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Decarbonization Potential of Energy Used in Detached Houses—Case Study

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Abstract: The main objectives of this study were the energy assessment of detached houses built in different periods in a central European city. A total of 236 detached houses built between 1930 and 2023 in Debrecen (Hungary) were analyzed from an energy perspective, and their CO_2 emissions were measured. It was found that the net floor area of family houses built in recent years has increased but that the compactness of buildings has increased as well. The specific heat loss coefficient and the specific energy demand for heating in new buildings have decreased to 15.2% and 18.5%, respectively, over the last 90 years. Furthermore, around one third of the analyzed buildings built several decades ago must have already been renovated at least once for energy efficiency, as their heat demands are 27.6–41.4% lower than estimated. Energy consumption in six houses built in recent years was measured and studied. It was found that the occupants' behavior may increase CO_2 emissions from heating by 26%, while CO_2 emissions from hot-water preparation may decrease by 38.2%. The potential of the locally available sources of renewable energy was calculated, and the costs of decarbonization packages for eight building groups were evaluated.

Keywords: decarbonization; detached houses; renovation; behavior; renewable energy sources

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1. Introduction

Efforts aimed at reducing the energy consumption of buildings have been ongoing for several decades in the countries of the European Union. The concept of nearly-zero-energy buildings (NZEBs) appears in the text of the 2010 energy directive [1]. Several researchers have attempted to define the concept of NZEBs. The energy flows and the use of primary energy factors that should be taken into account were clarified [2]; calculation examples were presented [3]; the differences between national regulations were elucidated [4]; and the energy-performance values for new, existing, residential, and non-residential buildings in the member states of the European Union were discussed [5]. Paleotti [6] and D'Agostino [7] concluded that different European countries interpret the concept of NZEB differently, so the NZEB requirements also differ. At the same time, it can be stated that thanks to the NZEB requirements, new buildings have a significantly lower energy demand than buildings built in the 2000s or before 2000 [5]. It is not only the countries of the European Union that strive to minimize the energy demand of buildings. Liu et al. [8] described how the concept of nearly-zero-energy buildings is interpreted in China, as well as the regulations currently in force. In another study [9], the same author presents the building-engineering systems and technologies that are widely used in NZEB buildings in China. Achievements in and barriers to energy-conservation policy in China was presented by Han et al. [10]. Cao et al. proposed practical, integrated, cost-effective solutions for residential buildings that meet the energy-use-intensity quota [11]. Machine learning models were proposed as part of a hybrid approach to quickly predict buildings' heating- and cooling-related energy consumption at the building stock level [12].

At the same time, NZEB buildings are not a definitive solution for minimizing energy consumption in buildings. Cao et al. [13] made a comparison focusing on the energy savings achieved by the construction of zero-energy buildings in the EU, China, and the USA. Furthermore, Magrini et al. [14] published a study regarding buildings characterized by higher energy production than energy consumption, an arrangement that allows the energy surplus to be sold into the energy system. The concept of decarbonized buildings appeared only a few years ago, and in this interpretation, the main goal is to minimize carbon-dioxide emissions during the entire life cycle of the building [15,16]. Through the use of high-performance thermal-insulation materials, the energy demand for heating and cooling of buildings can be reduced substantially. However, the degradation of the physical properties of these materials over time should be taken into account. In the case of aerogel blankets, the thermal conductivity depends on water absorption [17], temperature and external load [18], relative humidity of the air [19], and freeze-thaw cycles [20]. In the case of vacuum-insulation panels, special attention should be paid to the thermal-bridge effect [21].

Low-temperature surface heating and high-temperature surface cooling are preferred in NZEB buildings. Radiant heating systems can maintain a lower room air temperature than conventional all-air systems while achieving the equivalent thermal comfort [22] and should be considered for cost-optimal design of nearly-zero-energy buildings [23]. Renewable energy sources can be efficiently integrated [24] and appropriate thermal comfort provided [25]. In the case of embedded systems, the heat-storage capacity of the building structure can be used to increase the energy performance of the heating or cooling system [26]. Through use of the "screening index", the most appropriate heating schemes can be selected [27].

Special attention has to be given to the exergy used in buildings. Along with the energy quantity, the energy quality may influence carbon dioxide emissions. In their study, Rhee et al. [28] highlighted that one of the most important advantages of low-temperature radiant heating over "traditional" convection (radiator, fan-coil) heating is the provision of better thermal comfort. Absorption cooling systems and heat pumps can be appropriate technologies to reduce the carbon dioxide emissions caused by cooling processes [29,30].

Energy savings may be obtained by using personalized ventilation systems [31]. The local ventilation effectiveness and the energy performance of ventilation systems can be improved by using special air terminal devices [32,33]. The energy used for ventilation can be substantially decreased by integrating the indirect evaporative cooling in the air-handling units [34]. Finally, minimization of building energy consumption can be obtained by smart control of energy production, distribution, and utilization, depending on the ever-changing energy demand [35]. Nearly all materials and technologies needed to achieve the decarbonization goals are available. Heat pumps can be the main heat source used in residential buildings for heating and cooling. Additionally, photovoltaic systems and solar collectors ought to be integrated into energy systems so the solar energy potential can be used for electricity production and hot-water preparation. In new buildings, electricity may become the main energy source, soon replacing natural gas and wood. Nevertheless, it should be taken into account that the specific carbon dioxide emissions related to electricity are higher than those related to natural gas or wood. Therefore, the decarbonization of electricity production is one of the most important tasks.

The main purpose of the research carried out is to assess the energy consumption of detached houses in a Central European city (Debrecen, Hungary) to evaluate the decarbonization potential of the heat consumed in detached houses and to find good real-world examples that can encourage homeowners to reduce the utilization of fossil fuels in their homes. Furthermore, using the data on the measured energy consumption of some existing new buildings, we found that it is necessary to present possible decarbonization solutions for existing buildings. Along with the technical solutions, the costs of recommended interventions ought to be determined and provided.

The presented results can be useful in other countries as well, offering solutions to municipalities and stakeholders to reduce carbon dioxide emissions associated with energy use in the building sector.

