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Comparison of Energy Demand for Heating and CO_2 Emissions in Urban and Rural Areas, the Case of Hajdú-Bihar County, Hungary

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Abstract: Mitigating carbon dioxide emissions in the building sector is a primary global goal. This paper compares different residential buildings in urban and rural regions of Hajdú-Bihar County (Hungary). Significant differences were found between urban and rural single-family houses concerning their energy performance; however, the differences in CO_2 emissions were not significant. Only the differences in specific heat losses were significant between urban single-family and masonry-structured multifamily buildings. Panel buildings demonstrate the best energy performance from their construction period, but due to high investment costs and the inability to change the heat source, the CO_2 emissions from these buildings have a lower limit today. In both single-family houses and masonry-structured multifamily buildings, meeting the heat demand can be achieved with zero CO_2 emissions using existing technologies.

Keywords: urban residential buildings; rural residential buildings; multifamily buildings; heat losses; heat demand; CO_2 emissions

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1. Introduction

1.1. Energy-Saving Efforts in the Building Sector

Mitigating greenhouse gas emissions is one of the main goals of each country. In the European Union, Directive 2018/844 of the European Parliament and the Council stated that the Union is committed to developing a sustainable, competitive, secure and decarbonised energy system by 2050 [1]. Member states are required to set out a roadmap with measures, aimed towards the long-term 2050 goal of reducing greenhouse gas emissions in the Union by 80–95% compared to 1990. This is to ensure a highly energy-efficient and decarbonised national building stock and to facilitate the cost-effective transformation of existing buildings into nearly zero-energy buildings [1]. Moreover, in line with the scientific advice from the European Scientific Advisory Board on Climate Change and based on a detailed Impact Assessment, in 2024, the communication of the Commission to the European Parliament presents a 90% net GHG emission reduction compared to 1990 levels as the recommended target for 2040 [2]. In the Union, building stock is responsible for 36% of CO_2 emissions [1]. Ürge-Vorsatz et al. stated that globally, over 60% of residential energy is demanded for thermal uses [3]. Within this, space heating comprises 32–33% of the global total building energy use. They found that biomass is still by far the dominant fuel when a global picture is considered, covering most of the energy needs of the poor in the least developed countries, used with very low efficiencies. Berardi stated that the building sector deserves to be considered alone, without being mixed with other subsectors within a "third sector" besides transportation and industry [4]. Furthermore, he drew attention to the importance of data accountability and the reliability of buildings' energy consumption. He proposed that large countries should provide data on the energy consumption in buildings, dividing it into regions or provinces with the same climatic conditions [4]. Parshall et al. had the same opinion since they suggested counties as the best spatial scale for a local energy data inventory [5]. They argued that raw energy data are available at the county scale, and counties are a recognised political unit with some authority to formulate local policy.

1.2. CO_2 Emissions in the Building Sector

Zhou et al. evaluated trajectories for China's building sectors to 2050 and the potential impact of policies on fully deploying today's maximum techno-economically feasible efficiency and renewables measures for Chinese buildings using four scenarios [6]. They pointed out that by developing and implementing energy efficiency and renewable energy policies, China can achieve CO_2 emissions from the energy use in buildings that are just 20% above 2010 levels in 2050 and are likely to decline rapidly thereafter. Akan and Akan determined the optimum insulation thickness of buildings depending on the life cycle cost, considering the heating and cooling energy demands separately. They found that the CO_2 emissions can be reduced by approximately 66–76% during the heating season and by 46–69% during the cooling season using the optimal insulation thickness [7]. Canbolat and Albak performed a multi-objective optimisation of the whole external wall structure of buildings, considering the heat source as well [8]. The multi-objective optimisation aimed to obtain minimum CO_2 emissions with minimum costs. They obtained different structural materials and layers depending on the main goal of the optimisation. The study pointed out that the boundary parameters and the optimisation objectives have to be well defined to obtain appropriate results. Zhu et al. drew attention to the fact that besides the operational CO_2 emissions of buildings, the embodied CO_2 has to be considered [9]. They found that in China, the annual embodied carbon dioxide accounts for roughly one half of the total carbon dioxide emissions in the building sector in 2015.

1.3. Urban vs. Rural Buildings

Several authors studied the energy consumption of residential buildings built in urban and rural regions. Heinonen and Junnila showed that in Finland, cities are more energy intensive than the surrounding suburban and rural areas [10]. The authors explained this urban–rural difference with the higher incomes of urban residents. The same authors analysed holistically the residential energy consumption patterns and the overall housing energy requirements of urban and rural households in Finland [11]. They studied three of the most common housing types in Finland and found that each housing mode was less energy intensive in rural areas, the energy mixes vary significantly between the studied building types, and the behavioural differences are significant between the different housing modes. This finding suggests that not only are the construction technology and thermal requirements essential when the decarbonisation potential is analysed, but also the settlement type where the building was built. Nematchoua et al. claimed that consistent data at the neighbourhood level are crucial to understanding the origins of climate change at regional, urban and rural scales [12]. Cai and Jiang, through the example of Shaanxi province, found substantial differences between the energy sources used in rural and urban areas [13]. In rural areas, the place of coal was taken by biomass, while in urban areas, coal was replaced mainly by natural gas. Guan et al. established a bottom-up Adaptive Weighting Divisia decomposition model to analyse the differences in the per capita CO_2

emissions across urban and rural areas of different provinces in China [14]. Their results showed that the average household CO_2 emissions in urban areas consistently exceeded those in rural areas. Zhang et al. in their study concluded that residential energy consumption both in urban and rural regions rapidly increased in recent years [15]. However, the growth rate of urban residential energy consumption was faster than that of rural areas; hence, the gap in residential energy consumption per capita between urban and rural areas became narrower over the study period. In contrast, Cheshmehzangi concluded that urban housing has benefited much from China's green strategies and energy housing plans, while rural housing has experienced minimal change in the past few decades [16]. Zhou et al., taking the Shaanxi province as an example, developed a simulation model to predict the trends in carbon dioxide emission changes in urban and rural buildings [17]. They concluded that structural adjustments to the building energy consumption have the greatest potential for carbon reduction and play a central role in achieving a green, low-carbon pathway. Du et al. found that the rebound effect might impact the expected results in saving energy and reducing CO_2 emissions [18]. Differences can be observed between the rebound effect in urban and rural areas. In China, the magnitudes of the rebound effect for residential buildings in urban areas fluctuate between 79.43% and 110.00%, while that in rural areas increases from 115.28% to 120.40%. The rebound effect is mainly because the energy demand for residential buildings would increase when the energy efficiency improves [18]. Wang et al. developed a model to analyse the movement of CO_2 emissions gravity centres in China [19]. They found that per capita disposable income is one of the primary factors affecting the gravity centres. The findings of Zhou and Shi (obtained for the 2000–2015 period) contradict this statement. They concluded that urbanisation is an emollient for the inequality of urban–rural energy consumption because it could improve the rural residents' accessibility to modern energy services and the affordability of clean energy [20]. Based on balanced panel data covering 30 provinces of China for the period 1990–2012, Zhou et al. found that the impact of employment structural transformation on the energy consumption and CO_2 emissions across China was generally positive and statistically significant but differed considerably across regions [21]. He et al. concluded that in China, the lack of knowledge about building energy efficiency and the energy consumption habits of rural residents in comparison with urban residents is poor [22]. The effects of urban and rural residents' lifestyles on the energy consumption of buildings are also emphasised in [23–26]. The demand of urban residents for more electronics and improved indoor comfort drives energy consumption higher, while the traditional ways of using natural options are still dominant [25]. The differences between urban and rural energy consumption are also accentuated by the urban microclimate. Several studies have demonstrated that the urban heat island affects buildings' energy consumption [27–29]. Li et al. showed that the urban heat island effect can increase cooling energy consumption from 10% to 120% and decrease heating energy consumption from 3% to 45% [30]. The urban night-time air temperatures can be higher by 3–4 °C than adjacent non-urban areas [31]. Climate change also affects the energy consumption in buildings (decreased energy for heating and increased energy for cooling); however, the impact is different in urban and rural areas [32]. Madlener and Sunak showed that the effects of urbanisation differ considerably between developed and developing countries as well as within the group of developing countries [33]. Hence, this process should be well assessed in different countries to choose the optimal local building energy solutions. Myszczyszyn and Supron analysed data between 1996 and 2020 and found that in central European countries, the urbanisation rate affected CO_2 emissions, influencing the enhanced energy consumption [34].

