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Limits of household's energy efficiency improvements and its consequence – A case study for Hungary

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ABSTRACT

Many energy-efficiency programs at the national and EU levels target the residential building sector. Investment in the renovation of buildings results in increased energy efficiency and can minimise energy utilisation when up-to-date technique and accurate planning is performed. The realisation depends on many subjects. One critical objective in the planning process is the financial status of the families living in the building stock subject of the renovation projects. A complex approach is essential in housing renovation programs, and the consequences of different energy policies in each country should be considered. This study reports the possible level of Hungarian prebound and its consequence on the energy efficiency mortgage loans. The heating expenditure varies by household's income situation and/or the dwelling's technical characteristics. A mixed picture was found, reducing available expenditure and, typically, higher monthly savings rates for smaller dwellings. We found that the prebound and rebound effects and credit constraints might limit a nationwide energy renovation program. Furthermore, the fixed residential energy price policy can impair the effectiveness of housing renovation programs. We found a minimal positive effect on banks' expected credit loss and the regulatory capital requirement on home energy-efficiency improvements.

1. Introduction

Anthropogenic CO_2 emission reduction by increasing energy efficiency is at the centre of climate policies. The European Union has launched ambitious CO_2 reductions and energy efficiency goals for decays. The residential buildings are at the centre of these efforts (EC, 2021). In many cases, despite recognising the need for interventions to increase energy efficiency, actual implementation falls far short of what is necessary (Wilkinson and Sayce, 2020). It is typically the case for residential properties. Buildings are responsible for approximately 40% of EU energy consumption and 36% of the greenhouse gas emissions (UN, 2020). Facilities are, therefore, the single largest energy consumer in Europe. At present, about 35% of the EU's buildings are over 50 years old, and almost 75% of the building stock is energy inefficient. Simultaneously, only about 1% of the building stock is renovated yearly (EC, 2019). One element of the successful program implementation may be the financial sector's supportive attitude by granting preferential residential renovation loans.

The institutions responsible for the financial system's stability have recognised the financial sector's vital role to mobilise capital for green and low-carbon investments in the broader context of environmentally sustainable development. The Network of Central Banks and Supervisors for Greening the Financial System (NGFS) was set up in 2017. According to the NGFS status report, the relationship between greenness in the broader term and credit risk is a crucial research topic (NGFS, 2020). This type of action of central banks is a new phenomenon, which is also since during the 2008 crisis management, the social responsibility of central banks has generally become more emphasised (Lentner et al., 2017). In 2020 the EU Commission launched the European Green Deal, which aims to transform the EU into a modern, resource-efficient, and competitive economy. One of the vital elements of this initiation is making sustainability considerations an integral part of its financial system. A European green bond standard (voluntary)[1] has already been

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[1] https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/european-green-bond-standard_en.

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Nomenclature

FH	Family House
CD	Condominium
DHW	Domestic Hot Water
DSTI	Debt Service to Income ratio
EeMAP	Energy efficient Mortgages Action Plan
ÉMI	Construction Quality Control Innovation Ltd.
EC	European Commission
EQ	Energy Quartiles
ESG	Environmental, Social, and Governance
EU	European Union
EUR	Euro
HCSO	Hungarian Central Statistical Office
HE	Housing Estate
HUF	Hungarian Forint
HVAC	Heating Ventilating and Air Conditioning
ITM	Ministry for Innovation and Technology (Hungary)
KEOP	Environment and Energy Operational Program
l	large
LGD	Loss Given Default
LTV	Loan to Value ratio
MNB	Hungarian Central Bank
NGFS	Network of Central Banks and Supervisors for Greening the Financial System
NFM	Ministry for National Development (Hungary)
OSAP	National Statistical Data Collection Program
PD	Probability of Default
s	small
TJ	terajoule

framed by the Commission to help scale up the green bond market easing the fundraising of financial intermediaries to grant green loans.

In banking, the risk of credit applicants' default on loans is generally assessed by credit rating/score models. These statistical methods match the applicant's characteristics (income, loan-to-value ratio, education, etc.) to the probability that one is "default on loan" (probability of default, PD[2]). In the current practice, these models do not consider the effect of the energy efficiency of the residences. However (Burt et al., 2010), suggested incorporating energy and transportation costs into mortgage underwriting.

Based on a dataset of US home-energy certifications (Kaza et al., 2014), found that mortgage loans secured with more energy-efficient homes are associated with even lower credit risks (PD). In Europe, EeMAP Initiative aims to create a European energy-efficiency mortgage. EeMAP recent report conducted analyses for four European countries: Belgium, Italy, the Netherlands, and the UK. They could not strictly confirm a negative relationship between energy efficiency and the probability of mortgage default in Italy and the UK. On the other hand, in Belgium and the Netherlands, they found a negative and significant correlation between the two variables (EeMAP, 2019). Billio (2021) found that building energy efficiency is associated with a lower probability of mortgage default based on Dutch data. We still have minimal practical experience with the above expected negative relationship, even for developed countries and almost nothing related to Hungary.

