.	initial s.	initial s.	180 mm	230 mm	300 mm	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.
Floor insulation	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	60 mm	100 mm	140 mm	initial s.	initial s.	initial s.
Windows replacement	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	Triple U = 1.0	Triple U = 0.85	Triple U = 0.65
Ventilation	Mechanical ventilation with heat recovery unit—flow rate 2690 m^3/h, efficiency 78.4%											
Residence Building RB3	**VB1**	**VB2**	**VB3**	**VC1**	**VC2**	**VC3**	**VD1**	**VD2**	**VD3**	**VE1**	**VE2**	**VE3**
External walls insulation	60 mm	100 mm	150 mm	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.
Roof insulation	initial s.	initial s.	initial s.	60 mm	120 mm	180 mm	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.
Floor insulation	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	20 mm	60 mm	100 mm	initial s.	initial s.	initial s.
Windows replacement	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	initial s.	Triple U = 1.0	Triple U = 0.85	Triple U = 0.65
Ventilation	Mechanical ventilation with heat recovery unit—flow rate 1275 m^3/h, efficiency 78.4%											

2.4. Variations of Heating Source

The calculation of the energy required for heating was performed in compliance with the regulations set out in law no. 555/2005 [32], as implemented by the announcement of the Slovak Ministry of Internal Affairs and Communications no. 324/2016 Coll. [33], EN 15316 [34] and in accordance with STN EN ISO 13790/NA [35]. The calculation was carried out for the appropriate retrofitting on building thermal protection for four heat sources: heat pump + photovoltaic power plant, heat pump, gas-condensing boiler, and district heating by combined production of electricity and heat. The need for energy for heating is given by the sum of the net heat need for heating and the total losses of the heating system, from which heat gains and energy from renewable energy sources were deducted. When calculating the need for energy for heating, the individual energy carriers that were used to provide heating were respected. The input parameters used for the calculation were as follows:

- Temperature gradient of heating water in the heating system: 60/40 °C;
- Heat pump heating factor COP: 3;
- Efficiency of the gas-condensing boiler 100%;
- CHP pipeline losses: 7.5%;
- Efficiency of the CHP gas heat source: 90%;
- Photovoltaic power plant—output: 10 kWp;
- Number of photovoltaic panels: 22;
- Slope of photovoltaic panels: 15°.

2.5. Mean U-Value

The U-value is a common measure that incorporates the thermal conductance of a structure, as well as heat transfer due to convection and radiation. It indicates the amount of heat flow in watts per square meter of construction with 1 Kelvin temperature difference. The average value of the heat transfer coefficient of the building is determined by a weighted average based on the share of heat transfer coefficients. This simplified indicator considers not only the U-value of individual building structures according to their surface area, but also the effect of thermal bridges and the effect of unheated spaces. Standard STN 73 0540-2/Z1 + Z2: 2019 [31] gives the formula for expressing this.