2. Residential Buildings in Central and East European Countries

From an energetic point of view, the building stock in European countries is extremely diverse. Besides the thermophysical properties of the external building elements, the ratio of the envelope area (A) to the heated volume (V) is extremely important, expressing the compactness of the building. The lower the A/V ratio, the better the building is from an energy point of view. Single-family detached houses are characterized by high A/V ratios, while blocks of flats are characterized by low A/V ratios. According to Berndgen-Kaiser et al., in the UK, the share of single-family houses (detached and semi-detached) is 86%, while in Belgium, Netherlands, and France, it is 79%, 77%, and 67% respectively [36]. In Germany, single-family houses make up the lowest share: only 45%. The share of single-family houses in Serbia is 73%, while in Hungary it is 62%; in Bulgaria, 56%; and in the Czech Republic, 45% [37]. The remaining dwellings are located in multi-family houses (flats). The highest percentage of flats can be found in Germany and the Czech Republic (55%), while the lowest share of flats is found in the UK, Belgium and the Netherlands. The share of detached and semi-detached single-family houses in EU27+UK is 58% [36]. In Central-East European countries (Bulgaria, Czech Republic, Hungary, Poland, Romania, Serbia, and Slovakia) the residential building stock shows some similar features. In villages and towns, the oldest buildings have the smallest floor area and 40–50 cm-thick external walls are mainly made of adobe (thermal conductivity around 0.5–0.9 W/mK). In larger cities, the oldest buildings are mainly built of burnt clay bricks (thermal conductivity around 0.7–0.8 W/mK) and the outer walls are 40–60 cm thick. These buildings may have one or several flats. A smaller number of stone buildings (thermal conductivity greater than 1.0 W/mK) can be found in villages as well as in cities. After the Second World War, in addition to fired clay, concrete was used for various masonry elements, and then buildings built with industrialized technology became widespread. The prefabricated panels contained a polystyrene layer of 6–8 cm. These blocks of flats may have hundreds of apartments.

Besides sandwich panels, brick with vertical holes was used mainly for detached houses and blocks of flats with a maximum of four floors. From an energy point of view, these bricks have become better and better, so their thermal conductivity decreased from the initial 0.64 W/mK to 0.20 W/mK in the 1990s and has reached 0.1 W/mK today. Thermal-insulation layers (mainly polystyrene foam, but also including rock wool and glass wool) have been used for buildings built from bricks only in recent decades.

Other important information is related to the ownership of the buildings. The share of homeowners in Serbia is 99%, while in Bulgaria and Hungary it is 96%; in the Czech Republic, 91%; in Belgium, 72%; in the UK, 68%; in the Netherlands, 67%; in France, 63%; and in Germany, 53% [36,37]. Ownership is important because energy-related refurbishments (additional insulations, new windows, new heat source) are usually expensive and have to be carried out by the homeowners. It should be mentioned here that the ambitious European goal is to move from NZEB to zero-emissions buildings by 2030. Furthermore, it is planned to phase out fossil fuels in heating and cooling by 2040 at the latest [38].

The building stock in a country or city is extremely diverse. In Hungary, there are about 4.5 million households, out of which about 2.7 million are detached houses. Around 20,000 new flats are built yearly (0.04% renewal rate). To meet the decarbonization goals, besides providing highly efficient energy concepts for use in new buildings, scholars have to pay attention to existing buildings as well. Existing buildings were built in different periods with different materials and technologies and met different thermal-performance requirements, according to the regulations in force in the year of construction. Thus, buildings are quite different from the energy point of view; therefore, reliable and cost-effective intervention packages aimed at reducing carbon dioxide emissions must be properly identified and developed to achieve the decarbonization goals.

3. Methods

As a first step, thermal-performance requirements for buildings over the years in Hungary were analyzed. The thermal characteristics of the structures of residential buildings' envelopes were thoroughly analyzed. In the case of the city of Debrecen (Hungary), data related to the residential building stock were gathered from the central statistical office. Detached houses were studied in detail (construction materials, year of construction, energy sources). Because heating represents more than half of the total energy consumption of a residential building, parameters that greatly influence heating-related energy consumption were analyzed in detail. In this way, using the database of the Hungarian Meteorological Service and data provided by the Meteorological Observatory, University of Debrecen, the external temperatures over the past 90 years were examined and the solar radiation over the past five years was examined. A total of 236 detached houses built in the last 90 years in Debrecen were assessed and examined and their energy analysis was conducted according to the energy-performance decree in force. The energy demand for heating and the CO_2 emissions were determined. 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 for the analysis of the data gathered in this study. After the examined 236 buildings had been grouped into eight categories by year of construction (at least 20 buildings in each category), a building model was created for each category (eight different building models). Taking into account the determined average net floor area and assuming that the thermal requirements of the envelope were valid in the year of construction, the heat demand of modelled buildings was calculated and compared with the real values obtained from energy assessments. Measured energy consumption data for single-family houses (electricity and gas consumption) were used to elucidate the effect of occupant behavior on the energy used and to provide refurbishment packages and good examples of decarbonization possibilities for single-family houses. The costs of decarbonization packages were determined, taking into account the market prices of materials and construction. The flowchart presented in Figure 1 shows the method used and research steps performed.

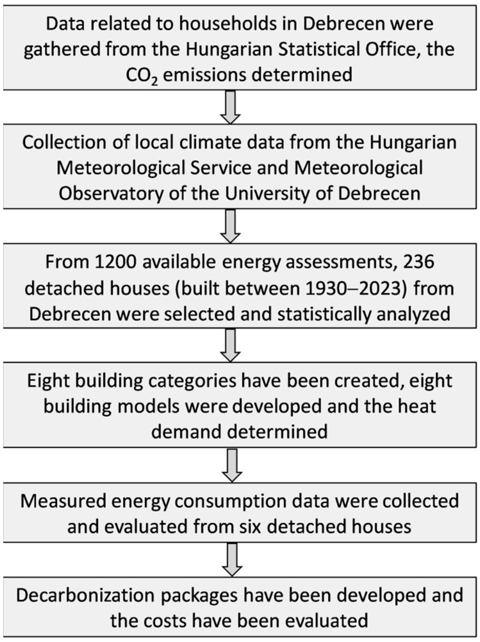

Figure 1. Flowchart of the research performed.

4. Energy-Performance Requirements for Buildings in Hungary

The energy performance of buildings can be illustrated through the "evolution" of the requirements related to the external walls. In 1934, regulations stated that the overall heat-transfer coefficient of the external walls should not exceed 1.68 W/m^{2}K [39]. In 1965, requirements were established regarding the overall heat-transfer coefficient of the external walls depending on the specific mass. The overall heat-transfer coefficients in the regulations varied between 1.4 W/m^{2}K (light structures) and 1.64 W/m^{2}K (heavy structures). In 1979, the requirement was set to 0.85 W/m^{2}K, and then in 1985, it was set to 0.7 W/m^{2}K. In 2006, the requirement regarding the overall heat-transfer coefficient was reduced to 0.45 W/m^{2}K, and later, in 2015, the requirement was reduced further to 0.24 W/m^{2}K. This is the current requirement as well (NZEB). So, the ratio between the highest and lowest values of the overall heat-transfer coefficient in regulations from the past 90 years is 7.0.