1.4. Research Goal

Summarising the references discussed above, it can be stated that the energy performance characteristics of the existing building stock have to be known in detail to meet the ambitious decarbonisation goals. Furthermore, the differences between rural and urban buildings have to be accounted for when decarbonisation strategies are elaborated. Employment, income, energy mix, and lifestyle strongly affect energy consumption. An unfortunate combination of these can lead to energy poverty [35]. Because of similar building policies implemented in the last 80 years, common features can be observed in the Central and Eastern European countries' building stocks. Different building typologies have already been created for these countries [36,37]. However, the urban–rural differences have not been researched so far from the point of view of energy consumption and CO_2 emissions. It is well known that the A/V ratio of the building affects the heat demand. Hence, the specific heat losses of single-family houses are expected to exceed those of multifamily buildings. Our research aimed to show the energy and CO_2 emission differences between urban and rural areas in Central and Eastern European countries through the example of Debrecen and Hajdú-Bihar county (Hungary).

2. Methodology

First, the available data on the building stock provided by the Hungarian Central Statistical Office were assessed and analysed. Thereafter, the energy assessment of 1200 flats/houses in Debrecen and Hajdú-Bihar county was carried out. Debrecen is the second largest city in Hungary. Out of 1200 energy assessments, 841 were suitable for the planned research: 236 were single-family houses in Debrecen, 372 were single-family houses in small towns and villages in rural regions of the county, 115 were flats in panel buildings in Debrecen, and 118 were flats in masonry-structured multifamily buildings in Debrecen. The building envelope and the building service systems were assessed on-site, and the calculations were carried out using Winwatt32 7.63 software, which integrates the energy-performance-calculation methodology used in Hungary. Based on the building energy data, statistical analyses were performed using the ORIGIN LAB 9.55 software. This software for data analysis and graphing, available at the University of Debrecen, offers all the features needed to analyse the data gathered in this study. The results are presented using box-plot diagrams. The linear fit method was used to see the variation trends over the years of different parameters [38]. To compare different groups of buildings, the paired sample *t*-test was performed at a $p = 0.05$ significance level [39]. The energy performance analysis of detached houses in Debrecen was already conducted [40]. Buildings built between 1930 and 2023 were classified into eight categories. In this manuscript, single-family houses from the rural region and masonry-structured multifamily buildings were classified similarly into eight categories: buildings built before 1959, followed by buildings built between 1960 and 1969, 1970 and 1979, 1980 and 1989, 1990 and 1999, 2000 and 2009, 2010 and 2019, and 2020 and 2023. The assessed panel buildings (insulated concrete sandwich panels) were built in Debrecen only in two decades: 1960–1969 and 1969–1970. The A/V values, the net heated area, the specific heat loss coefficient, the net energy demand for heating and the specific CO_2 emissions were statistically analysed for all buildings. Using the paired sample *t*-test method at a $p = 0.05$ significance level, the differences between rural and urban single-family houses were analysed for each category; thereafter, the significance analysis of the differences between urban single-family houses and masonry-built multifamily houses was conducted.

Finally, through some good examples, rational envelope refurbishments, energy sources and heat generation modes were proposed for the analysed typical buildings to obtain minimum CO_2 emissions. The steps of the performed research are presented in Figure 1.

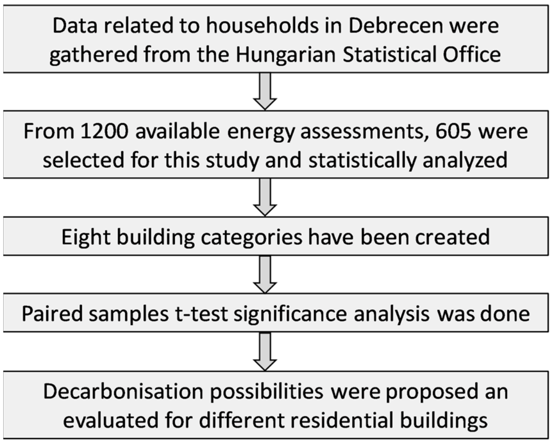


Figure 1. Flowchart of research algorithm.

3. Features of Building Stock

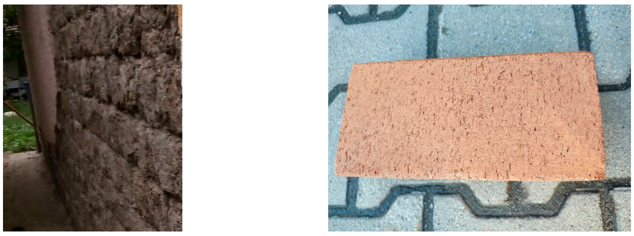
In Hungary, heating accounts for approximately 71% of households' total final energy consumption [41]. Obviously, single-family houses predominantly characterise rural areas, while urban areas feature a significant number of flats in multifamily houses. According to the Hungarian Central Statistical Office, the number of single-family houses in Debrecen is 37,615, while the number of flats placed in multifamily houses is 50,008, of which 26,233 are flats in panel buildings (26,776 are flats in masonry-structured multifamily buildings). In Hajdú-Bihar county, there are 208,075 households in total [42].

When analysing the building structures, it can be observed that the building stock is extremely diverse. However, specific building materials have been used for external building elements in different decades over the last century. The differences can primarily be shown through the structure of the external walls. Until 1960, masonry blocks were mainly made of adobe mixed with grain crumbs (Figure 2a). The thermal conductivity of this mixture was between 0.40 and 0.65 W/mK, depending on the density of the material (1100–1400 kg/m^3, respectively). The wall thickness ranged from 40 to50 cm resulting in an overall heat transfer coefficient of 0.70 to 1.28 W/m^2K. The ground level floor consists of concrete without an insulation layer. The beam-framed slab under the attic is covered again with adobe mixed with grain crumbs.

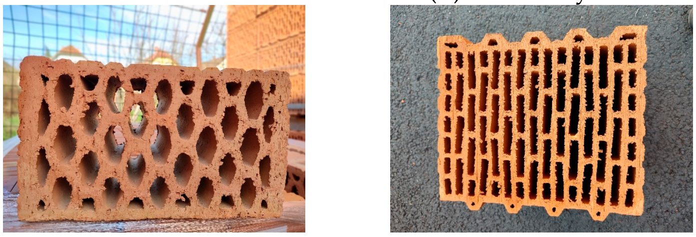
After the 1960s, the adobe was gradually replaced by burnt clay bricks (Figure 2b). The thermal conductivity of burnt clay bricks is 0.78 W/mK, making the overall heat transfer coefficient of the 38 cm walls 1.43 W/m^2K.

From the years 1970 to 1980, the burnt clay bricks with several vertical holes became widely used. These bricks were called B30, as their length and the thickness of the walls built from them was 30 cm (Figure 2c). They were also commonly used for multifamily buildings. The thermal conductivity of these bricks is 0.64 W/mK, leading to an overall heat transfer coefficient of 1.47 W/m^2K for a 30 cm thick wall.

Later, the B30 brick was enhanced by increasing its length to 38 cm and increasing the number of vertical holes in a special arrangement (HB38 brick). However, this brick was not widely used. Instead, a similar brick but with better thermal properties, PTH38, saw extensive use after the year 2000 (Figure 2d). The thermal conductivity of this brick was 0.2 W/mK, and the length (thickness of the wall) could be either 30 cm, 38 cm or sometimes 44 cm. Consequently, the overall heat transfer coefficient of the wall was 0.58 W/m^2K (30 cm), 0.47 W/m^2K (38 cm) or 0.41 W/m^2K (44 cm). In the latter two cases, even the requirements of the 7/2006 Building energy performance regulation (0.45 W/m^2K) were satisfied.



(**a**) External wall from adobe bricks (**b**) Burnt clay brick



(**c**) B30 brick (**d**) PTH 30 brick

Figure 2. Building materials used for residential building walls.