$$U_{mean} = (\sum b_{x,i}\, U_i\, A_i + \Delta U \sum A_i)/\sum A_i \tag{1}$$

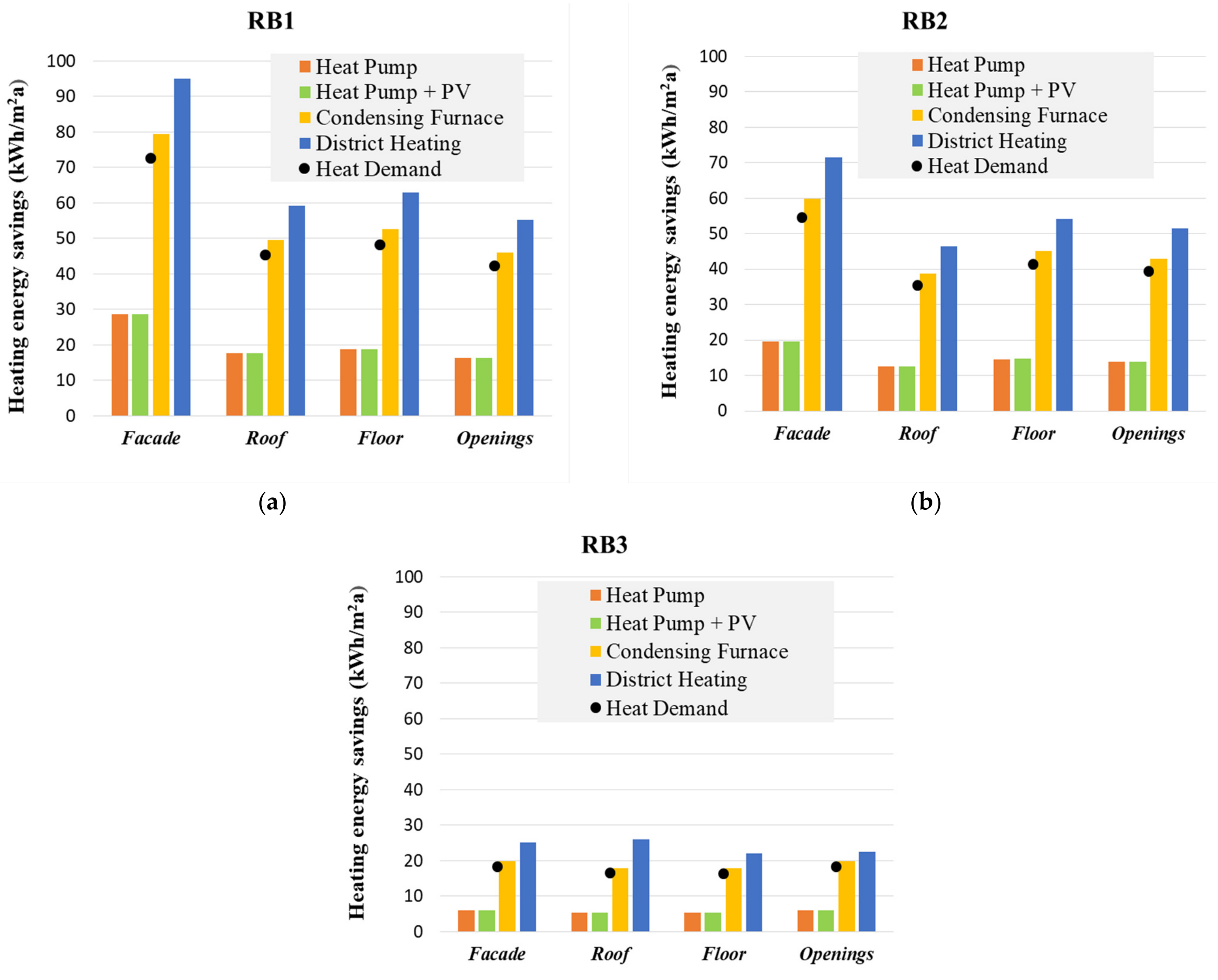
where U_{mean} is the mean thermal transmittance in W/m^2 K, b_x is reduction factor (-), U is the thermal transmittance of envelope structure in W/m^2·K, A is the area of envelope structure in m^2, and ΔU is added thermal transmittance due to thermal bridges in W/m^2·K [36]. In this study, we calculated ΔU using a lumped value of 0.1 W/m^2·K for the original condition (VA) and a value of 0.02 W/m^2·K for all other versions of the thermal retrofitting.

3. Results and Discussion

The impact of building insulation on energy savings after thermal retrofitting was evaluated in two steps. Firstly, the thermal retrofitting from the original building construction to a low-energy standard was assessed. Secondly, the potential savings after further insulation of the already insulated building structures were evaluated.

3.1. Thermal Retrofitting for Achieving Low-Energy Values

The results, which show the potential for energy savings in all three types of residential buildings, are presented in graph form in Figure 4. The savings were quantified by implementing thermal insulation on one type of construction from the building envelope to the low-energy standard value of thermal resistance in combination with the reduction in ventilation losses achieved by installing forced ventilation with a heat recovery unit. The retrofitting type indicated in Table 3 by the number 1 (VB1, VC1, VD1, VE1) corresponds to the adaptation to the low-energy standard. The calculation of energy savings was based on the difference between the simulated heating demand in the original state (VA) and the heating demand for the other variants. Upon examining the RB1 apartment building, it is evident that the most significant energy savings for heating can be achieved through the insulation of the facade, rather than any other structural modifications (in the case of central heat supply up to 95 kWh/m^2 per year). The thermal retrofitting of the facade is the most advantageous action, because the original facade from the 1970s has very low thermal resistance. Also, this building has such a shape that the facade surfaces are dominant. This can be said about the RB2 apartment building, although the facade insulation loses some of its dominance. Residential buildings from the 1980s already have a higher facade thermal resistance, so potential savings from their thermal retrofit appear to be less. Regarding the RB3 apartment building, which represents the recently built stock, the dominance of the facade retrofitting completely disappears. The RB3 apartment building has a completely different architecture already, which is characteristic for low-rise buildings in an organized line structure. Its compact shape, almost like a cube, features large fenestrations that significantly reduce the wall area. In such conditions, all retrofit actions are almost equally effective in terms of heating energy savings.



(**a**) (**b**)

(**c**)

Figure 4. Heating energy demand savings after partial thermal retrofit of (**a**) residential building RB1 built in the 1970s, (**b**) residential building RB2 built in the 1980s, (**c**) residential building RB3 built in 2015 according to heating sources—partial retrofit means the insulation of some part of the envelope (facade, roof, floor or openings) and installation of forced ventilation with a heat recovery unit.