Nevertheless, it is of the utmost importance that in 1992, a requirement related to the specific heat loss coefficient of the building was introduced. The requirement was established in function of the A/V ratio of the building (0.6 + 0.1·A/V). As can be observed, this value is around 0.7 for a single-family house characterized by A/V = 1.0. In 2006, this requirement was tightened, and the new requirement was set to (0.086 + 0.38·A/V), with a maximum value of 0.58 W/m^{3}K. If the A/V ratio were 1.0, the requirement would be 0.466. Currently, for NZEB buildings, this requirement is (0.071 + 0.23·A/V), which means the value is 0.301 W/m^{3}K for a building with A/V = 1.0. So, the ratio between the highest and lowest values from the last 30 years of regulations for the specific heat loss coefficient of a building with A/V = 1.0 is 2.325. Specific primary energy use has been limited for NZEBs since the 1st of November 2023 to 76 kWh/m^{2}a. As a new requirement, specific CO_2 emissions were introduced (20 kg/m^{2}a). Taking into consideration the extremes of the heating-energy needs for buildings constructed in different periods, it should be stated first that the capacity to build technical systems based on RES that can be installed economically is not unlimited. So, first and foremost, the energy demand of buildings has to be minimized; thereafter, RES ought to be used to cover the energy need.

5. Features of Local Climate in Debrecen

Debrecen, with its 201,582 inhabitants (2022), is Hungary's second largest city. Having a Central European location, its climate is humid continental (Köppen Dfb). Debrecen is one of the cities with the largest forests in Europe; 34% of its territory, more than 15,000 ha, is forest.

When the energy consumption of a building is analyzed, the outdoor temperatures are an essential factor. According to different sources, heating represents the greatest percentage of the total energy consumption of a building [40]. The daily outdoor temperatures are available for Debrecen from 1901 to 2020 [41]. Taking into account the thermal-storage capacity of buildings, the daily mean temperatures were adequate for energy-performance analysis. However, this statement is no longer true in the case of well-insulated, smart buildings with intelligent control of energy systems. In these cases, hourly analysis gives better results. As for external design temperatures, currently, three climatic regions are recognized in Hungary and must be considered: -11 °C (south-western region); -13 °C; and -15 °C (north-eastern region). Debrecen belongs to the coldest region, the Nord-East, with external temperatures of -15 °C. To understand about the variation in external temperatures in the heating season, three different thirty-year-long periods (from 1 September to 30 April) were analyzed: 1931–1960, 1961–1990, and 1991–2020. The minimum mean temperature values for each day are presented in Figure 2.

The fit curves were determined using polynomial fit grade 4. As can be observed, there are differences between the daily mean values of the analyzed periods. From the significance analysis at a 0.05 significance level, it was found that there are significant differences among all analyzed periods. The minimum values of the external temperatures shown by the fit curves are -14.00 °C (1930–1960), -12.96 °C (1960–1990), and -11.14 °C

(1990–2020). The increase in external temperatures in recent decades has led to lower energy use for heating. This fact has importance in at least three aspects. Most building refurbishments are supported by the municipality, the state, or the European Union. The expected energy savings after refurbishments and the reduction in CO_2 emissions should be calculated and provided in the application. Misleading results can be obtained if the energy-performance analysis of a building is based on the outdoor temperatures recorded 40–50 years ago. Another problem is the question of the external design temperature. If the heat demand of a building is calculated based on the external design temperature established almost one hundred years ago, all elements of the heating system will be over-dimensioned. In the last 30 years, the currently valid external design temperature has occurred once.

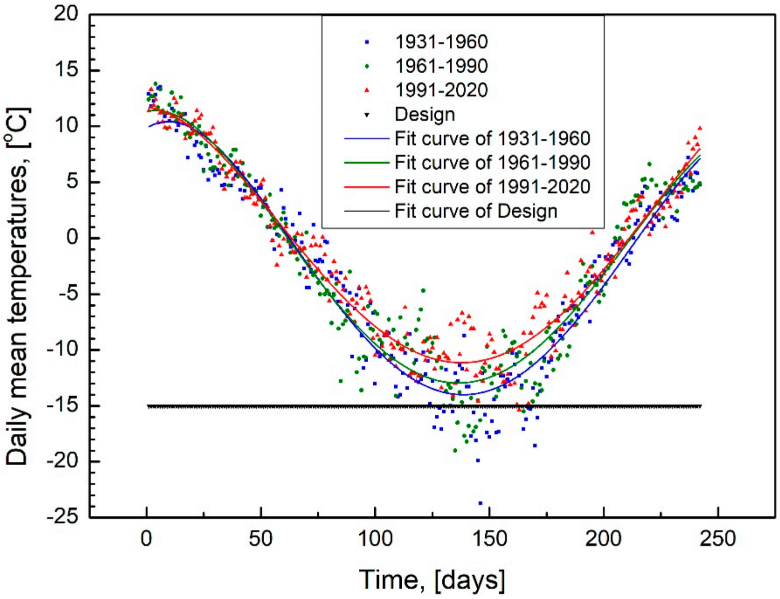

Figure 2. Minimum values of the daily mean temperatures. (1 September–30 April).

The last aspect is related to the SCOP calculation of air–water heat pumps. Better results are obtained if the updated variations in outdoor temperature are taken into account.

The presentation used in Figure 2 is appropriate for choosing the external design temperatures but can be misleading for energy calculations (the daily minimal temperatures are presented). In Figure 3, the degree–day curve is presented for the last 30 years (1990–2020).