One fundamental question is whether, in the case of residential mortgage loans or consumer credits for real estate modernisation, the increase in the building's energy efficiency reduces the credit risk through the positive impact of higher disposable income? Providing a scientific response is a complex research task that can be carried out in collaboration with several fields.

Fig. 1 represents the individual subtasks or sub-processes of our approach. Quantifying the variation of the credit risk is ultimately a banking issue. However, it is necessary to establish a database on which the necessary calculations can be carried out to achieve this quantification. The content of the knowledge and data revealed by the research determines the quality of the result. The adaptive-communicative relationship between the different disciplines is essential. In the course of the work, it is necessary to reconcile and understand the basic concepts and processes of the cooperating disciplines.

We examined Hungary's current housing stock's energy quality following our research flow, defining the general starting point. The typology matrix is used for modelling the entire Hungarian housing stock (Csoknyai, 2013; NFM, 2015). The typology matrix of buildings is the basis for examining several aggregate effects on buildings at the country level. The applied building matrix *represents the entire domestic residential stock* (Table A1 placed in the Appendix, introduces the Hungarian building matrix.). Thus, it is possible to determine the primary energy savings available at the national level, the potential reduction of CO_2 emissions or the necessary renovation's technical content (NFM, 2015; ITM, 2020). The significant problems with this aggregated data are that the prebound and rebound effects are ignored since the calculations are based on only the technical data according to the national regulation (NFM, 7/2006 & 2021).

Resolving the residential buildings' actual energy status is not sufficient in itself, and it is necessary to establish the *actual costs* associated with this state due to the prebound effect. Indeed, the building energy industry's consensus hypothesis is that the vast majority of flats are underheated. According to the literature summary and findings of Sunikka-Blank and Galvin (2012), the prebound effect measured as a percentage of calculated consumption varies between 26 and 43% in Western-European countries. In other words, the actual technical condition's energy consumption should be more than the amount of energy purchased by households living in homes in need of modernisation. (Comparing the energy needs of total housing stock calculated by the actual technical condition and the national energy consumption statistics lights that.) Therefore, the energy needs assigned to the existing technical condition should not form the basis for determining the pre-renovation costs. Therefore, *actual housing energy expenditure* statistics should be used (HCSO, 2020a, 2020b). The statistical data have been re-processed to establish the relationship between *the building matrix's income, expenditure, and housing.* Many factors may limit the potential reduction in expenditure, e.g., actual consumption patterns, current income situation and the so-called rebound effect (Freire-Gonzalez, 2017). Altogether, those effects cause the energy performance gap (Cali et al., 2016).

The difference between actual costs and (in principle) expenditure on the target status after renovation theoretically increases the disposable income. This amount[3] (HUF/month) of potential income increase is defined in detail for the typology matrix and the income quintile elements. Since the apartment's technical conditions and the floors are the fundamental factors within each building and the typical floor areas, it is necessary to consider additional measures. In addition to potential savings, the need for energy efficiency investment should be assessed considering creditworthiness. The need for specific investment (HUF/m^2) in each building category was determined by employing the price

[2] Probability of default (PD) is a financial term describing the likelihood of a default over a particular time horizon. It provides an estimate of the likelihood that a borrower will be unable to meet its debt obligations.

[3] Since the high volatility of the HUF the results are not converted to EUR or USD.

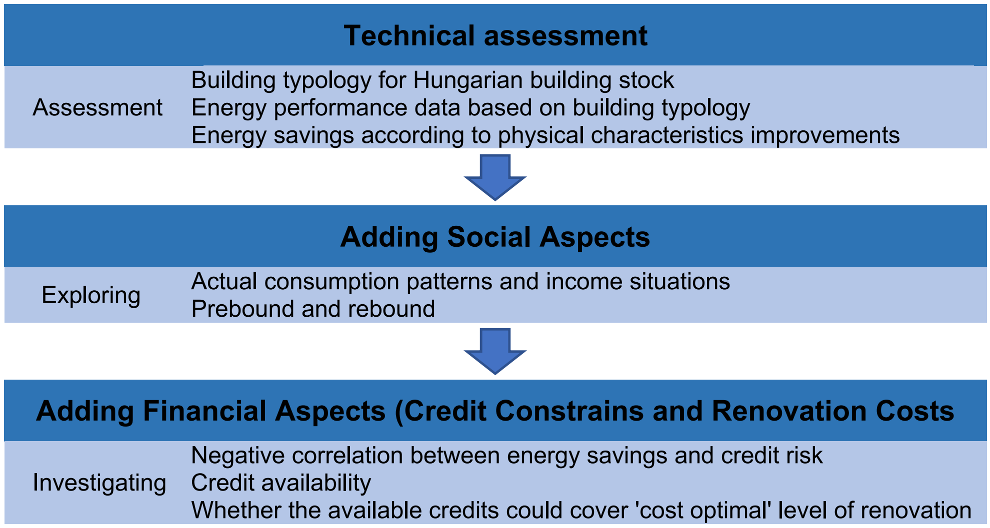

Fig. 1. Process flow of the assessment.