After the year 2000, PTH bricks were extensively used even in multifamily buildings. Moreover, these bricks (or some improved versions) are used today, insulated with 15–20 cm of expanded polystyrene (EPS). These external walls have an overall heat transfer coefficient of 0.2 W/m^2 K (15 cm thick EPS) or 0.16 W/m^2 K (20 cm thick EPS).

It can be observed that shifting from adobe bricks to burnt clay bricks and B30 bricks led to an increase in the overall heat transfer coefficient of the walls. Subsequently, a significant reduction in the overall heat transfer coefficient was achieved in the year 2000 with PTH bricks, and again after 2020 (imposed by the requirements of nearly zero energy buildings), the overall heat transfer coefficient was reduced nearly by half.

It should be mentioned that in the 1970s and 1980s, silicate bricks were also used in considerable quantities. When producing silicate, aluminium paste is added to water, cement and lime, which reacts with the water to form hydrogen gas. In the silicate structure, pores form in place of the hydrogen, improving the material's heat conductivity (0.22–0.36 W/mk depending on the density). This is what we call aerated concrete today (heat conductivity 0.13–0.15 W/mk). The wall thickness was primarily 30 cm.

Currently, several single-family houses are built from light-frame (wood or metal) structures (plasterboard, OSB, 16 cm mineral wool, OSB, 10 cm EPS, plaster).

During the years 1970–1980, buildings constructed with industrialised technology gained popularity in Central and Eastern European countries. The prefabricated panels already included a polystyrene layer of 6–8 cm. These blocks of flats may contain hundreds of apartments. Due to thermal bridges, the walls of these buildings have a mean overall heat transfer coefficient of 1. 04–1. 96 W/m^2 K (even reaching 1. 98 in some cases). These buildings are mostly connected to the district heating system. Despite the advantageous A/V parameter, these buildings exhibit relatively high energy consumption (due to the high overall heat transfer coefficient of the external walls).

4. Results and Discussion

4.1. Rural Single-Family Houses

The analysed buildings were categorised into eight groups. The thermal performance requirements related to the external building elements have changed several times in the last decades, but were set out in a decree only in 2006. A building pocket book mentioned first the overall heat transfer coefficient (U) of external walls in 1934 [43]. The authors recommended U values lower than 1.68 W/m^{2}K. Later, lower overall heat transfer coefficients were recommended in standards or prescriptions, but these were not compulsory. Hence, the overall heat transfer coefficients of the external building elements (especially the walls) were determined mainly by the construction materials and technology. Consequently, it was decided to carry out an energy performance analysis, grouping the buildings depending on the year of construction. It was shown in the previous section that the development and utilisation of different building blocks strongly affect the thermal properties of external walls. The same grouping methodology was used in the case of urban single-family houses [38].

The A/V parameter and the net heated area for rural single-family houses in Hajdú-Bihar county, based on 372 assessments, are presented in Figure 3. It can be observed that the decade-by-decade variation in the A/V parameter is not significant, but the decrease is significant between the oldest and newest buildings. The net floor area is increasing, but the decade-by-decade differences are not significant. However, the difference between the oldest and the recently built buildings is significant. The specific heat loss coefficient and the net heat demand by groups are presented in Figure 4. A continuous decrease in these parameters can be observed over the years.

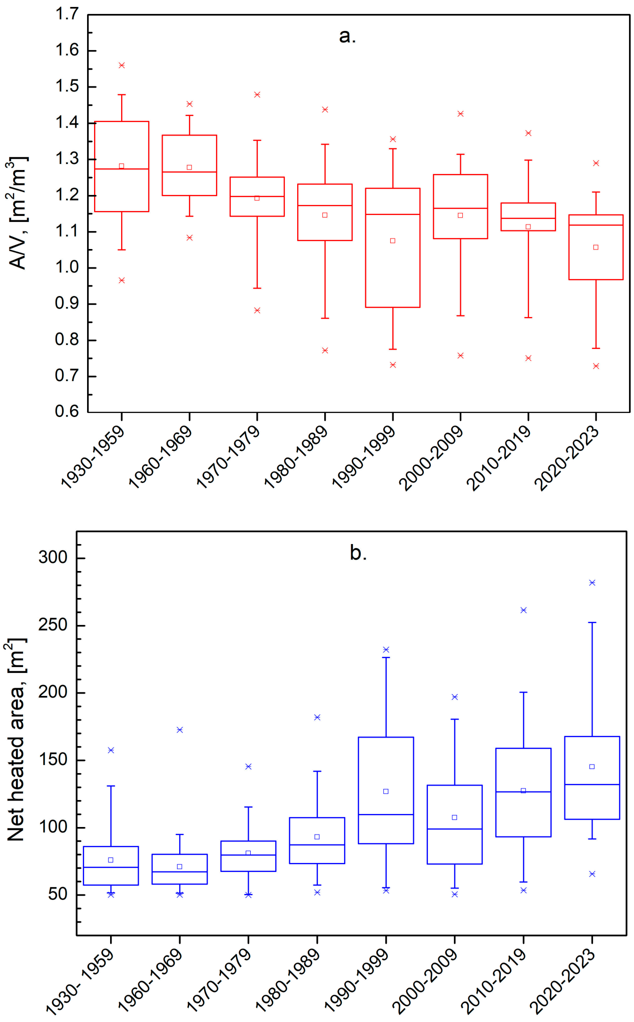


Figure 3. A/V ratio (**a**) and net heated area (**b**) of the analysed rural single-family houses.

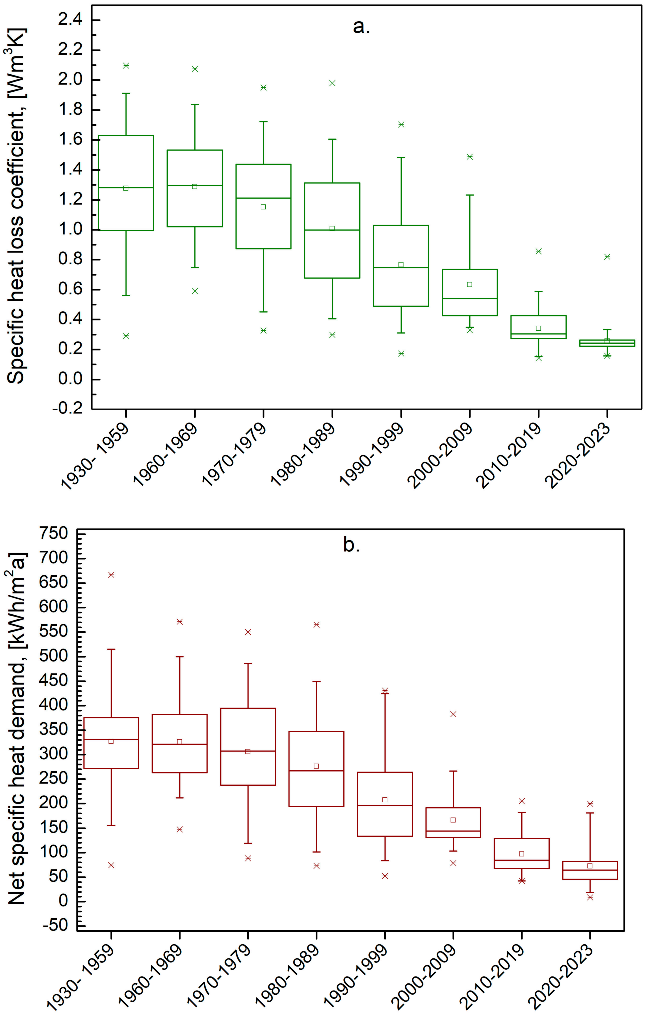


Figure 4. Specific heat loss coefficient (**a**) and net specific heat demand (**b**) of the analysed rural single-family houses.

The specific heat loss coefficient and the specific heat demand are shown in Figure 4.

The specific CO_2 emissions related to the energy consumption are presented in Figure 5.