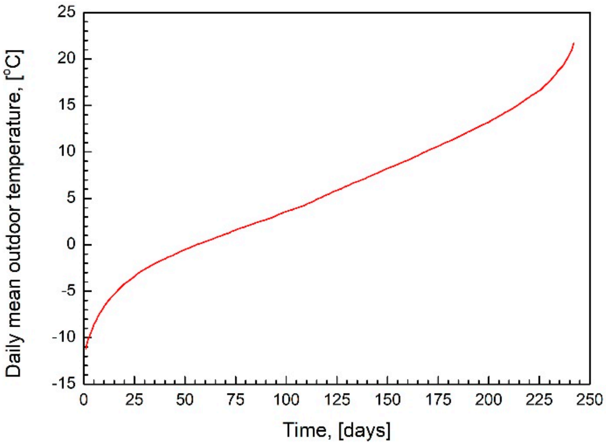

Figure 3. Degree–day curve for Debrecen, Hungary (1990–2020).

In Hungary, until 1990, the district heating systems started heat delivery to consumers when the daily mean outdoor temperature for three subsequent days was lower than 12 °C (practically, this temperature was considered the balance point temperature). Most detached houses were characterized by a higher balance point temperature. Thus, the heating season was about six months in the case of blocks of flats connected to the district heating systems, while for detached houses, the heating season lasted more than half the year.

Nowadays, the balance point temperature of NZEB buildings is about 8 °C, so the heating season is shorter (about five months). Furthermore, it can be observed that about 60 days have mean temperatures lower than 0 °C. This is important information because air–water heat pumps are widely used and because their coefficient performance (COP) depends on the external temperature.

The daily mean solar-energy yield on vertical surfaces (Figure 4) was calculated using the hourly global solar-radiation data provided by Meteorological Observatory, University Debrecen (Hungary) [42]. If the hourly solar-radiation data are not available for a certain location, these can be determined based on the monthly mean global-irradiation data [43].

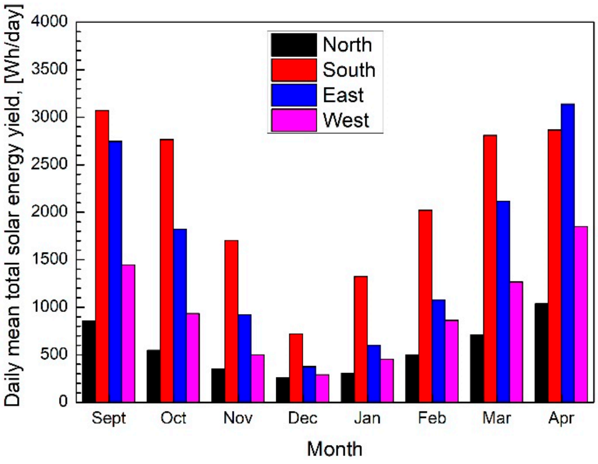

Figure 4. Daily mean solar-radiation yield in Debrecen (heating season).

6. Residential Building Stock in Debrecen

In terms of energy consumption, the year of construction of the building is decisive, as the thermal requirements and the available building materials and technologies have changed significantly over the years. A total of 11.1% of the housing stock was built before 1960, while 37.8% was built between 1961–1980, 31% between 1981–2000, 12.7% between 2001–2010, and 7.4% after 2010. Table 1 contains the main construction data for the housing stock in Debrecen.

Table 1. Housing stock in Debrecen by construction mode.

External Walls	Ratio, [%]
Brick, stone masonry	61.5
Prefabricated panels	25.7
Concrete and medium and large masonry elements	7.0
Adobe	3.1
Other	2.7

A total of 8.9% of inhabited apartments have one room, while 33.1% have two rooms, 30.7% have three rooms, and 27.3% have four or more rooms. Further, 31.6% of the apartments are equipped with district heating, 59.4% are heated with gas, 7.4% are heated with electricity, 12.9% are heated with wood, and 0.9% are heated by other fuels. General data on the number of flats and energy consumption (2018–2022) can be found in Table 2.

Table 2. Number of households and gas and electricity consumption of households.

Year	No. of Households	No. of Electricity Consumers	Electricity Consumption of Households, [MWh]	No. of Gas Consumers	No. of Gas Consumers for Heating	Gas Consumption, [1000 m^3]
2018	96,654	114,912	220,006	69,180	58,045	70,492.2
2019	97,012	114,893	216,757	69,501	58,379	68,168.8
2020	98,493	115,626	213,078	69,794	58,785	69,110.1
2021	98,940	116,249	224,061	70,553	59,611	77,478.1
2022	100,040	116,931	216,012	69,491	69,490	71,992.5

Taking into account the specific CO_2 emissions of district heating (374 g/kWh), natural gas (297 g/kWh), and electricity (455 g/kWh), the total CO_2 emissions of Debrecen's households in 2022 were 395,824.3 tons (~4 tons/household).

7. Energy Assessment of Detached Houses

7.1. Energy Performance Calculations

Energy-performance analysis was carried out according to the energy regulations in force for buildings for 236 single-family houses built between 1930 and 2023. 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. These buildings were classified into eight groups (at least 20 buildings in each group). Besides the primary energy consumption, the specific heat loss coefficient, the net specific heat demand, the A/V ratio, the net floor area, and the CO_2 emissions were determined. The results are presented in Figures 5–7.

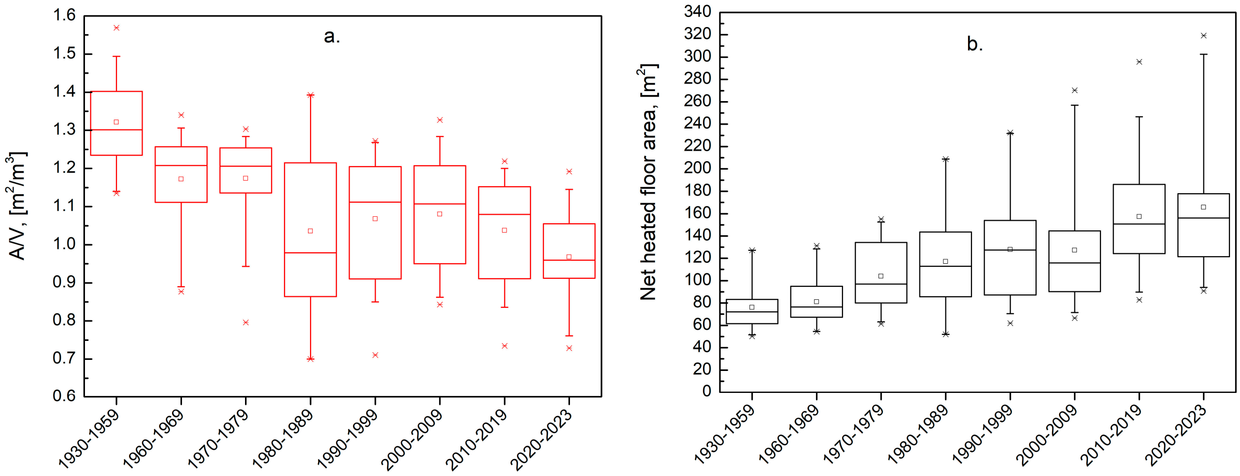

Figure 5. A/V ratio (**a**) and net heated floor area (**b**) by year of construction.