index for construction 2020 of the Hungarian Central Statistical Office (HCSO). Once the level of savings and the need for investment is known, it is advisable to put the results obtained in the context of narrowing it down to the creditworthy population. The result can be obtained by displacing the investment needs for the typology matrix elements with the level of available loans that depend on income, i.e., creditworthiness. In our last step, we apply for income elasticity of mortgage PDs from previous studies to determine the credit risk effect of green mortgages (more precisely, the income/PD channel of credit risk).

Hungary has a fixed residential energy price policy, which is unique in Europe. Our framework helps to understand the negative effect of this policy on CO_2 emission reduction by decreasing financial incentives and the progressivity of this price subsidy. Despite that, our multidisciplinary approach is general and could be used by other European countries to assess the limits of household energy efficiency policies. In this study, we investigate the credit risk effect of building's energy efficiency improvements. The results can be generalised to other countries.

This study consists of six subsections, first was the introduction above, it is followed by the summary of the energy status of the Hungarian building typology matrix elements and the residential housing stock energy state. An analysis of household expenditures and incomes situation decreasing energy savings (prebound effect) is introduced in the third section. The fourth section includes results and discussion about the saving of energy efficiency improvements considering the prebound and some rebound as well. The fifth section focuses on financial aspects: access to credit as an additional constraint of energy efficiency investment and, finally, the credit risk effect of home energy efficiency improvements. The last section contains two subsections, the conclusions and the policy implications, such as how the fixed residential energy price policy impairs the effectiveness of the housing renovation programs and the other controversial consequences.

According to the authors' knowledge, this study is the first that applies actual, statistical energy expenditures for the determination of virtue income increase caused by renovation in Hungary and reports data about the prebound effect.

2. Energy status of the housing stock

2.1. Building's typology matrix

To assess the overall picture and to survey the impact of massive investments in energy efficiency (and renewable energy), studies should, in principle, be extended to all buildings that might be considered in this respect, which is nonsense. Data obtained from the HCSO censuses (normal and micro-census) and other surveys on the state of residential property are available as primary sources. It is impossible to carry out studies extended to the entire building stock to establish the necessary resources and conditions after the varying degrees of residential properties' renovation. However, it is possible to create a replacement representative building stock (typology matrix) capable of achieving the desired results using statistical and other methods to determine the targets (resource demand, reduction in energy consumption, etc.) based only on the results of tests and calculations for this narrowed building stock. Extending and synchronising the national typology matrixes is the subject of EU financed programs like TABULA (2012).

The typology matrix used in this paper is considered the result of the most well-established survey (KEOP-7.9.0/12-2013-0019, 2013–2015), (KEOP, 2013) and represents Hungarian residential properties well for all physical characteristics (ÉMI, 2015).

The typology matrix is based on the building stock's typifying, known as the bottom-up model, and this approach is widely applied in the literature to evaluate the effect of different energy-saving measures (Csoknyai et al., 2016). This means that the building stock is classified into a building register (also known as a building typology matrix) based on characteristic properties (mainly geometric, technological and date of construction). A building model is created for each category of cadastre that represents the average properties of that type. Subsequently, considering the physical characteristics and HVAC systems of the model buildings, an energy model calculation can be made, and the result can be projected to the national level, taking into account the statistical data. The reliability of the bottom-up model depends on the proper set up of the typology matrix, which depends on the thorough assessment of the building stock on the one hand, on the other hand, the proper taking of appropriate building statistics and its determination as to the result of an iteration process (Csoknyai et al., 2016).

The advantage of the bottom-up model is that it is suitable for modelling the impact of modernisation measures, which is impossible for top-down methods since we only know consumption there, but not what physical properties or HVAC systems are behind it. Their disadvantage, however, is that consumer behaviour is not considered - they usually consider standard conditions (Sunikka-Blank and Galvin, 2012). In other words, it is assumed that the entire floor areas of buildings are in continuous use, so there is no prebound. To avoid this disadvantage in our present research, we obtained energy consumption data directly from the annual national statistics, as mentioned earlier.

2.2. Hungarian energy certification system of buildings

Energy certification of buildings has been required in Hungary by law since 2008. Since 2013, the *e-certification* online registration system has been in place, and since then, it has been mandatory to record the registration number of certificates in the sales contract, so we can only really consider the system to be operational from 2013. Experience shows that around 100–150 thousand certificates are issued each year, of which 90–95% are residential properties. The classification scale changed in 2016 and since then has been double lettered.