The second important retrofit action is to insulate the floor between the first inhabited floor and the basement (in the case of the central heat supply, this was more than 60 kWh/(m^2·a)). This is because the concrete slab between the unheated basement and heated floor provides little thermal resistance in older buildings. The thermal resistance requirement for these constructions was introduced into Slovak standards in 2002.

When considering energy savings from the perspective of the heat source, there was always an anticipated difference in energy demand for heating between a central district heating supply, a gas boiler, and a heat pump. The production of heat from the central supply was the most energy-intensive option, followed by the gas boiler or heat pump. The air–water heat pump was the least demanding heat source. Therefore, it can be concluded that energy savings are also proportionally several times smaller for a heat pump than for a gas boiler or district heating. The calculations also demonstrate that retrofitting the facade and changing the heating source simultaneously is the most effective strategy for improving energy efficiency in "middle-aged" apartment buildings. In contrast, for newer apartment buildings heated by a heat pump, structural interventions only result in minor energy savings.

3.2. Savings after Secondary Thermal Retrofitting

Further energy savings can be achieved by further increasing the insulation thickness of structures beyond the low-energy standard values. Figure 5 documents the calculated savings for the additional insulation of facades, floors, roofs, and window replacements as average values from three apartment buildings. The data indicate that the potential for energy savings decreases as further thermal retrofitting is carried out. In the case of heating with a heat pump, the values were typically very small, reaching up to 0.8 kWh/(m^2·a). This could be a compelling factor in deciding on further thermal upgrades. However, it is unlikely to significantly affect the energy class in the building's energy performance certification.

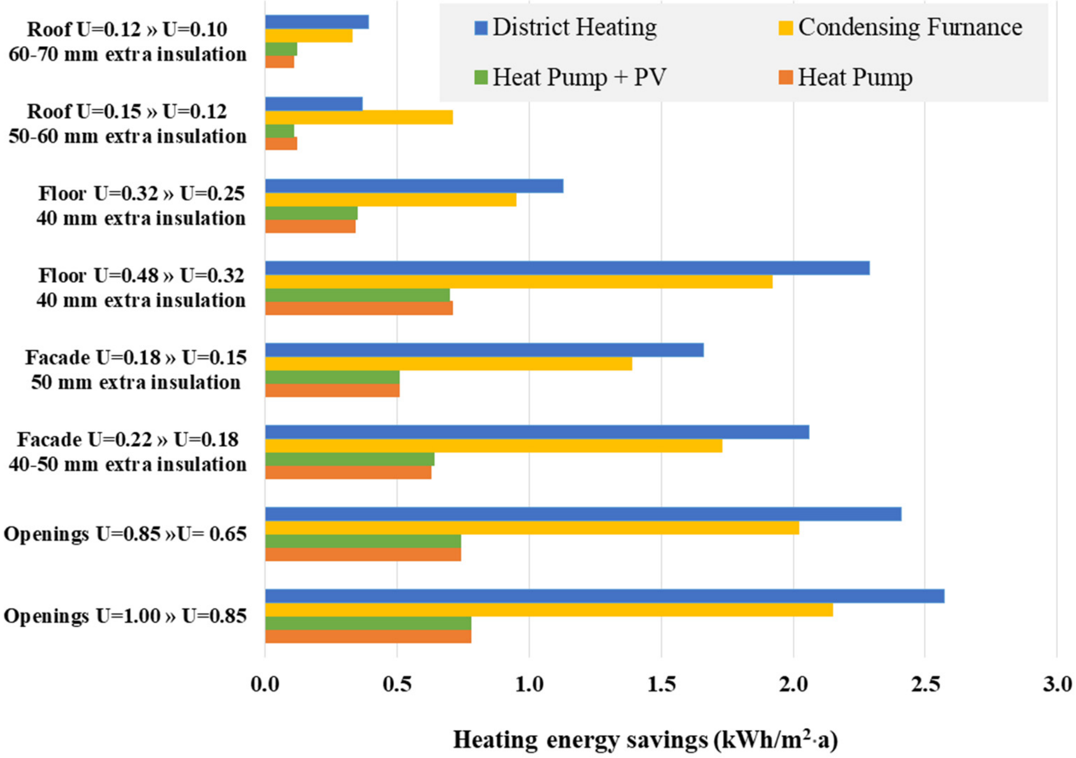


Figure 5. Calculated mean heating energy demand savings after additional partial thermal modernization of residential buildings according the heating sources. The additional modernization means the additional insulation of structures that already reached the minimal criteria of heating resistance.