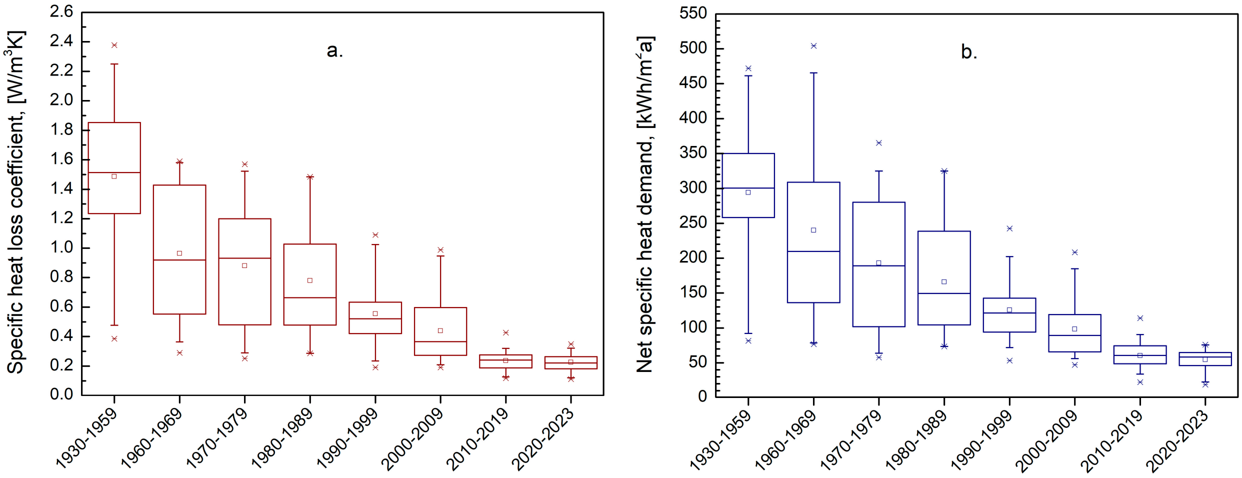

Figure 6. Specific heat loss coefficient (**a**) and net specific heat demand (**b**) by year of construction.

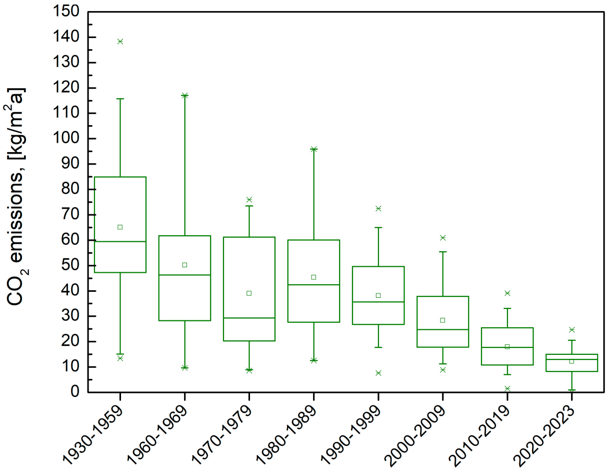

Figure 7. Specific CO_2 emissions by year of construction.

Examining the thermal characteristics of the assessed family houses, the following lessons can be learned:

- in recent decades, architects have paid attention to the energy performance of the buildings they are designing even from the conception phase, since the A/V ratio is decreasing;
- the comfort needs of homeowners are increasing, since the net floor area of the buildings is increasing;
- even though buildings are larger and larger, the specific heat loss coefficient and the energy needed for heating is decreasing, so the buildings are well insulated;
- properly refurbished buildings have similar specific energy needs for heating.

Taking into consideration the average CO_2 emissions and the number of houses in a category, the yearly total CO_2 emissions of detached houses in Debrecen can be estimated at 289,746 tons.

The real heat demand values of the examined buildings are lower than the theoretical values that would be obtained in the case in which the thermal properties of external building elements only meet the requirements valid in the year of construction (Figure 8), which means that some of the investigated buildings have been thermally refurbished at least once (especially for the 1960–1969 and 1970–1979 categories) or that new buildings had better thermal characteristics than required (especially after 2010).

Figure 8. Heat demand of the investigated buildings.

The NZEB requirements in Hungary were published in 2015. They were planned to be compulsory from 1 January 2021, but the introduction of the requirements was eventually postponed. These requirements were mandatory only in the case of refurbishments supported partially by the state. However, it can be seen that buildings built in the 2010–2019 period already fulfill the NZEB requirements. Nevertheless, the CO_2 emissions of these buildings are higher than the CO_2 emission of buildings built between 2020–2023. The explanation is that in most buildings built in 2020–2023, renewable energy sources are integrated.

7.2. Effects of Occupants' Behavior on Energy Consumption for Heating

Measured data on energy consumption were collected from five similar two-story buildings built in the years 2014–2020 (Figure A1). For each building, the net floor area is 128 m^2; the external walls are made of 30 cm brick with vertical holes and 15 cm EPS polystyrene; the slab under the attic is insulated with 30 cm rock wool; and the floor laid on the ground contains 10 cm EPS polystyrene. In these single-family houses, the number of occupants is five (two adults and three children). Natural ventilation is used to provide fresh air for occupants. A condensing boiler prepares the heat necessary for heating (floor heating) and DHW (domestic hot water) preparation. In the construction period of the analyzed buildings, the requirement related to primary energy use was 100 kWh/m^2a (this includes heating, ventilation, air conditioning, and hot-water preparation).

The energy used from 1 March 2022 to 28 February 2023 is shown in Table 3.

Table 3. Measured yearly energy use in similar single-family detached houses.