Government Regulation governs energy certification rules and energy categories 176/2008 (NFM, 2008), and Figure A1 shows it in the Appendix. Since 2016, the classification has been based on the aggregate energy characteristics of the property in percentage. The overall primary energy consumption divided by the reference value – 100 kWh/m^{2}a for residential properties – means the certification value. For example, if the property's overall energy performance is 140 kWh/m^{2}a, the quotient is 140%, the building falls into category DD. In other words, we can deduct the magnitude of the aggregated energy characteristic from the classification. The reference value is an overall energy performance in kWh/m^{2}a, and the energy authority sets it. In that regard, the certification categories can be tightened by reducing this reference value. The reference value includes the heating, cooling and DHW primary energy. The energy performance calculation is based on the physical characteristics of the building according to the very detailed (NFM, 7/2006 & 2021) regulation.

The ability of the certification database is limited in analysing the energy situation of the building stock (Olaussen et al., 2017; Cozza et al., 2020). However, in the housing market, the certification importance score is like price and location (Franke and Nadler, 2019). Based on the certificate database, estimating the energy consumption of the residential building stock may be given, but the consistency between countries may be questioned (Semple and Jenkins, 2020). In this research, the classification by certificate was used only to determine the degree of renovation required resulted in for the household to satisfy the CC class (101 kWh/m^{2}a < Ep < 130 kWh/m^{2}a).

2.3. Energy status of the dwellings of the typology matrix (2015)

Table A2 and Figure A2 in the Appendix present the essential energy indicators – Ep, CO_2 emission and shape factor – taken from ÉMI (2015). The Ep is the aggregate energy characteristic, the dwelling's overall primary energy consumption (including heating, cooling and DHW primary energy and excluding lighting and household appliances primary energy). It should be mentioned here that these data represent the engineering calculations results which generally may differ from the actual energy consumption. The weak energy status of the homes does not mean a high level of energy consumption since it depends on many circumstances (Mrówczyńskaa et al., 2020), and the hidden energy poverty might be identified (Betto et al., 2020). Renovation of the low energy efficiency houses offers less energy utilisation, but these benefits cannot be realised for low-income households (Berger and Höltl, 2019).

The most important conclusions on the primary energy data from ÉMI (2015) might be summarised as follows. The specific use of primary heating energy for family houses (types 1–12) generally is higher than that of households in condominium houses (types 13–16). Condominium houses' energy performances are, in most cases, behind the housing estate houses (types 17–23). This is because small buildings have a larger specific heat transfer surface as their shape factor (thermal envelope against conditioned volume ratio) is higher due to their smaller volume (See shape factors in the Appendix's Table A2).

3. The household's expenditures and incomes

The previous chapters provided the technical description of the typology matrix elements. The energy consumptions and savings calculated based on technical conditions, calculated in energy values, are only theoretical potential (Madlener and Alcott, 2009; Balezentis et al., 2021). The following gives an overview of HUF/month expenditures and energy consumption according to the household's income quintiles for the typology matrix. The difference between the two approaches results in the estimation of the prebound. (While the heating period is only six months, it is general in Hungary that the energy bills are paid equally for twelve months, and our study follows this method.)

3.1. Heating expenditures of the households

Like all consumption, the energy-related expenditures on living (heating, hot water, lighting) depend on several components (Dustmann et al., 2018; Schirmer et al., 2020). In the credit context, the expenditure on energy should be presented together with the income situation since the renovation caused expenditure reduction cannot be assessed in itself. The incomes of the families living in the typology matrix apartments have to be assigned with the expenditures based on the available statistics. The HCSO survey on the household's expenditures applies the earlier version of the Hungarian building typology, and this continues due to comparability, and this is the validated source for energy expenditures. Later 2029 houses were surveyed in the frame of KEOP-7.9.0/12-2013-0019. The surveyed houses represent the building stock statistics. The survey resulted in defining the synthetic house elements based on all observed physical properties. The energy performances were determined by the thermal characteristics, the standard degree days and a nominal comfort (20 °C). Regarding the energy calculations on Hungarian building stock, the data set in Table A2 is considered a validated source. The KEOP typology is an extension of the earlier typology, parts of the earlier elements were kept, and some house categories were split. The energy performances of the earlier typology elements were determined by mapping and interpolations.