The apartments could achieve significant energy savings by improving the windows, particularly by reducing the heat transfer coefficient from 1.0 W/m^2·K to 0.85 W/m^2·K and then to 0.65 W/m^2·K, which requires the best windows available on the market. Additional savings can be achieved by improving the thermal insulation properties of the facades and the floor. In terms of the use of the floor as a boundary structure between heated and unheated environments, the tipping point is at a heat transfer coefficient of U = 0.32 W/m^2·K. Further insulation beyond this point does not contribute significantly to heating energy savings. It should also be noted that the additional insulation of an already thermally upgraded roof is the least necessary measure. In the case of heating with a heat pump, this can result in savings of only around 0.15 kWh per m^2 of heated floor area per year. This number is significantly smaller than the average annual energy consumption of an apartment building.

Figure 6 presents an analysis of the impact of the thermal reconstruction of the facade and windows on the mean U-value of the residential building's entire envelope. The calculation method for the mean U-value was explained in Section 2.5. U_{mean} change was calculated as the difference between the mean U-value in the original state (VA) and the mean U-value for the other retrofitting variants.

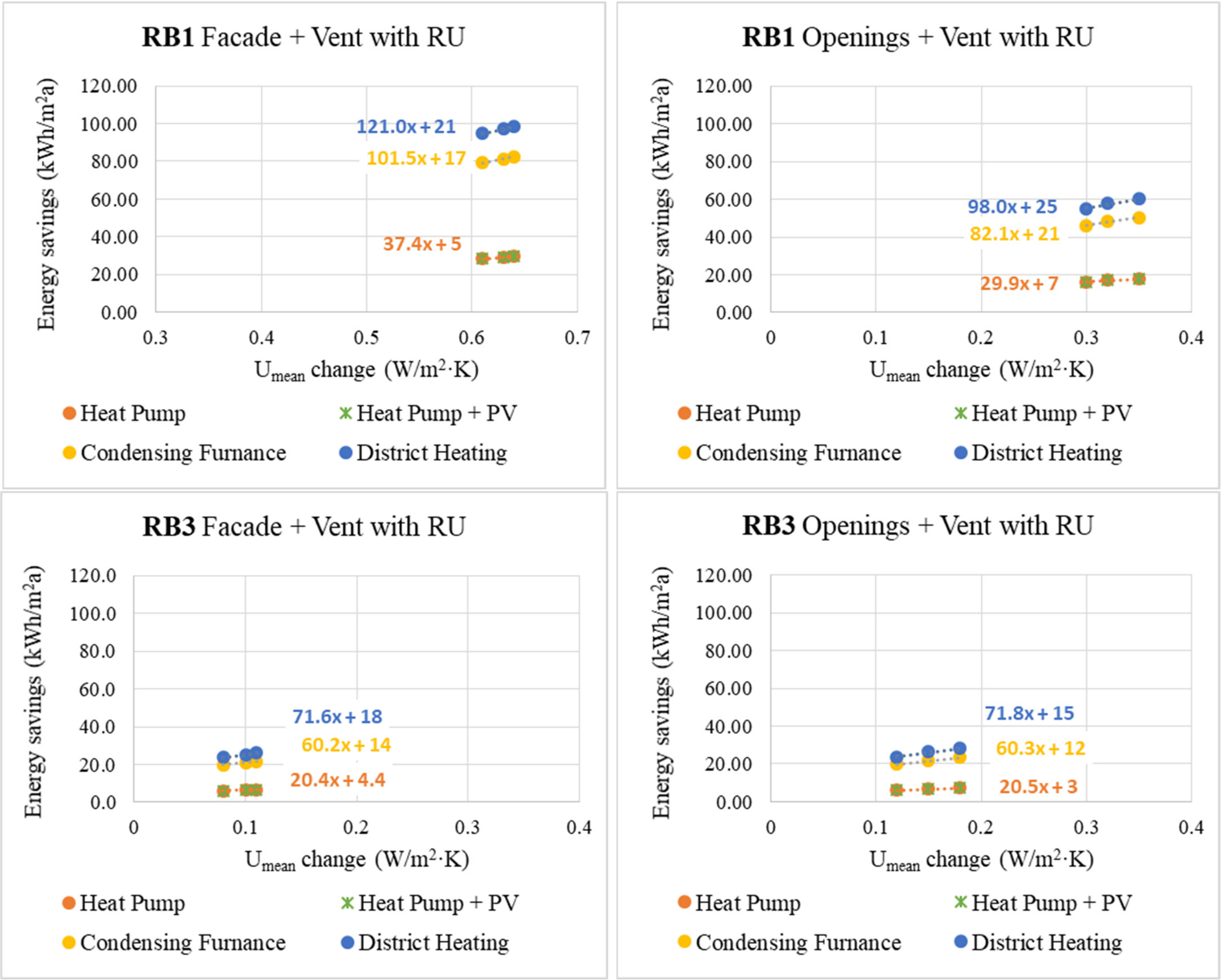


Figure 6. Calculated heating energy demand savings after additional partial thermal retrofitting of residential building RB1 built in the 1970s and RB3 built in 2015 according to heating sources. The additional modernization means just an additional insulation of structures that already reached minimal thermal resistance.