Building	Declared Set Indoor Temperature in the Heating Period, [°C]	Gas Consumption, [kWh]	Electricity Consumption, [kWh]
b1	23	7215.55	3060
b2	26	15,602.22	2679
b3	23	9123.33	3294
b4	24	10,105.55	3363
b5	25	11,899.99	2109

In each house, LED lamps are used for lighting, and similar split air conditioners are installed for cooling. For cooking and baking, only gas is used in building b2 and only electricity is used in buildings b1, b4, and b5. In building b3, gas is used for cooking and electricity is used for baking. The air conditioning system generally operates for only a few days a year (6–10 days) for several hours (3–5 h/day). The electricity consumption for cooling was about 384 ± 96 kWh/a. In building b5, the air conditioners were not switched on at all. Moreover, in building b5, the electric stove is usually switched on only for a short time in a day. From an analysis of the measured electricity consumption, it can be stated that about 1500 ± 150 kWh/year of electricity is used for lighting, TVs, PCs, chargers, washing, drying, security systems, etc. The energy used for cooking and baking is estimated to be 1200 ± 60 kWh/year.

These buildings do not use RES at all, and the average CO_2 emission of the analyzed buildings is 4.5 ± 0.84 tons/a (35.3 ± 6.6 kg/m^2a).

In the energy-performance calculations, a 20 °C indoor setpoint temperature had to be taken into account during the heating period. As can be seen, the set point temperatures in the analyzed buildings are higher. If the indoor temperature were set to 20 °C in these buildings, then the average value of the energy used for heating would be 4845.3 kWh/a (37.9 kWh/m^2a). The average value of carbon dioxide emissions for analyzed buildings would be 3331.2 kg/a (26 kg/m^2a). Practically, in the analyzed buildings, 26% of the total CO_2 emissions are caused by the occupants' behavior (setting higher indoor temperatures than recommended).

In each analyzed building, there are two bathrooms. One is equipped with a bathtub and the other one with a shower. Assuming the design values of DHW consumption prescribed in standards, the calculated energy needed for hot-water preparation is 3120 kWh/year. Assuming that the hot-water consumption is similar in each building, an analysis of the monthly measured gas consumption of buildings shows that the energy used for DHW preparation is 160.55 kWh/month (1926.66 kWh/year; or 15 kWh/m^2a). It can be observed that due to occupants' behavior, the consumed energy for hot-water preparation is 38.2% lower than expected.

The last example is a single-family ground-floor detached house (b6) with a 326 m^2 net floor area that was built in 2016 (Figure A2). The number of occupants is five (two adults and three children). The external walls have a 20 cm-thick EPS insulation layer. This building uses RES for energy supply. Heating and DHW preparation depend on a geothermal heat pump. Electricity is used both for cooking and baking. The total yearly electricity used is 9450 kWh. A photovoltaic system is installed on the roof, and the yearly electricity production is 9280 kWh. The building is not connected to the national gas network but is connected to the national electricity grid, and electricity is billed based on the annual balance. Overall, this building, besides the electricity produced by its photovoltaic system, used 170 kWh/a electricity (0.52 kWh/m^2a), which means 77.35 kg/a CO_2 emissions (0.24 kg/m^2a). However, the indoor set point temperature during the heating season in this house is 26 °C. If a lower indoor temperature were set, this building would be a positive-energy building.

8. RES Potential for Detached Houses

Based on the b6 detached house example, it can be stated that the efficient integration of RES can be the best solution for the decarbonization of detached houses.

8.1. Solar Collectors

Using solar collectors, a portion of the heat used for DHW preparation can be saved. Assuming orientation to the south and an inclination angle of 35°, the heat produced in a year by solar collectors is 646.4 kWh/m^2. However, the monthly energy yield shows substantial differences. The average heat produced in a month with its standard deviation is 53.86 ± 29.83 kWh/month.

8.2. Air–Water Heat Pumps

The daily variation in the outdoor temperature (Figure 9) can be exploited to obtain a higher seasonal coefficient of performance of the air–water heat pumps. Usually, the heat pump is chosen to cover the heat demand at −15 °C. In the case of days with higher mean temperatures, the output of the heat pump exceeds the heat demand, so with a properly dimensioned buffer tank installed in the heating system, the daily energy needed for heating can be produced during the hours with higher temperatures (for example, temperatures >1.0 °C), obtaining in this way COP values greater than 3.0 (40 °C supply temperature for heating).

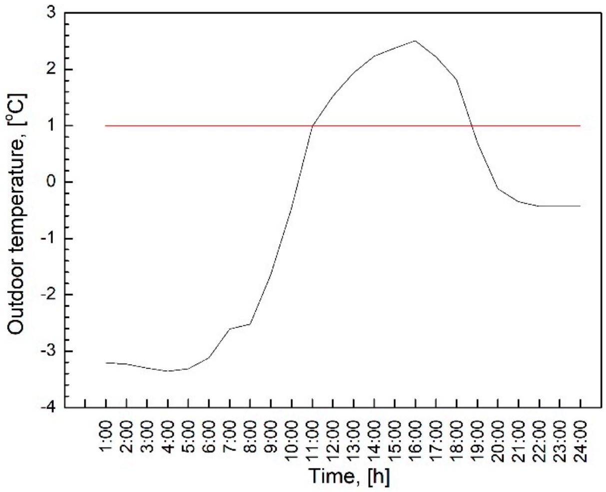

Figure 9. Daily variation in the outdoor dry-bulb air temperature (6 February 2010).

Obviously, in this case, low-temperature radiant heating systems are recommended. Radiant heating systems should not be installed on the external building elements because the increased heat losses of the heating system lead to lower energy performance of the heating process [42]. However, slabs between stories and internal walls can be used for heat storage, but the maximum allowable surface temperatures should be taken into account. Based on the variation in outdoor temperature presented in Figure 8 (daily mean temperature of −0.51 °C) the daily energy demands for heating of the single-family houses built in Debrecen between 1930–2023 were determined (Figure 10).

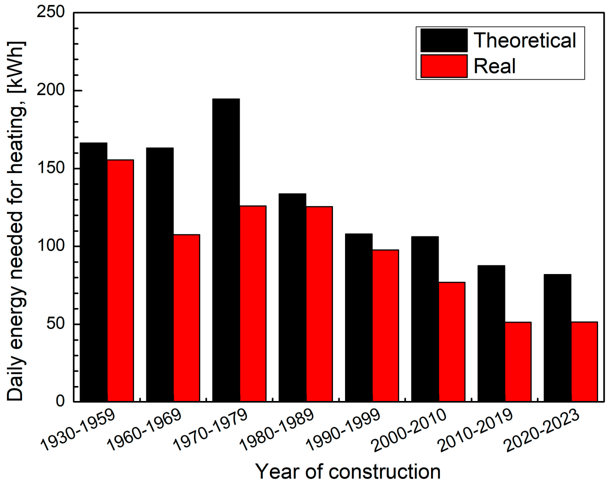

Figure 10. Daily energy needed for heating.