The heating expenditures are categorised by *building type* and *heating methods*, resulting in 32 typical apartments. The income data are not assigned directly to those typical apartments, but the incomes were arranged into quintiles and then assigned with the heating expenses from the raw collected data. This arrangement resulted in 32 typical apartments being assigned five different heating expenses corresponding to the income quintiles. According to the earlier national typology, the 32 typical apartments situate in 15 typical buildings, while the validated energy characteristics are known for the 23 elements of the typology matrix. Therefore, matching the two building sets was carried out based on the physical properties and updating the dwelling's pre-renovation status energy indicators. The apartment's energy certificate indicators were also assigned based on the (E_p) energy indicators. The targeted data analysis - the actual heating expenditures, the incomes, the pre-renovation energy status, and the energy certificate indicators - were assigned. According to the authors' knowledge, no similar results were evaluated on the Hungarian dwellings data.

Tables 1–3 contain the data on family houses, condominiums, and housing estates according to the groups' increasing energy characteristics. In parenthesis following the acronyms of houses, the numbers refer to heating methods as follows: local heater (1), circular heating (2), central heating in family houses (3), central heating (4) in multi flat houses, district heating (5). According to the values given in the tables, most of the energy is used for heating, a smaller part for DHW production (not including consumption of household appliances and lighting). Two values in the energy indicator (E_p) column mean that two different typical floor areas are considered for this specific type of flat.

Monthly heating costs relate to the year 2015. Since the price of natural gas and electricity *has been fixed* for the households since 2013, heating expenditure depends on the needed energy related to the heating season's average temperature, more precisely on heating degree-days. Table 4 shows the total national household heating energy demands; values in 2015 are close to the average of 2013–2019 years heating energy; in the following, the 2015-year values are applied

Table 1
Data assessment results for the family houses (FH) and small family houses (sFH).

HSCO names	HSCO numbers	Time range of construction	Floor <80 m^2	Floor >80 m^2	Energy certificate	Monthly heating costs (2015), HUF quintiles of total household income according to bottom to top				
			Energy indicators kWh/m^{2}a			Q1	Q2	Q3	Q4	Q5
FH-44 (2)	32	- 1944		448	II	14 306	16 023	13 546	17 974	19 263
FH-44 (1)	31	- 1944		448	II	13 505	13 628	16 862	16 128	18 927
sFH-44 (2)	30	- 1944	443		II	14 332	13 256	15 870	16 472	11 817
sFH-44 (1)	29	- 1944	443		II	11 265	14 897	14 197	12 609	12 091
FH45-79 (3)	28	1945–79	398	398	HH	17 320	17 180	18 978	17 598	20 044
FH45-79 (2)	27	1945–79	398	398	HH	15 512	16 647	16 675	17 885	19 926
FH45-79 (1)	26	1945–79	398	398	HH	13 076	14 887	15 154	15 482	17 709
FH45- (3)	25	1945 -	398		HH	16 339	16 186	16 105	17 803	19 409
FH45- (2)	24	1945 -	398		HH	14 139	15 894	15 904	15 562	15 655
FH45- (1)	23	1945 -	398		HH	12 200	13 498	13 405	14 526	14 847
FH80-89 (3)	22	1980–89	348	255	GG	14 607	17 183	15 119	19 993	22 033
FH80-89 (2)	21	1980–89	348	255	GG	18 722	17 863	18 203	19 050	19 136
FH80-89 (1)	20	1980–89	348	255	GG	13 503	15 582	16 993	15 137	18 178
FH90-05 (3)	19	1990–05	245	185	FF	15 000	18 315	16 136	17 992	20 188
FH90-05 (2)	18	1990–05	245	185	FF	17 322	16720	19 131	16 699	19 623
FH90-05 (1)	17	1990–05	245	185	FF	15 064	16 673	18 178	22 288	19 704
FH06- (2)	16	2006 -	164	153	DD	17 024	13 386	16 030	22 727	18 363

Table 2
Data assessment results for the households in condominiums (CD) and large condominiums (lCD).

HSCO names	HSCO numbers	Time range of construction	Floor <80 m^2	Floor >80 m^2	Energy certificate	Monthly heating costs (2015), HUF quintiles of total household income according to bottom to top				
			Energy indicators kWh/m^{2}a			Q1	Q2	Q3	Q4	Q5
lCD-44 (1)	15	- 1944	327	258		7826	10872	15737	9597	16575
lCD45-79 (2)	14	1945–79	271	227		11635	10485	11214	11353	11733
lCD45-79 (1)	13	1945–79	271	227		12424	12066	12340	15051	15733
CD80-89 (–)	12	1980–89	226	168		not enough data for separation				
CD90-05 (2)	11	1990–2005	182	126		14330	15441	13047	13094	16771
CD06$^-$ (–)	10	2006 -	113	111		not enough data for separation				

Table 3
Data assessment results for the households in housing estates (HHE).