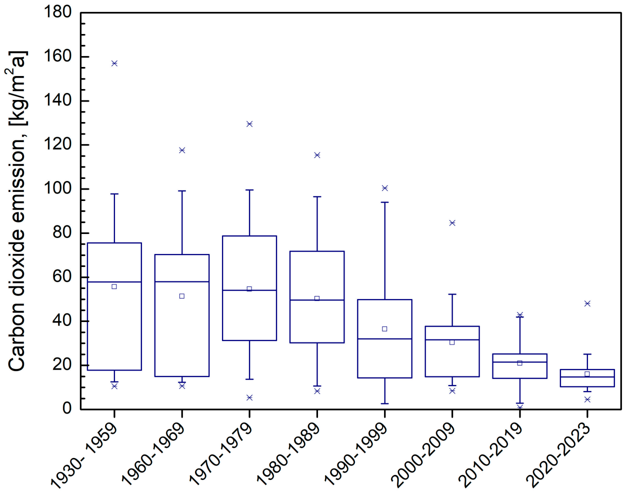


Figure 5. Specific CO_2 emissions of the analysed rural single-family houses.

It can be seen that there is practically no difference between the specific CO_2 emissions of rural single-family houses until 1989. Thereafter, a decrease can be observed caused by the thermally efficient masonry blocks and strict energy performance requirements set out in the 7/2006 decree [44]. The extremely high emission value was observed in the case of a building with poor thermal properties of the envelope, and coal was used for heating and electricity for domestic hot water production. However, it can be observed that in each analysed decade, there are buildings with specific CO_2 emissions below 10 kg/m^{2}a. Currently, the requirement is 20 kg/m^{2}a. This means that there are lots of already refurbished single-family houses.

4.2. Masonry-Structured Multifamily Buildings

A total of 118 analysed flats were placed in masonry-structured multifamily buildings in Debrecen. Figures 6–8 show the results obtained for these buildings.

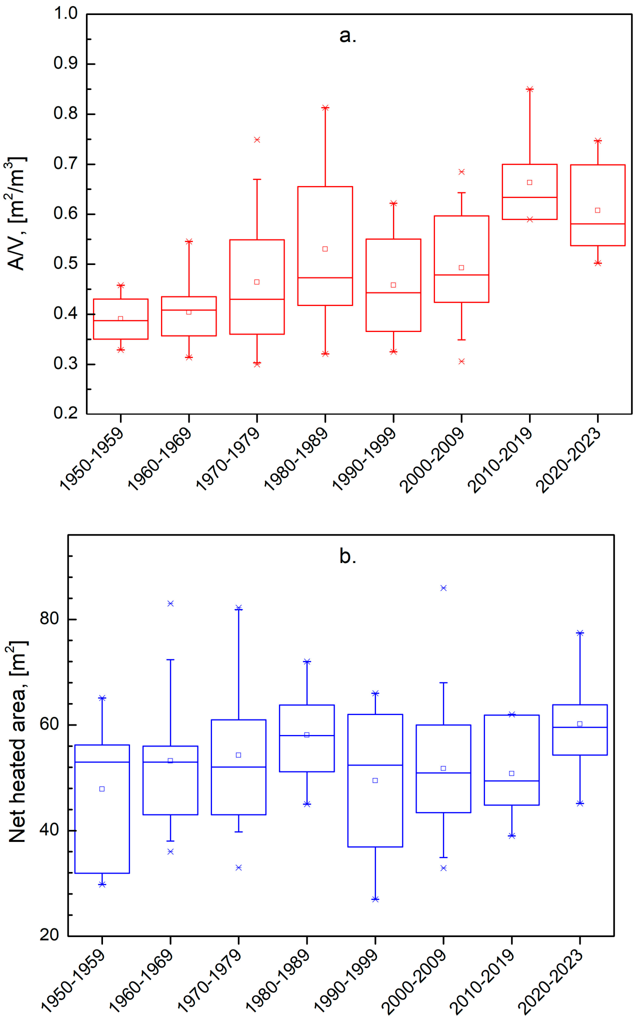


Figure 6. A/V ratio (**a**) and net heated area (**b**) of the analysed masonry-structured multifamily buildings.

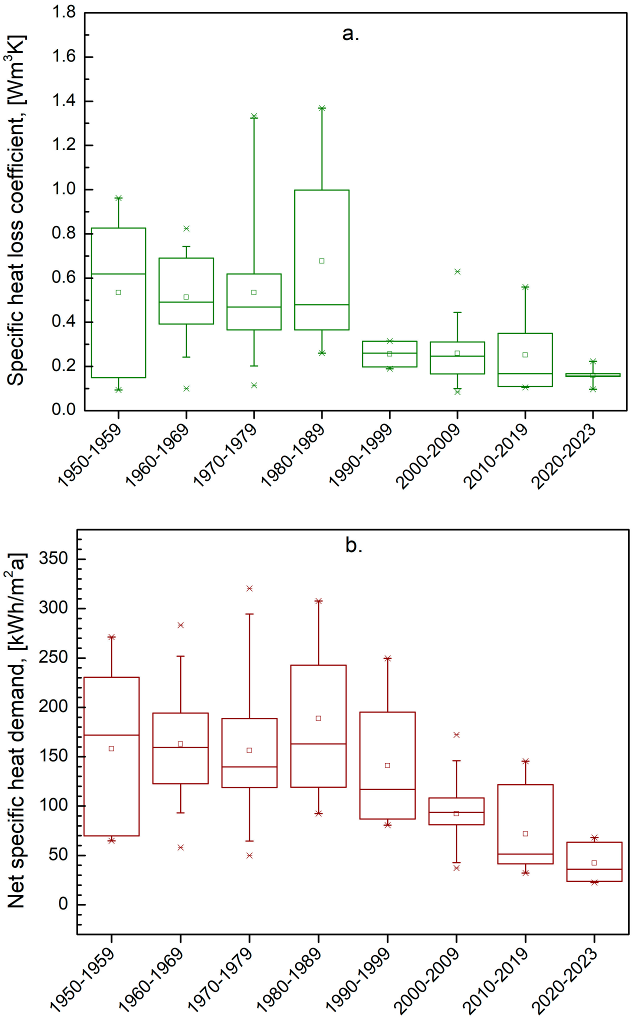


Figure 7. Specific heat loss coefficient (**a**) and net specific heat demand (**b**) of the analysed masonry-structured multifamily buildings.

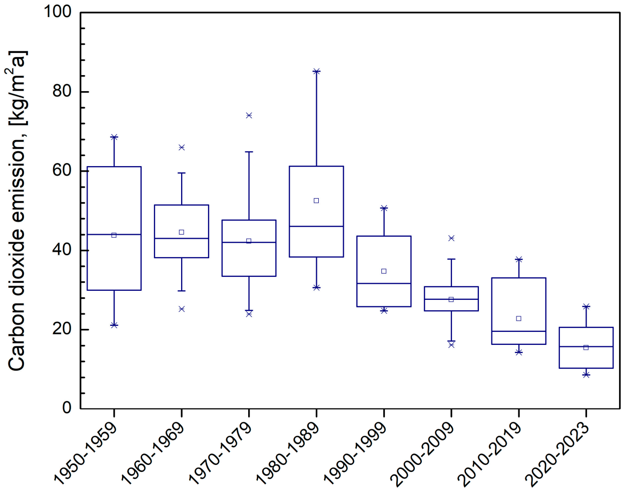


Figure 8. Specific CO_2 emissions of the analysed masonry-structured multifamily buildings.

It can be observed that the A/V parameter of masonry-structured multifamily buildings increased over the years.

The differences are not significant except for the decades 2000–2009 and 2010–2020. Practically, this means that the number of flats in a building decreased in the last decades.

The net heated area of a flat shows a small variation during the analysed decades, but only between the 1980–1989 and 1990–1999 decades (the political change) can a significant decrease be observed.

Analysing the specific CO_2 emissions, it can be affirmed that before 2000, there were no buildings with emissions below 20 kg/m^{2}a. Most buildings with emissions below 20 kg/m^{2}a were found only after 2020.

4.3. Panel Buildings

In the framework of this research, 115 apartments placed in industrialised panel buildings were assessed. These buildings were built only between the years 1970 and1989, so the obtained results only apply to these two decades (Figures 9–11).