As can be observed, the daily heat demand is between 50–155 kWh for the analyzed buildings. These heat quantities can be stored in properly dimensioned buffer tanks (a 2 m^3 buffer tank is needed for buildings built after 1990, while buildings built between 1930–1959 need a 5 m^3 buffer tank). In this case, the heat pump will operate during the analyzed day for only 8 h (when the outdoor temperature exceeds +1.0 °C).

8.3. Geothermal Heat Pumps

Geothermal heat pumps carry a higher investment cost but are characterized by a higher and almost constant COP. In practice, for single-family houses, two 100 m-deep 63 mm-diameter boreholes are constructed and used as heat sources. The output depends on the ground's thermal properties, but it can be considered to be around 50 W/m (as can be seen, one borehole would be more than enough for NZEB buildings, but for safe and secure energy supply, two boreholes are usually constructed). Geothermal heat pumps are characterized by a SCOP = 4.5.

8.4. Photovoltaic Systems

If heat pumps are installed for detached houses, their electricity demand will increase considerably. Installation of a photovoltaic system with proper inclination and orientation can meet almost all of the electricity needs of the house (including the heat pump; a 5 kW_p photovoltaic system installed in Debrecen produces about 5750 kWh electricity in a year but requires 42 m^2 sunny roof area with appropriate inclination and orientation). Therefore, in those cases when there is no place for both solar collectors and photovoltaic panels, it is recommended to install a photovoltaic system instead of solar collectors.

9. Recommendations and Decarbonization Packages for Existing Residential Buildings

9.1. Buildings b1–b5

These buildings were built in the last ten years, but they have no renewable energy source.

With the installation of two plate solar collectors (2×2.32 m^2) facing to the south on the roof of the analyzed buildings (b1–b5), the energy used for DHW preparation can be reduced. With an optimal angle of inclination (30°), the yearly heat produced is 299.3 kWh. This system produces more than 100% of the required heat for DHW preparation from March to October. However, it provides 44.8% of the required heat in January, 72.8% in February, 69.4% in November, and 31.3% in December.

The integration of such a solar collector system in buildings b1–b5 will decrease the average carbon dioxide emissions to 2902 kg/a (22.7 kg/m^2a).

Changing the condensing boiler to air–water heat pumps with SCOP = 3.0 will decrease the CO_2 emissions to 2347 kg/a (18.3 kg/m^2a). In this case, the electricity needed by buildings will be 6497 ± 899.3 kWh/a. This electricity can be produced by a 6.5–7.5 kW_p photovoltaic system with an optimal orientation and inclination angle.

The installation of geothermal heat pumps instead of the condensing boiler (SCOP = 4.5) can reduce the CO_2 emissions to 2004.7 kg/a (15.7 kg/m^2a). In this case, the electricity needed by buildings will be 5298 ± 615.5 kWh/a. This electricity can be produced by a 4.7–5.8 kW_p photovoltaic system with optimal orientation and inclination angle.

In the case of photovoltaic systems, the produced electricity in a year is in balance with the yearly consumption; however, substantial differences between production and consumption can be observed during the day. The electricity production of these systems is ever-changing, so the storage of energy produced should be addressed. Until recently, these systems could be connected to the national energy grid, but such a large number of systems were built that the load threatened the safe operation of the national grid. However, the isolated operation of photovoltaic systems makes the system more expensive on the one hand, and there is no serious experience in their operation on the other. Therefore, in this study, it was considered that photovoltaic systems are connected to the national grid.

It can be seen that when heat pumps and photovoltaic systems are installed, the yearly CO_2 emissions of these detached houses converge to zero.

9.2. Detached Houses Built between 1930–2023

According to practitioners, in the case of buildings built before 2009, not only the building envelope but the whole heating system has to be renovated, alongside the changing of the heat source. We assumed that in the original state, the heating was in each building category provided by a gas boiler, which should be exchanged for a heat pump. It is proposed that external building elements should be additionally insulated and refurbished to meet the current NZEB requirements in Hungary. The proposed photovoltaic system (without storage) is dimensioned with a power output that covers the electricity needs of the heat pumps. Heat pumps were chosen with an output that covers both the heat demand and DHW preparation (so the CO_2 emissions related to heating and DHW preparation converge to zero). The costs of these investments for analyzed buildings are shown in Table 4.

Table 4. Costs of building energy refurbishments.

Year of Construction	Mean Net Floor Area, [m^2]	Total Costs, [Euro] Air-Water Heat Pump	Total Costs, [Euro] Geothermal Heat Pump
1930–1959	65.5	28,450	35,818
1960–1969	78.7	30,678	37,257
1970–1979	87.4	34,638	41,217
1980–1989	100.6	32,984	39,563
1990–1999	105.8	34,422	39,685
2000–2009	125.6	36,559	41,822
2010–2019	142.4	32,851	40,746
2020–2023	171.7	16,842	24,737

It is worth mentioning that, currently, the average monthly gross wage in Hungary is about 1500 euros [44].

10. Discussion

Reducing the carbon dioxide emissions of the building sector is a priority objective in many countries. The renewal and renovation rate of the existing building stock unfortunately falls far short of expectations. Loga et al. presented building typologies created in 20 European countries to support communication about refurbishment measures and achievable energy-performance levels [45]. However, while optimal solutions are difficult to find at the national level, they can be determined at the local level. Theodoridou et al. analyzed the Greek building stock, providing detailed information on typical large and small Greek cities [46]. They also found that the energy consumption of homeowners with higher incomes is higher. This was not the goal of our research, but considering that homeowners of new buildings with large net floor areas have higher incomes, we can conclude that the energy use in these buildings is the lowest. Lupisek et al. provided information on the Czech building stock, analyzing the effects of different scenarios on CO_2 emission [47]. In this study, the CO_2 emissions were not analyzed assuming different scenarios, but the current CO_2 emissions were determined and decarbonization packages were developed for existing buildings built in different periods.

Taking into account the decarbonization goals in the EU, practically buildings built before 2020 must be renovated. Obviously, the investment costs of the interventions needed are different, but photovoltaic systems and heat pumps should be installed for all buildings. Murray et al. concluded that for Switzerland biomass or heat pumps seem to be the most favorable option [48]. In our opinion electricity based energy supply will dominate in the future building sector. However, in Hungary, the national electricity grid has to be renovated taking into account the loads caused by the fluctuation of production and consumption.