HSCO names	HSCO numbers	Time range of construction	Floor <80 m^2	Floor >80 m^2	Energy certificate	Monthly heating costs (2015), HUF quintiles of total household income according to bottom to top				
			Energy indicators kWh/m^{2}a			Q1	Q2	Q3	Q4	Q5
HE45-79 (5)	9	1945–79	175	175		12 112	12 271	12 851	13 167	14 551
HE45-79 (4)	8	1945–79	216	216		98 15	9664	9421	15 584	16 042
HE45-79 (2)	7	1945–79	216	216		9657	10 148	11 212	11 122	13 815
HE45-79 (1)	6	1945–79	226	226		8985	9947	10 331	9791	11 633
HE80-89 (5)	5	1980–89	168	168		11 131	13 134	13 977	14 548	14 302
HE80-89 (2)	4	1980–89	168	168		9693	10 928	11 183	11 967	11 116
HE80-89 (1)	3	1980–89	168	168		9628	8701	10 789	9723	13 285
HE90-05 (2)	2	1990–2005	126	126		10 419	10 349	7104	9262	12 636
HE06- (–)	1	2006 -	110	110		not enough data for separation				

(9 and 5 houses are districts heated and have been insulated as a result of several "Panel-programs", as the housing estates are called "panel houses" in Hungary).

without correction.

3.2. Characteristics of the heating expenditures

We have met with some imaginations that we are not certain. Working on this study, we realised that there is a possibility of quantifying and lighting what can be the reality. Without actual knowledge of the data, it is often assumed in Hungary that heating costs for people living in energy waster buildings are higher than those in energy-efficient, more modern properties. Regarding the heating habit (Csoknyai et al., 2016), considered the underheating and intermittent heating in several rooms but reported the insufficient available data. Another wide belief is that those with higher incomes also spend more money to provide comfort. Hache et al. (2017) found that the income is crucial in determining the level of energy consumed, and other household characteristics also play significant role. This may be nuanced by the pre-set that higher incomes are associated with living in higher-quality buildings so that it is not necessary to spend more on greater comfort. The higher the income, the higher the percentage of insulated buildings, as Santamouris et al. (2007) reported. It is

Table 4
Heating demands and the seasonal temperature average.

Year	Energy TJ	Temperature °C	Heating degree-days
2013	189 339	8.58	2687
2014	172 936	10.39	2272
2015	182 585	9.34	2593
2016	190 617	8.40	2707
2017	194 807	8.00	2742
2018	178 902	9.73	2472
2019	179 546	9.66	2489
Average	184 104	9.15	2565

somewhat less on a specific scale (per 1 m^2) because higher incomes can be associated with larger dwellings, resulting in a more favourable specific indicator of the same HUF/month cost. Janky and Kocsis (2021) investigated the role of occupants' efforts in saving on space heating costs. They found that the proper information on savings is one of the key requirements. It is also worth noting again that it is also a pretty general consideration that the heating expenditure of residents of buildings with unfavourable energy parameters is not proportionate to the negative energy indicators of buildings, i.e., buildings are not fully heated. This phenomenon – prebound – can also have a negative impact on the cost-saving potential of energy efficiency investments (Sunikka-Blank and Galvin, 2012). As shown in the following, actual data validate some beliefs, some or only partially support some imaginations.

Fig. 2 introduces the average heating costs for each residential building category ascending by the HSCO identity numbers, while Fig. 3 introduces the average expenditures ascending by their value sequences. The maximum heating expenditure is almost twice the minimum value. Energy-best expenditures are estimated values (1 and 10). Based on the collected data, the minimum expenditure is for household 2. The building with the worst energy rating (32, SFH-44) is not at the end of the sequence. At the beginning of the expenditure order (ascending direction), one finds residential buildings (2, 6, 3, 4, 7, 8). At the end of the order (19, 22, 18, 25, 17, 21), single-family houses are characterised by good and moderately good energy characteristics but have a large area and the highest heating costs. Buildings with the worst energy indicators are in the middle of the sequence. The order of actual expenditure is interesting in terms of which categories typically spend a lot on heating. Typically high heating costs can be an important motivation for energy efficiency investments. Where the building is favourable, the large size and comfort demand above the basic comfort (20 °C) together cause high nominal costs compared to other heating costs, which in many cases represent a low proportion of income as a quintile's percentage.

Generally, the essential attitudes of the decision to invest in energy efficiency improvement are unknown, and studies of this kind not or barely have been carried out in Hungary. As a hypothesis, it can be assumed that the willingness to modernise may be more significant the more outdated the dwelling is energetically (e.g., space heating with solid combustion). The renovation also requires an adequate income.

Electricity consumption is a significant part of residential energy consumption. This energy and its primary energy content are not part of the building energy classification, but the heat dissipated by the appliances is considered as a heat profit specific to an area, and according to the regulation (NFM, 7/2006 & 2021), this predicted value is 5 W/m^2. The effect of this is low for buildings with unfavourable energy properties.

If one compares the above results given in Cali et al. (2016) for German family houses, the adaptation curves are nearly identical if we would also put the data of Cali et al. (2016) into Fig. 4. The linear regression equation for German family houses is $y = 125.3–0.7485·x$, while for Hungarian family houses, it is $y = 120.2–0.726·x$.