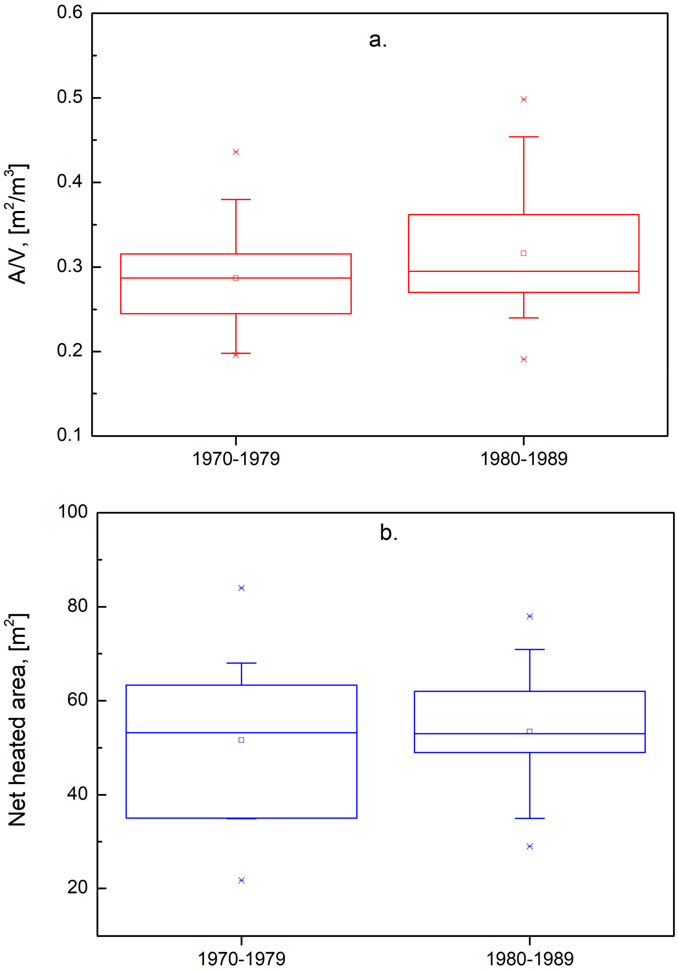


Figure 9. A/V ratio (**a**) and net heated area (**b**) of the analysed panel buildings.

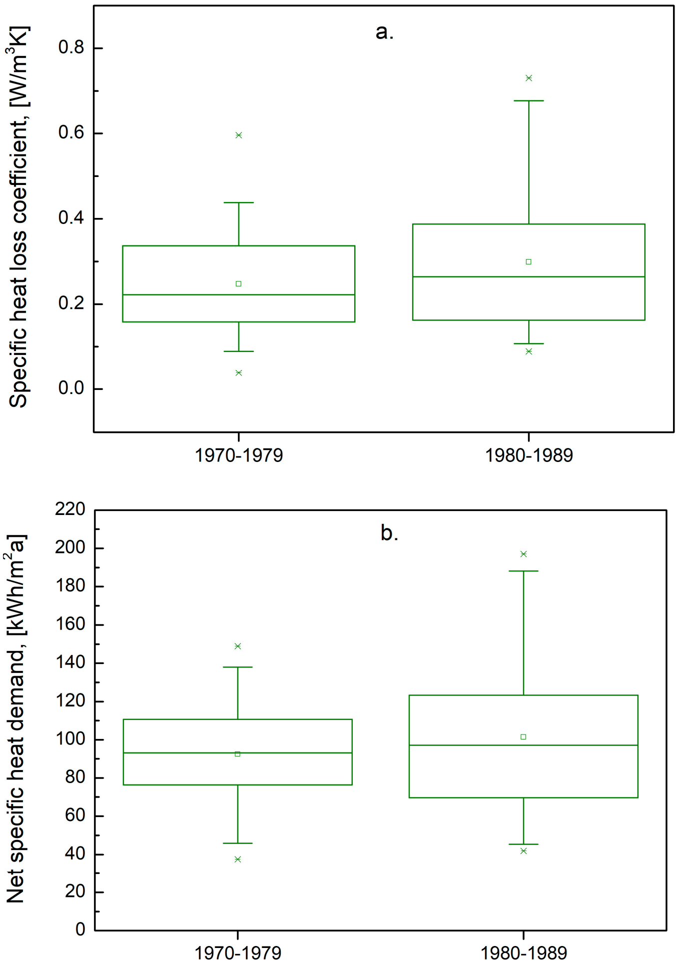


Figure 10. Specific heat loss coefficient (**a**) and net specific heat demand (**b**) of the analysed panel buildings.

Figure 11. Specific CO_2 emissions of the analysed panel buildings.

Most of the analysed panel buildings have ten or eleven storeys, but some have five levels. The insulation layer inserted between the two steel concrete layers was 6–8 cm thick. Regarding the A/V parameter and the net heated area of a flat, no significant differences can be observed between the buildings built in the two decades. Moreover, the differences are not significant when comparing the net heated area of flats in masonry-structured multifamily buildings and panel buildings. Analysing the specific CO_2 emissions, it can be observed that, despite thermal refurbishments, in the framework of this study, no building was identified with a specific CO_2 emission below 20 kg/m^2a.

4.4. Comparison of Urban–Rural Single-Family Houses

To show the variation trends during the analysed 93 years, linear regression curves were determined (Figures 12–14). The goodness of fit is given by the adjusted R-squared values.

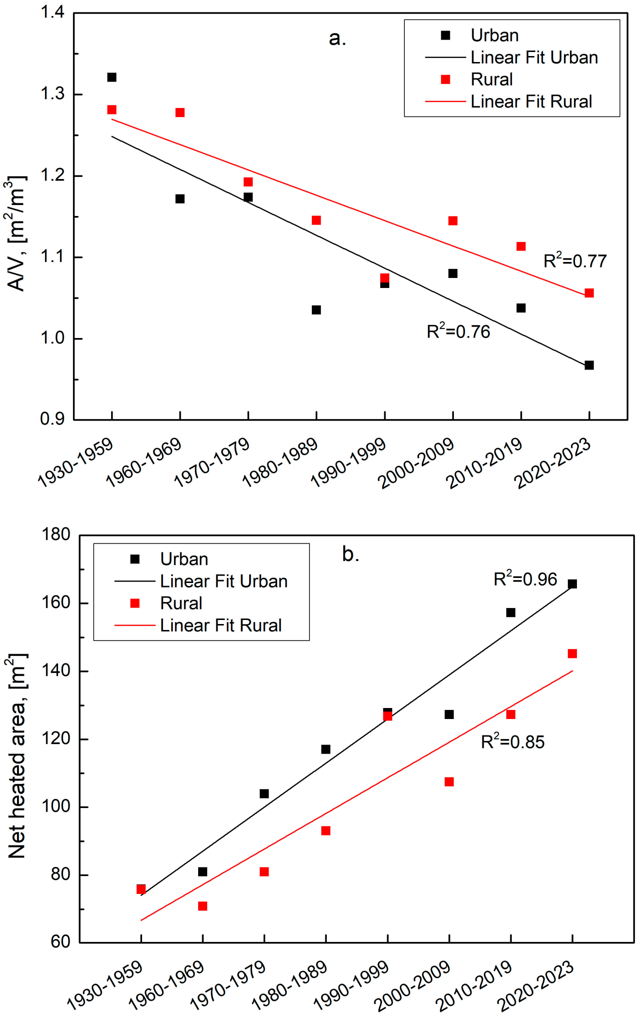


Figure 12. Trends of A/V ratio (**a**) and net heated area (**b**) of the analysed urban–rural single-family buildings (R^2—adjusted R-squared).

The statistical analysis of the differences between groups (means of urban–rural single-family houses, urban single-family houses–masonry-structured multifamily buildings, and rural single-family houses–masonry-structured multifamily buildings) was performed at a p = 0.05 significance level using the paired sample t-test.

It can be observed that the trend is similar in the case of each analysed parameter, yet important differences can be identified. While the A/V parameter of rural single-family houses is higher, the net heated area of urban single-family houses exceeds the net heated area of rural houses. This means that urban buildings are larger but energy conscious, being more compact. The differences are significant in both cases. The trend lines of the specific heat loss coefficient are almost parallel. The heat loss coefficients of single-family houses in rural areas exceeds those in urban areas; hence, the heat demand of rural houses is higher than the heat demand of urban buildings. The differences are significant in both cases. However, the differences between CO_2 emissions are not significant. The reason is the fact that in rural buildings, biomass and wood are used extensively, while in urban regions, mainly natural gas is used (the CO_2 emissions of wood and biomass are lower than those of natural gas).