Homeowners have a huge task and responsibility to achieve the decarbonization goals. After minimizing the energy demands, heat pumps, solar collectors, and photovoltaic panels should be integrated efficiently. The decarbonization of electricity should be carried out at the country level as well [49]. This statement agrees well with the conclusions of Conci et al., namely to reach climate targets extensive integration of local energy generation from renewable sources is required [50]. In the case of new or properly refurbished buildings, the passive solar techniques should be used appropriately in an energy-conscious way since solar gains may cover an important rate of the heat demand. A higher percentage of homeowners can be found in East European countries. Since the annual income in these countries is generally lower compared to Western European countries, in our opinion, the expected home renovations cannot be fulfilled unless there are continuous national calls for tenders that support this type of investment. A homeowner with an average income in Hungary needs nearly 2.5 years of total income for the energy renovation of a building. As it was shown the analyzed single-family detached houses show already lower energy needs for heating than calculated based on the specific building energy requirements in force in the year of construction of these buildings. The differences are between 20–52%. However, these data don't reflect the energy status of the whole building stock. New buildings have to meet the current strict energy performance requirements, but the energy assessment of an existing residential building is carried out only when the house/flat is sold, rented, or refurbished with the support of the state or municipality. It was shown by Gróf et al. that there are many causes for the fact that energy consumption in residential buildings is lower than expected [51]. However, in our case, these differences were found not between the energy consumptions, but between the specific heat losses, which means that most of the analyzed buildings were already thermally refurbished. This means that homeowners are committed to decreasing the energy use of their houses and should be convinced to continue the energy-conscious interventions further. In Hungary, the specific primary energy need of an average residential building, based on the 1.6 Million energy certificates issued so far, is about 250 kWh/m^{2}a (average energy quality). Until November 2023 the requirement of an NZEB building was 100 kWh/m^{2}a. Since 1 November 2023 the requirement was lowered to 76 kWh/m^{2}a and the CO_2 emission requirement was introduced, which must be a maximum of 20 kg/m^{2}a. It can be observed that the mean CO_2 emissions of buildings built after 2010 analyzed in this study is lower than this requirement. It is supposed that investors have always built energetically better buildings than required. These buildings could be sold rapidly and the price could be a little bit higher. Based on the 70 thousand energy certificates issued between 2016 and 2020 for family houses Bene et al. found that about 80% of flats were included in the average or better-than-average energy performance category [52]. Moreover, by the end of 2023, more than 250 thousand households were equipped with photovoltaic systems with an installed capacity of 2317 MW [53]. The electricity produced by these systems decreased substantially the energy used in buildings.

It should always taken into account that investments in decarbonized buildings are made primarily not out of a desire for profit, but to achieve energy independence and provide a clean, liveable environment for future generations.

11. Conclusions, Limitations, and Future Work

This study aimed to give an overview of the energy performances and CO_2 emissions of detached houses in Debrecen, Hungary, providing decarbonization packages for existing buildings. The main lessons learned are the following:

- The specific heat loss coefficient and the specific energy demand for heating in new buildings decreased to 15.2% and 18.5% respectively in the last 90 years. Furthermore, most of the analyzed buildings built several decades ago have already been renovated at least once from an energy point of view as their heat demands are 27.6–41.4% lower than expected.
- New family houses are characterized by a smaller A/V factor, which means that architects pay attention to minimizing heat losses. Furthermore, the net heated floor area of residential buildings has increased over the years, but the heat loss and the specific heating energy demand have decreased.
- Occupants' behavior has a substantial influence on energy consumption and CO_2 emissions. Setting higher indoor temperatures than recommended, the CO_2 emissions

may exceed the expected values by 26%. However, the CO_2 emissions caused by DHW preparation are lower by 38.2%, than the expected value.
- External design temperatures determined 90 years ago cannot be used for planning. Existing heating systems are oversized as temperatures have increased over the past few decades.
- Using heat pumps and photovoltaic systems the CO_2 emissions caused by heating and DHW preparation in NZEB detached houses converge to zero.

Implementing the presented decarbonisation packages the CO_2 emissions in Debrecen can be reduced by 289,746 tonnes/a. This would contribute substantially to the greening of the city. However, taking into consideration the ownership relations of existing buildings, the average income of homeowners, and the estimated investment costs, the decarbonization goals hardly can be reached without substantial support from the state. Nevertheless, newly built buildings are expected to show better energy performance than required. In the case of existing buildings, continuous campaigns must be carried out to ensure that homeowners understand the need to switch from fossil energy sources. These investments can make the energy supply safe and sustainable in the long term, and these investments can ensure a liveable clean environment for future generations.

The presented case study results are useful for policymakers and homeowners not only in Hungary but also in other central and East European countries providing data about the carbon dioxide emissions of detached houses in Debrecen and decarbonisation packages and costs for buildings built in the last 90 years.

A limitation of the study stands in the number of analyzed buildings. 236 detached houses were assessed from an energy point of view and measured energy consumption data were gathered from six houses. A higher number of buildings would have led to more accurate results. Costs were calculated with an exchange rate of 1 euro = 380 HUF.

In the future long-term monitoring of the energy used in detached houses and decarbonization studies in different types of residential buildings is planned. Besides the CO_2 emissions caused by the energy consumption of detached houses the embedded carbon is important as well. This will be covered in a future study.

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Abbreviations

NZEB	nearly-zero-energy buildings;
A	envelope area, [m^2];
V	heated volume, [m^3];
COP	coefficient of performance, [-];
SCOP	seasonal coefficient of performance, [-];
EPS	expanded polystyrene;
DHW	domestic hot water;

Appendix A

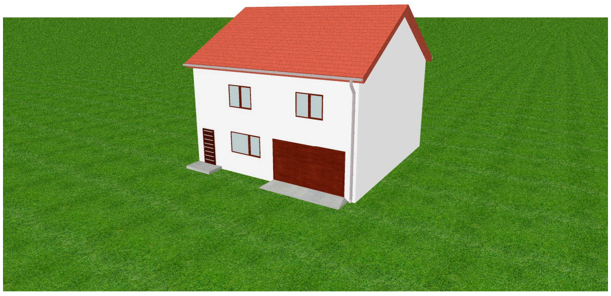

Figure A1. b1–b5 building type.

Figure A2. b6 building type.

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