The thermal retrofit of the facade up to the low-energy level standard has the greatest impact on the mean U-value in older apartment buildings. Conversely, in newer apartment buildings, the mean U-value is most significantly affected by window replacement. The higher thermal resistance of the facade and the larger fenestration area result in this consequence. By linking three key parameters—adjusting the thermal resistance of the construction, changing the mean U-value of the building, and heating energy savings—it becomes clear that facade insulation was the most effective action. This applies not only to older apartment buildings, but also to new ones. Reducing the mean U-value through the use of the best facade insulation will give the same savings as reducing the mean U-value through window replacement. Based on Figure 6, it can be concluded that reducing the mean U-value results in small energy savings of 20.6–37.4 kWh/(m^2·a) per unit change in mean U-value when using a heat pump as the energy source. However, heating with a gas-condensing boiler has the potential to reduce energy demand by 60.3–101.5 kWh/(m^2·a) per one unit change in mean U-value. District heating shows the most significant savings, with up to 121.0 kWh/m^2·a per one unit change in mean U-value.

3.3. Heating Cost Savings

Figure 7 shows the specific financial savings calculated on the basis of the mean U-value. The calculations assume a cost of EUR 0.17 per 1 kWh of heat pump electricity energy, EUR 0.055 per 1 kWh of gas boiler heating energy, and EUR 0.11 for 1 kWh of district heating energy.