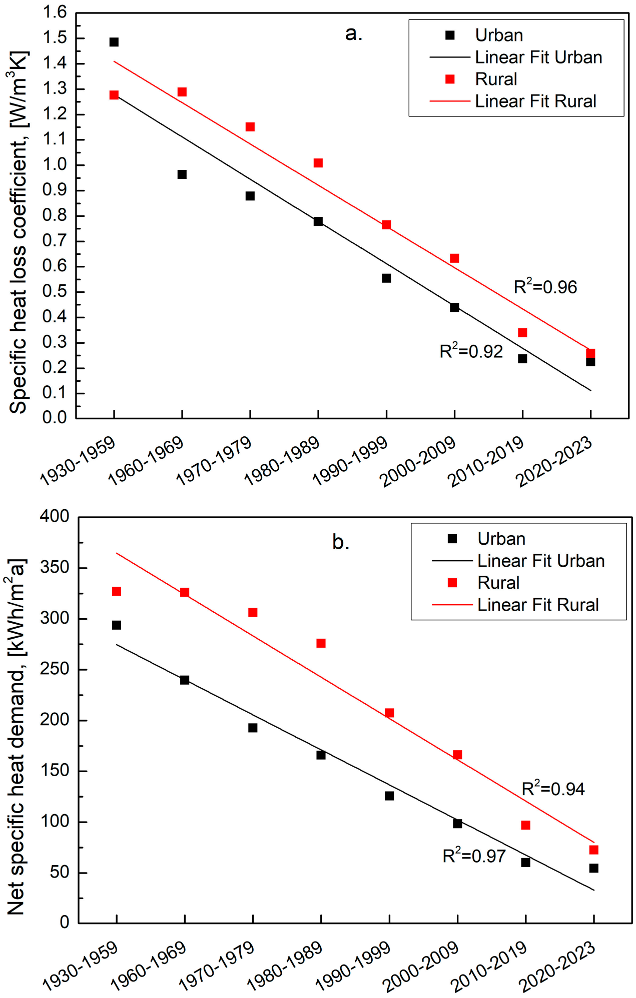


Figure 13. Trends of specific heat loss coefficient (**a**) and net specific heat demand (**b**) of the analysed urban–rural single-family buildings (R^2—adjusted R-squared).

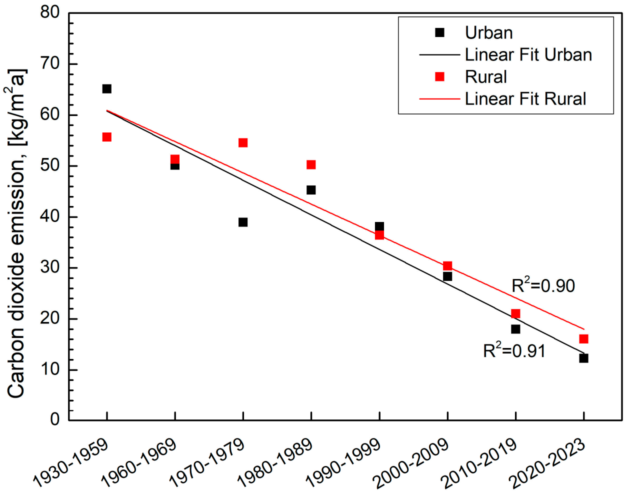


Figure 14. Trends of specific CO_2 emissions of the analysed urban–rural single-family buildings (R^2—adjusted R-squared).

4.5. Comparison of Urban Single-Family Houses and Masonry-Structured Multifamily Buildings

The trend lines for the specific heat loss coefficient, net specific heat demand and CO_2 emissions for urban single-family houses and masonry-structured multifamily buildings are presented in Figures 15 and 16. It can be observed that single-family houses show a steeper trend line in both cases. As a result, the trend lines intersect. It can generally be said that the heat loss coefficient and the heat demand of single-family houses are higher than those of multifamily buildings. However, there are decades when the situation is the inverse. While the differences between the urban and rural specific heat loss coefficients are significant, the differences between the net specific heat demand are not significant.

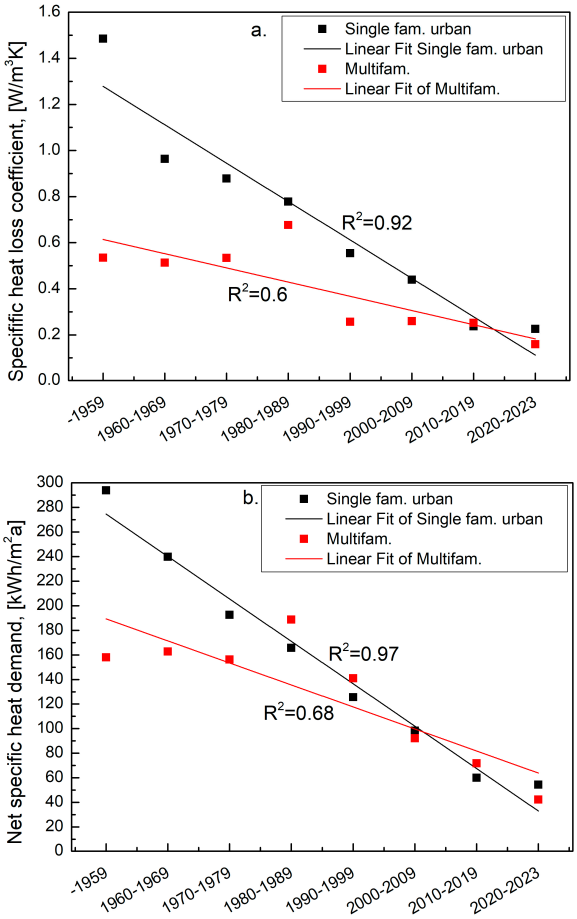


Figure 15. Trends of specific heat loss coefficient (**a**) and net specific heat demand (**b**) of the analysed urban single-family and urban masonry-structured multifamily buildings (R^2—adjusted R-squared).

Similarly, the inclination angle of the specific carbon dioxide emissions trend line in the case of single-family houses is higher than that of multifamily buildings. This means that the rate of carbon dioxide emission reduction from decade to decade was greater for single-family houses than for multifamily buildings. The differences between CO_2 emissions are not significant. The reason can be the fact that until 1990, in multifamily buildings, gas convectors were widely used as heaters. Higher efficiency can be obtained in the case of central heating systems with radiators. After 1990, similar heat sources and heating systems were used, and the differences between the net specific heat demand are not significant.

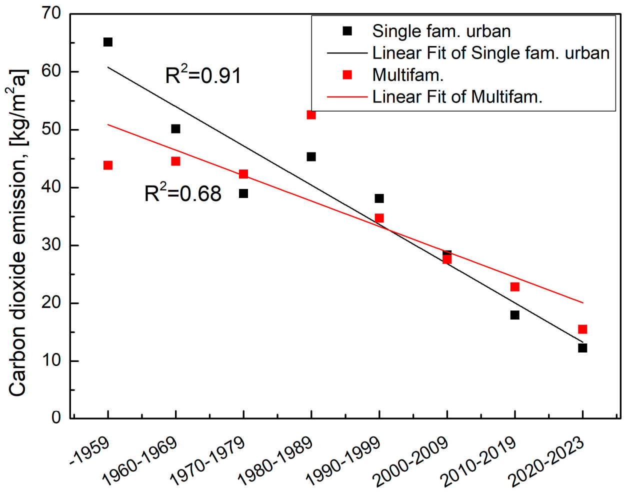


Figure 16. Trends of specific CO_2 emissions of the analysed urban single-family and masonry-structured multifamily buildings (R^2—adjusted R-squared).

4.6. Comparison of Rural Single-Family Houses and Masonry-Structured Multifamily Buildings

Finally, the specific heat loss coefficient, the net specific heat demand and the specific CO_2 emissions were compared in the case of rural single-family houses and multifamily buildings (Figures 17 and 18). There is no point in comparing the A/V coefficient and the net heated area. The results are similar to those presented in the previous subsection. The differences are significant in the case of the specific heat loss coefficient and net specific heat demand, but the differences are not significant in the case of specific CO_2 emissions. The reason can be found in the heat source (natural gas vs. biomass and wood) and heating system type (gas convector vs. central heating system).