4. Determination of energy savings

4.1. Heating expenditures

The calculations necessary to determine the reduction in post-renovation expenditure were made as follows. Energy indicators are available for calculations per square metre of residential floor area. When several area sizes can characterise the households, we found it appropriate to examine more than one size. When there's only one area, that's what we're counting on. When the energy status of the building could not justify the statistical heating expenditure, we searched for the residential area where the actual cost and the cost of the comfort were in harmony by changing the area of the dwelling. The energy rating represents a specific range in each category. However, it does not matter

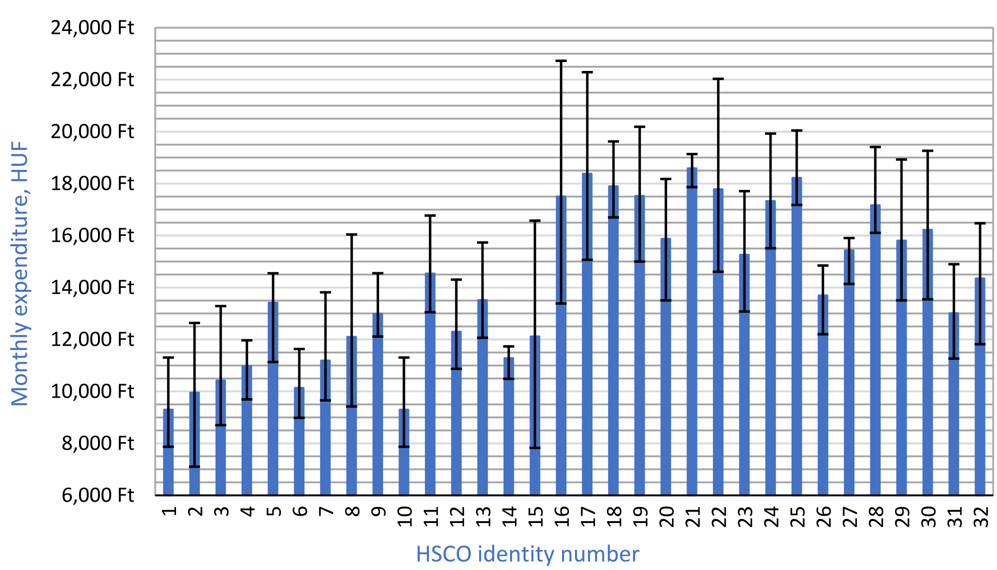

Fig. 2. Average monthly expenditures, indicating the max and min values as well (1–9 housing estates, 10–15 condominiums, 16–32 family houses).

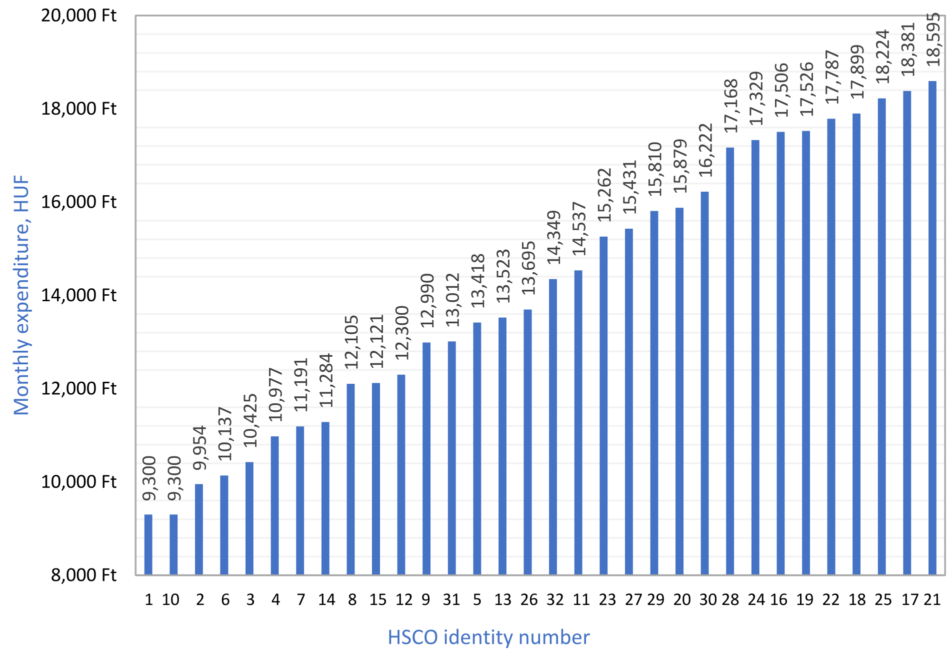

Fig. 3. Average monthly expenditures in ascending order (1–9 housing estates, 10–15 condominiums, 16–32 family houses).