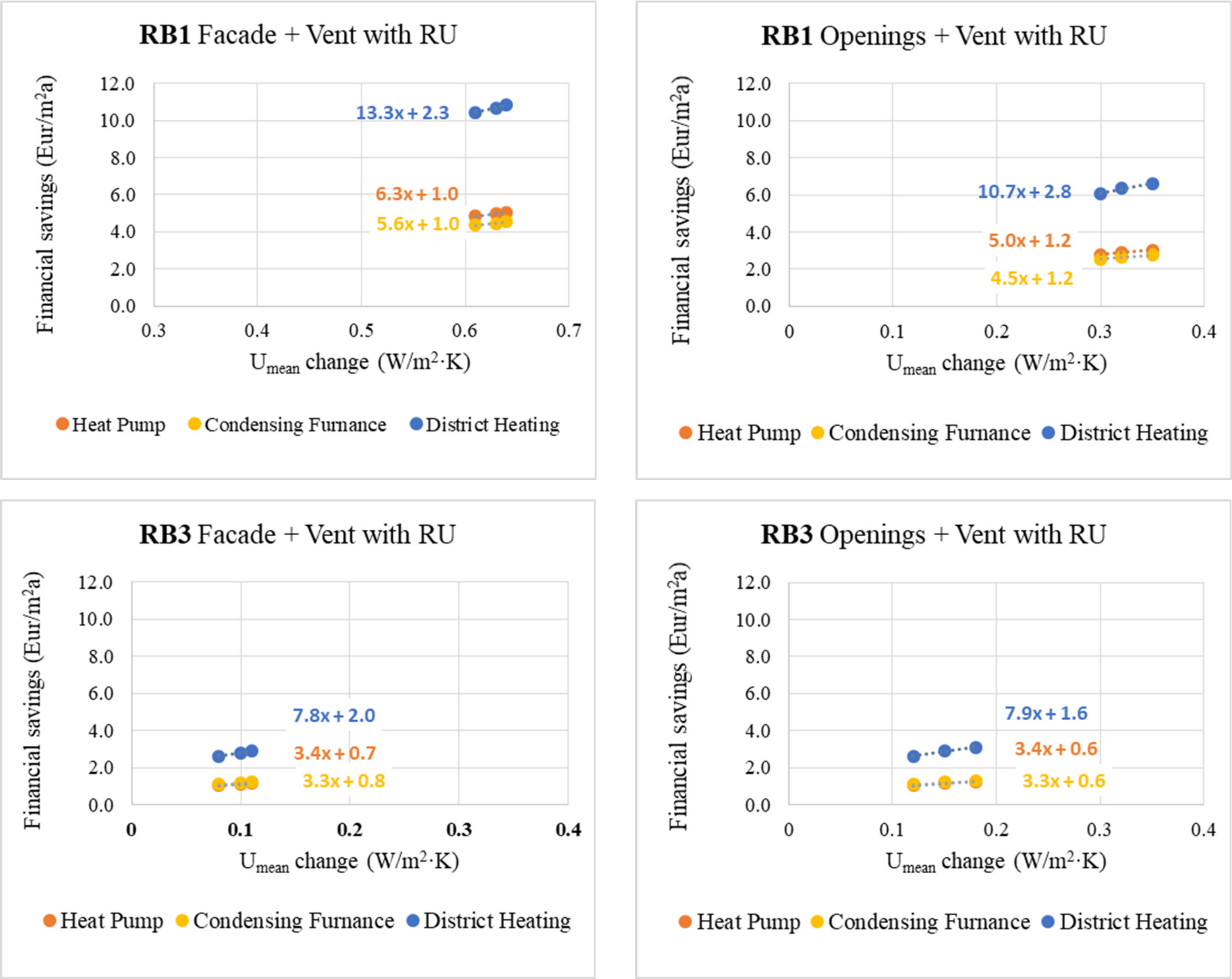


Figure 7. Calculated financial savings after additional partial thermal retrofitting of residential building RB1 built in the 1970s and RB3 built in 2015, according to heating sources. The additional retrofitting means the additional insulation of structures that already reached the low-energy standard criteria of thermal resistance.

Based on these prices, which reflect the current relatively stable situation in the energy market as of December 2023, financial savings from the thermal retrofitting of walls and windows are most significant when heating is provided by a district heating source. However, the potential for financial savings is lower and almost identical when heating is provided by a heat pump or a gas-condensing boiler. This coincidence is noteworthy because it appears to be unintentional. It is likely due to the lower gas prices in Slovakia.

4. Conclusions

This study evaluated various thermal retrofit options for apartment buildings with different energy sources. The following sources of heating were used in the calculations: heat pump + photovoltaic power plant, gas-condensing boilers, and district heating through the combined production of electricity and heat. The first step involved evaluating the potential savings from retrofitting the original building to a low-energy standard. In the second step, the potential savings after further insulation of the already insulated building structures were evaluated. Additionally, the mean U-value change in structures on the building envelope was evaluated in relation to energy and financial savings. Based on the evaluation, the following conclusions were drawn:

1. For semi-old apartment buildings built in Slovakia during the 1970s and 1980s, the most effective retrofit action to reduce the energy needed for heating is still the retrofitting of the facade, rather than the roof, the floors above the unheated floor or the replacement of windows. These results are in line with a similar study carried out by the Bulgarian authorities [37].
2. In a sample of a recently constructed apartment building, it was found that the insulation of any structure on the envelope had approximately the same effect on heating energy. However, due to the use of bricks with a higher thermal resistance value, adding extra insulation of the same thickness to the facade is not the most effective action to reduce heating energy, but all retrofit actions are probably almost equally effective. As building construction in the new millennium is governed by stricter standards, this conclusion confirms that the set criteria for envelope structure thermal properties were optimally established, leaving no gaps. Thus, there are no building structures that would remain undervalued and would need to be addressed urgently.
3. From a construction technology perspective, it is common to replace windows before or simultaneously with a facade thermal retrofit. According to calculations, it is advantageous to replace windows to the highest possible level (in this case, $U = 0.65$ $W/(m^2{\cdot}K)$) for future savings. Further reducing the thermal conductivity of the facade below the low-energy level (less than $U = 0.22$ $W/(m^2{\cdot}K)$) may not be as effective as a deeper thermal retrofit of the floor above the unheated basement.
4. A single action such as adding extra thermal insulation to the roof with satisfactory thermal resistance (to meet low-energy level requirements), in an apartment building heated by a heat pump, has a minimal impact on energy savings. In this case, the savings were less than 0.30 kWh/m^2 per year.
5. When adding extra insulation to already insulated apartment buildings, it is important to select a unique strategy based on the building's heating source. For semi-old apartment buildings that are connected to a district heating supply or heated by gas boilers, retrofitting the facade during the simultaneous replacement of windows appears to be particularly advantageous. If the heating source is a heat pump, retrofitting the building envelope structures will result in minimal energy savings. It cannot be assumed that the owners of these buildings would be motivated to save energy for heating in this way, apart from the danger of high electricity prices. It has already been indicated for 10 years [38] that, in Germany, which is often considered a leader in building efficiency policy, the annual rate and average depth of thermal retrofit actions were significantly lower than expected. The authors suggest that, if improving the efficiency of existing buildings remains voluntary, policies need to change. More targeted retrofitting instructions that suit specific buildings will be necessary.