In the case of panel buildings, having data only for two decades prevents a comprehensive comparison across all the categories. The mean A/V parameter of panel buildings was 0.286 m^{-1} for the decade 1970–1979 and 0.316 m^{-1} for the decade 1980–1989. The mean specific heat loss values were 0.247 W/m^3K for the decade 1970–1979 and 0.298 W/m^3K for the decade 1980–1989. The mean specific heat demands were 92.4 kWh/m^2a (SD = 27.92) for the decade 1970–1979 and 101.38 kWh/m^2a (SD = 38.27) for the decade 1980–1989. The specific CO_2 emissions were 34.18 kg/m^2a (SD = 7.26) for the decade 1970–1979 and 35.63 kg/m^2a (SD = 9.18) for the decade 1980–1989. It should be noted that almost all panel buildings are connected to the district heating system, where heat is produced primarily using natural gas. In the same decades, masonry-structured multifamily buildings had mean specific CO_2 emissions of 42.35 kg/m^2a (SD = 12.62) and 52.55 kg/m^2a (SD = 18.05), respectively. Urban single-family houses exhibited a mean specific CO_2 emission of 38.97 kg/m^2a (SD = 21.55) for the decade 1970–1979 and 45.31 kg/m^2 a (SD = 23.38) for the decade 1980–1989. In contrast, rural single-family buildings fared worse, with emissions of 54.54.53 kg/m^2a (SD = 30.17) and 50.25 kg/m^2a (SD = 26.73), respectively. It can be stated that panel buildings built during their construction period demonstrate better energy performance, with lower CO_2 emissions than all the other building types. However, all the other building categories have shown substantial improvements in their energy performance over the past few decades, while progress has stalled for panel buildings. The issue is that the cost of thermal and energy refurbishment for these buildings is substantial, and the flats are privately owned, meaning that each owner must contribute to the refurbishment expenses. Unfortunately, many homeowners, such as pensioners, are unable to afford these costs. Nevertheless, there are project programmes for panel buildings that allow the residential community to apply for funding to cover up to 50% of the refurbishment costs. However, this does not guarantee a reduction in CO_2 emissions below the required 20 kg/m^{2}a, as this is heavily influenced by the heating mode and energy source. The district heating company must fully or at least partially transition from natural gas to renewable energy sources (e.g., geothermal).

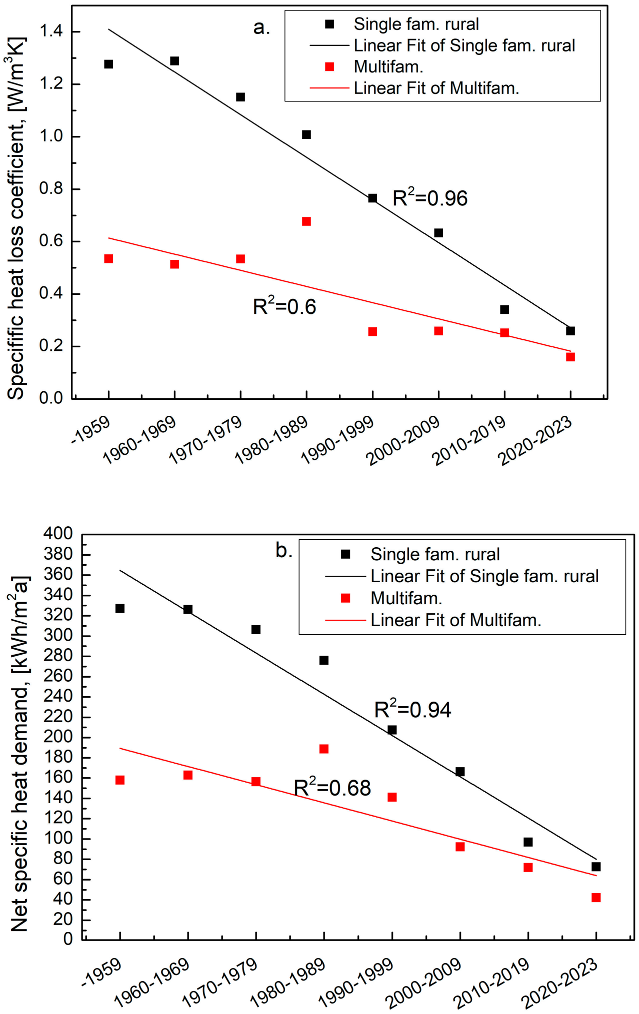


Figure 17. Trends of specific heat loss coefficient (**a**) and net specific heat demand (**b**) of the analysed rural single-family and urban masonry-structured multifamily buildings (R^2—adjusted R-squared).

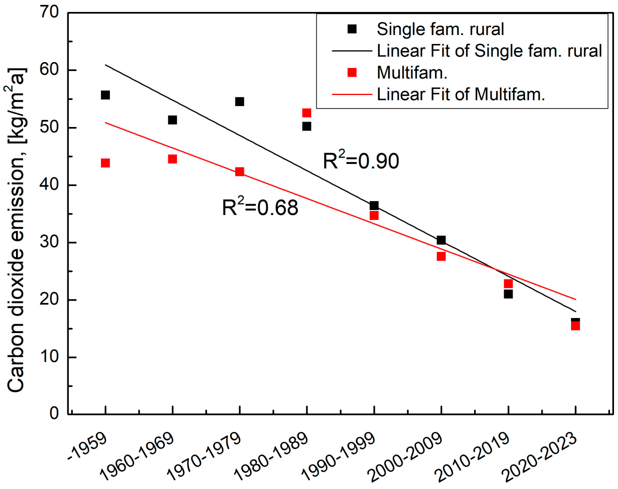


Figure 18. Trends of specific CO_2 emissions of the analysed rural single-family and masonry-structured multifamily buildings (R^2—adjusted R-squared).

4.7. Good Examples of Refurbishments

Between the analysed 605 houses and flats, good examples could be identified and selected which can serve as the model for other buildings.

4.7.1. Single-Family Houses

In the case of single-family houses, the same model can be followed by either urban or rural houses; the only difference is the heat carrier: wood and biomass cannot be recommended in cities.

Wall structures need 15−20 cm of insulation, while slabs under the attic or flat roofs need at least 30 cm of insulation. The floor laid on the floor or the slab above the cellar should have, at minimum, a 10 cm insulation layer. Windows and doors should have an overall heat transfer coefficient lower than 1.1 W/m^2K. With these thermal characteristics of the envelope, the specific heat loss coefficient will be 0.2 ± 0.04 W/m^3K. Having thermostat-controlled central heating with radiators, a buffer tank and wood as the heat carrier, the specific CO_2 emission will be 9.8−10.6 kg/m^2a. By installing a central heating system with an air–water thermal pump as the heat source, the specific CO_2 emission will be 10 ± 0.4 kg/m^2a. By installing a 5.1 kW_p photovoltaic system with the optimal orientation and inclination angle, the specific CO_2 emission can be reduced to 4.0 ± 0.5 kg/m^2a. If the photovoltaic system has a peak output of 15 kW_p, then the specific CO_2 emission will be negative: −11.8 kg/m^2a. It can be observed that in these refurbished model buildings, natural gas is not used at all.