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References

1. Odyssee-Mure Project. Energy Efficiency Trends for Households in the EU. 2020. Available online: https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/ (accessed on 20 December 2023).
2. European Commission. *A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*; European Commission: Brussels, Belgium, 2011; Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0112:FIN:en:PDF (accessed on 1 November 2023).
3. Economidou, M.; Atanasiu, B.; Despret, C.; Maio, J.; Nolte, I.; Rapf, O.; Laustsen, J.; Ruyssevelt, P.; Staniaszek, D.; Strong, D.; et al. *Europe's Buildings under the Microscope: A Country-by-Country Review of the Energy Performance of Buildings*, 1st ed.; Building Performance Institute Europe: Brussels, Belgium, 2011; p. 30.
4. Esser, A.; Dunne, A.; Meeusen, T.; Quaschning, S.; Wegge, D. *Comprehensive Study of Building Energy Renovation Activities and the Uptake of Nearly Zero-Energy Buildings in the EU*; European Commission: Brussels, Belgium, 2019.
5. Mainali, B.; Mahapatra, K.; Pardalis, G. Strategies for Deep Renovation Market of Detached Houses. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110659. [CrossRef]
6. Pernetti, R.; Pinotti, R.; Lollini, R. Repository of Deep Renovation Packages Based on Industrialized Solutions: Definition and Application. *Sustainability* **2021**, *13*, 6412. [CrossRef]
7. Ascione, F.; Bianco, N.; De Masi, R.F.; Mauro, G.M.; Vanoli, G.P. Cost-effective refurbishment of Italian historic buildings. In *Cost-Effective Energy Efficient Building Retrofitting: Materials, Technologies, Optimization and Case Studies*; Elsevier Inc.: Amsterdam, The Netherlands, 2017; pp. 553–596. [CrossRef]
8. Zanni, J.; Cademartori, S.; Marini, A.; Belleri, A.; Passoni, C.; Giuriani, E.; Riva, P.; Angi, B.; Brumana, G.; Marchetti, A.L. Integrated Deep Renovation of Existing Buildings with Prefabricated Shell Exoskeleton. *Sustainability* **2021**, *13*, 11287. [CrossRef]
9. Tirelli, D.; Besana, D. Moving toward Net Zero Carbon Buildings to Face Global Warming: A Narrative Review. *Buildings* **2023**, *13*, 684. [CrossRef]
10. Ohene, E.; Chan, A.P.C.; Darko, A. Prioritizing barriers and developing mitigation strategies toward net-zero carbon building sector. *Build. Environ.* **2022**, *223*, 109437. [CrossRef]
11. Singh, R.; Walsh, P.; Mazza, C. Sustainable Housing: Understanding the Barriers to Adopting Net Zero Energy Homes in Ontario, Canada. *Sustainability* **2019**, *11*, 6236. [CrossRef]
12. Pan, W.; Pan, M. Drivers, barriers and strategies for zero carbon buildings in high- rise high-density cities. *Energy Build.* **2021**, *242*, 110970. [CrossRef]
13. Heffernan, E.; Pan, W.; Liang, X.; De Wilde, P. Zero carbon homes: Perceptions from the UK construction industry. *Energy Policy* **2015**, *79*, 23–36. [CrossRef]
14. Longo, S.; Montana, F.; Riva Sanseverino, E. A review on optimization and cost-optimal methodologies in low-energy buildings design and environmental considerations. *Sustain. Cities Soc.* **2019**, *45*, 87–104. [CrossRef]
15. Long-Term Strategy for the Renewal of the Building Stock Ministry of Transport and Construction. 2020. Available online: https://energy.ec.europa.eu/system/files/2021-02/sk_2020_ltrs_0.pdf (accessed on 20 December 2023).
16. Fernandez-Antolin, M.-M.; del Río, J.M.; Costanzo, V.; Nocera, F.; Gonzalez-Lezcano, R.-A. Passive Design Strategies for Residential Buildings in Different Spanish Climate Zones. *Sustainability* **2019**, *11*, 4816. [CrossRef]
17. Summa, S.; Remia, G.; Sebastianelli, A.; Coccia, G.; Di Perna, C. Impact on Thermal Energy Needs Caused by the Use of Different Solar Irradiance Decomposition and Transposition Models: Application of EN ISO 52016-1 and EN ISO 52010-1 Standards for Five European Cities. *Energies* **2022**, *15*, 8904. [CrossRef]
18. Bianco, F.; Degerfeld, M.; Ballarini, I.; De Luca, G.; Mamak, P. Sensitivity Analysis of the Thermal Energy Need of a Residential Building Assessed by means of the EN ISO 52016 Simplified Dynamic Method. *E3S Web. Conf.* **2020**, *197*, 02012. [CrossRef]
19. van Dijk, D.; Kurnitski, J. The EPBD recast: How to come to a transparent and fair ZEB definition? *The REHVA European HVAC J.* **2022**, *4*, 10–15.
20. *EN ISO 52016-1:2017*; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Head Loads—Part 1: Calculation Procedures Performance. European Committee for Standardization: Brussels, Belgium, 2017.
21. van Dijk, D. EPB standards: Why choose hourly calculation procedures? *REHVA Eur. HVAC J.* **2018**, *55*, 6–12.

22. Di Giuseppe, E.; Ulpiani, G.; Summa, S.; Tarabelli, L.; Di Perna, C.; D'Orazio, M. Hourly dynamic and monthly semi-stationary calculation methods applied to nZEBs: Impacts on energy and comfort. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 072008. [CrossRef]
23. Vertal, M.; Zozulák, M.; Vašková, A.; Korjenic, A. Hygrothermal initial condition for simulation process of green building construction. *Energy Build.* **2018**, *167*, 166–176. [CrossRef]
24. Juras, P.; Jurasova, D. Outdoor Climate Change Analysis in University Campus: Case Study with Heat-Air-Moisture Simulation. *Civ. Environ. Eng.* **2020**, *16*, 370–378. [CrossRef]
25. Dréau, J.L.; Heiselberg, P. Energy flexibility of residential buildings using short term heat storage in the thermal mass. *Energy* **2016**, *111*, 991–1002. [CrossRef]
26. Wiekiera, R. Technical and Economic Analysis of the Use of Heat Pumps in a Public Facility. *Civ. Environ. Eng. Rep.* **2022**, *32*, 376–388. [CrossRef]
27. Carlander, J.; Trygg, K.; Moshfegh, B. Integration of measurements and time diaries as complementary measures to improve resolution of BES. *Energies* **2019**, *12*, 2072. [CrossRef]
28. Rakha, T.; Rose, C.; Reinhart, C. A framework for modeling occupancy schedules and local trips based on activity based surveys. In Proceedings of the 2014 ASHRAE/IBPSA-USA Building Simulation Conference, Atlanta, GA, USA, 10–12 September 2014.
29. Andersen, F.M.; Baldini, M.; Hansen, L.G.; Jensen, C.L. Households' hourly electricity consumption and peak demand in Denmark. *Appl. Energy* **2017**, *208*, 607–619. [CrossRef]
30. Crawley, D.B.; Lawrie, L.K.; Winkelmann, F.C.; Buhl, W.F.; Huang, Y.J.; Pedersen, C.O.; Strand, R.K.; Liesen, R.J.; Fisher, D.E.; Witte, M.J. EnergyPlus: Creating a new-generation building energy simulation program. *Energy Build.* **2001**, *33*, 319–331. [CrossRef]
31. Slovak Technical Standards (STN) 73 0540-2/Z1 + Z2: 2019, Properties of Environment and Building Products-Parts 3: Thermal Performance of Buildings and Constructions. Thermal Protection of Buildings. Slovak Office of Standards, Metrology and Testing. Available online: https://www.unms.sk/?home (accessed on 25 November 2023).
32. The Act. No. 555/2005 on the Energy Performance of Buildings and on the Amendments to Certain Laws Ministry of Transport and Construction of the Slovak Republic. Available online: https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2005/555/vyhlasene_znenie.html (accessed on 5 January 2024).
33. Slovak Ministry of Internal Affairs and Communications, Decree of ministry of Internal Affairs and Communications No. 324 /2016. Available online: https://www.slov-lex.sk (accessed on 25 November 2023).
34. *EN 15316-4-3:2014*; Heating Systems in Buildings—Method for Calculation of System Energy Requirements and System Efficiencies. European Committee for Standardization: Brussels, Belgium, 2017.
35. *STN EN ISO 13790/NA/Z1*; Energy Performance of Buildings. Calculation of Energy Use for Space Heating and Cooling (ISO 13790:2008). (Energetická Hospodárnosť Budov. Výpočet Potreby Energie na Vykurovanie a Chladenie (ISO 13790: 2008). Slovak Office of Standards, Metrology and Testing: Bratislava, Slovakia, 2012.
36. Buday, P.; Ingeli, R.; Vavrovič, B. Comparison of Thermal Bridges Calculate Method through Typical Details in Low Energy Designing. *Adv. Mater. Res.* **2013**, *855*, 126–129. [CrossRef]
37. Doseva, N.; Chakyrova, D. Life Cycle Cost Optimization of Residential Buildings in Bulgaria: A Case Study of the Building Envelope. *Civ. Environ. Eng.* **2021**, *17*, 107–116. [CrossRef]
38. Galvin, R. Why German homeowners are reluctant to retrofit. *Build. Res. Inf.* **2014**, *42*, 398–408. [CrossRef]