4.7.2. Masonry-Structured Multifamily Buildings

The building taken as an example has five floors and 48 apartments (Figure A1). The walls are constructed from B30 masonry blocks without insulation prior to thermal refurbishment. The flat roof has a thickness of 20 cm of reinforced concrete and 15 cm of perlite concrete (average thickness). The slab above the cellar consists of reinforced concrete without any insulation. The net floor area of the building is 2486.1 m^2, and the A/V parameter is 0.52. The specific heat demand was found to be 0.871 W/m^3K, while the net specific heat demand was 251.67 kWh/m^2a. Gas convectors are utilised for heating, and hot water is provided by gas instantaneous water heaters. The specific carbon dioxide emission was found to be 58.8 kg/m^2a. After the initial step of energy refurbishment, the external walls received an additional 12 cm of EPS thermal insulation, while the flat roof was enhanced with an additional 15 cm of EPS insulation. Meanwhile, the slab above the cellar was equipped with an additional 10 cm of EPS thermal insulation. The specific heat demand decreased to 0.189 W/m^3K, and the net specific heat demand was 34.11 kWh/m^2a. Heating was supplied through a central heating system with a buffer tank, maintaining supply and return temperatures of 55 °C and 45 °C, respectively. The heat was centrally controlled, depending on the outdoor temperature. An air–water heat pump was utilised as the heat source (installed on the flat roof), and hot water was prepared indirectly through a storage tank. Following these interventions, the specific carbon dioxide emission was reduced to 10.82 kg/m^2a. In the second step of refurbishments, solar energy integration took place. The flat roof area measures 702.1 m^2. A 47.3 kWp photovoltaic system was installed on the roof (the output of a photovoltaic panel is 430 W, the distance between the panel rows is 1.71 m, the area required by a 1 kW system is 8.78 m^2, the inclination angle is 20 degrees, and the panels are oriented toward the south). A 100 kWh storage package was installed in accordance with new regulations, with a total area requirement of 450 m^2 for the system. Additionally, a 10 m^2 solar collector system was mounted on the roof, oriented towards the south, with a 40-degree inclination angle. With these two systems, the specific CO_2 emission was reduced to 2.59 kg/m^2a. It can be concluded that zero emissions (resulting from the heat demand for heating and hot water preparation) could have been achieved if the external building structures had received thicker thermal insulation layers during the first phase of the renovation (external walls at least 15 cm, flat roof 30 cm).

4.7.3. Panel Buildings

From an energy perspective, the main difference between the panel building and the masonry-structured multifamily building is that the panel building is connected to the district heating system. There are local regulations that recommend or allow district heating in downtowns only. Homeowners have few possibilities to change the heat source or integrate renewable energy sources. These essential decarbonisation steps must be carried out by the district heating company. However, rising energy prices have placed district heating companies in a challenging position. The heat losses from the pipe network reduce the system's efficiency. Furthermore, substantial electricity is consumed by the circulation pumps and control motor valves in the heat centres. This energy consumption is related to the district heating system rather than the building, but through the primary energy, it significantly influences the energy performance and CO_2 emissions of the building.

The building taken as an example has eleven floors, 88 apartments and an advantageous A/V parameter of 0.302 (Figure A2). The net heated area is 5579.37 m^2. Before thermal refurbishment, the layers of sandwich panels were as follows: 15 cm reinforced concrete, 5 cm EPS and 7 cm reinforced concrete. The flat roof had 20 cm of reinforced concrete and 15 cm (average thickness) of perlite concrete. The slab above the cellar was 20 cm uninsulated reinforced concrete with additional covering layers. The heating system was a one-pipe-with-bypass central heating system with control of the supplied heat in the heat centre depending on the outdoor temperature. The radiators were fitted with thermostatic valves. The supply temperature was 90 °C, and the return temperature was 70 °C. The heat was produced in gas boilers and provided by the district heating system, with a primary energy transformation factor of 1.26. The hot water was produced indirectly in storage tanks. The specific heat loss coefficient was 0.509 W/m^3K, and the net specific heat demand was 160.6 kWh/m^2a. The specific carbon dioxide emission was 44.9 kg/m^2a. By adding 12 cm EPS to the external walls, 20 cm to the flat roof and 12 cm to the slab above the cellar, the specific heat loss coefficient was reduced to 0.102 W/m^3K, and the specific net heat demand fell to 25.78 kWh/m^2a. A 4 kWp photovoltaic system oriented to the south, with an inclination angle of 20°, was installed on the roof to cover the auxiliary electricity demand of the heating and hot water system (8 kWh accumulators are also necessary). Assuming that the heat source is a biomass-based power plant, the primary energy transformation factor can be reduced to 0.5394. This factor currently cannot be reduced to zero, because of the auxiliary energy consumption. The supply and return temperatures are 75 °C and 55 °C, respectively. Consequently, the specific carbon dioxide emission will be reduced to 22.99 kg/m^2a.

It can be concluded that for panel buildings connected to the district heating system, the CO_2 emissions have a lower limit, which cannot be reduced further using the current technologies. This limitation arises from the efficiency of the district heating system (heat losses, auxiliary energy use), heat source and heat production.

Nevertheless, new technologies could aid in the mitigation of energy use and CO_2 emissions. Currently, these technologies are not widely used because of the higher investment costs. The energy use and CO_2 emission can be reduced further in all residential buildings using special insulation materials [45]. However, in this case, the changing of the physical parameters has to be taken into account [46]. Currently, in residential buildings, fresh air is provided widely through natural ventilation. The ventilation heat demand can be reduced using special personalised ventilation systems with heat recovery [47].

5. Conclusions

- In this study, based on the energy assessment of 605 single-family houses and flats in multifamily buildings, a heat demand and CO_2 emission survey in urban and rural residential buildings in Hajdú-Bihar County (Hungary) was conducted. Analysing the obtained results statistically, the following conclusions can be drawn:
- In both rural and urban regions, the compactness of single-family houses has improved in recent decades (with a more pronounced decrease in urban regions), and the net floor area of the buildings is increasing in both urban and rural areas (though the increase is more notable in urban regions). Hence, the trends of the A/V parameter and net heated area are similar in urban and rural single-family houses; however, the A/V parameter is significantly higher in rural houses, while the net heated area is significantly greater in urban houses.
- Between 1930 and 2023, the specific heat loss coefficient was reduced by 6.7 times in urban buildings and by 4.9 times in rural buildings. For the net specific heat demand, a reduction of 5.4 for urban houses and 4.5 for rural houses is observed, respectively. The specific heat loss coefficient and net specific heat demand exhibit similar trends in both urban and rural single-family houses. However, these parameters are significantly higher in rural buildings.
- The specific CO_2 emissions show a reduction of 5.3 times in urban houses and 3.5 times in rural houses. At a $p = 0.05$ level, no significant differences can be observed between urban and rural single-family houses.
- It can be stated that urban buildings have significantly better thermal properties, though the differences in CO_2 emissions are not significant. The reason for this lies in the heat carriers used. In old rural buildings, biomass and wood are predominantly used, while natural gas is used in old urban buildings. In new buildings, there are no significant differences between the heat sources; however, wood and biomass are still utilised in rural houses, while rarely utilised in urban houses. Heat pumps are widely used in both regions.
- Comparing masonry-structured multifamily buildings with urban and rural single-family houses, similar results were obtained. The specific heat loss coefficient, the net specific heat demand and the specific CO_2 emissions are higher in single-family houses than in multifamily houses. In multifamily houses, the specific heat loss coefficient was reduced by 3.5 times, the net specific heat demand by 3.7 times and the CO_2 emissions by 2.8 times, respectively. The differences between urban single-family houses and masonry-built multifamily buildings are significant only in the case of specific heat losses, while the differences between rural single-family houses and masonry-structured multifamily buildings are significant for both specific heat losses and the net specific heat demand.
- Panel buildings constructed between 1970 and 1989 show the best thermal and energy performance. Due to the high investment costs and the inability to change the heat source, these buildings now exhibit poor thermal performance.
- Single-family houses in both rural and urban regions can be effectively transformed into positive energy houses by utilising heat pumps and properly designed photovoltaic systems with appropriately chosen accumulators.
- In the case of masonry-structured multifamily buildings, zero CO_2 emissions (from heating and hot water preparation) can be achieved by using air–water heat pumps, photovoltaic systems with accumulators and solar collectors.
- For panel buildings connected to the district heating system, the CO_2 emissions have a lower limit that cannot be reduced further by using the current technologies. This is

due to the efficiency of the district heating system (including heat losses and auxiliary energy use), heat sources and heat production.

6. Future Work

The further reduction in CO_2 emissions in panel buildings is extremely important. New, energy-efficient solutions for heat supply must be found for these buildings.

7. Limitations

In this study, 605 buildings and flats were assessed from an energy point of view. By increasing the number of assessments, more accurate results would be obtained.

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Nomenclature

A/V	ratio of the building envelope area A, [m^2] and heated volume V, [m^3];
p	level of significance;
R^2	adjusted R-squared value (goodness-of-fit measure);
SD	standard deviation (average amount of variability in the dataset);
GHG	greenhouse gases;
EPS	expanded polystyrene;
B30,HB38, PTH	bricks with vertical hole types.

Appendix A

Figure A1. Masonry-structured multifamily building.

Figure A2. Panel building.

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