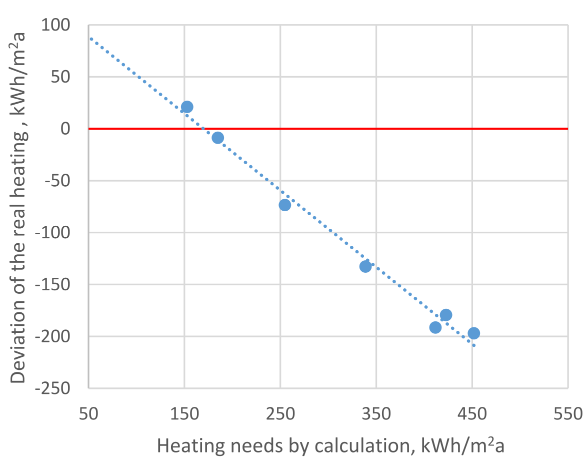

Fig. 4. The measure of prebound effect for Hungarian family houses (Points themselves represent averages of the observed expenditures.).

where the property is within this range, especially in the broad ranges of weaker ratings. The ranges are divided into 4 parts (quartiles) maintaining this. In reality, investment in energy efficiency does not put the dwelling in the same quartile, but we still use this assumption to avoid excessive opportunities.

Another vital element in determining the level of savings is that we approach the issue not from a specific technical investment need but from an investment amount. This is a more complex, multi-component approach that we are applying to uncouple the studies' results from the current price uncertainty of investments.

Before further, to better understand, we summarise what we know and what we do not know to determine the level of savings:

1. We know what specific energy indicators belong to each energy certificate class. The primary energy needs are calculated according to the regulations. The Hungarian regulation's energy and power factors for heating are provided in Appendix Tables A5 and A6.
2. We can determine, based on the energy data and energy prices for the given technical condition, the costs of maintaining the reference comfort (20 °C) temperature, supplemented/deducted from DHW and electricity consumption in each class.
3. We found the costs paid by housing users, according to statistical data, in buildings that were also matched to the building matrix. The missing data were replaced by an estimate based on the regression obtained from the heating expenditure investigation.
4. Data have supported the hypothesis that actual expenditures do not reach the level of comfort associated with the building's energy status, i.e., in many cases, full heating is not achieved, so purely technical estimates overestimate the potential of energy efficiency improvements.
5. The vast majority of households still spend little on household energy, which in many cases is just about or only a little above the cost of the base comfort in a modern dwelling. In these cases, we see the need to examine further the conditions for improving energy efficiency (comfort needs, attitudes, etc.).
6. Knowing the actual costs of investments is a crucial element in the calculations. The available statistical data are rapidly[4] obsolete due to the market changes, so it is crucial to update price changes continuously.
7. The rebound effect is taken into account partly in the results. For all under-heated dwellings, after renovation, households are considered choosing to heat for basic comfort (20 °C) and not the usual under-heating. Maintaining the under-heating attitude would mean further savings, but we assume this disappears after the renovation.
8. We considered that the renovations result in homogenising the heating methods, and the same type of houses with previously different heating methods are merged into one category after the renovations.

We expect the following results from the determination of savings:

[4] In 2021 the extraordinary price increase happened in the building sector.

- Based on typical dwelling sizes, what are the households where current expenditure on purchasing heating energy equal to or even less than the cost of providing comfort for the CC rating's energy characteristics? DHW and electricity costs are taken unchanged. In these cases, the economic rationality of modernisation on the residents' side is not apparent, but it can still be motivated to achieve better comfort conditions.
- What are the households where the current expenditure exceeds the comfort state calculated on the CC rating's energy characteristics? We consider these households to be where economic rationality is reflected in the intention and attitude to improve energy efficiency.

Showing the details of the calculations for each building goes beyond the scope of this article. The workflow of our calculation is provided in the Appendix in Figure A3. The floor area of dwellings determines the total renovation cost and the amount of energy utilisation. The average dwelling's floor size in Hungary in 2016 was 79 m^2. In single-family houses, 93 m^2 and in housing estates, 67 m^2 (HCSO, 2018).

Table 5 is an example of how the Excel calculation sheets look for each household. Such tables are made for all 32 HSCO apartments, with the addition that when two or more floor areas had to be examined, we added tables furthermore.

Reading of the result:

"EQ" is the energy quartiles setting parameter. The "Floor" is the area of the dwelling in m^2.

"Quintiles" is the range of the household income.

"Minimum" is the minimum expenditure of households living in FH45-79 with an income QX rate.

"Maximum" is the maximum expenditure of households living in FH45-79 with an income QX rate.

The minus signed monthly expenditure reductions represent no reduction since the actual expenditure is less than the cost of the base comfort in the related certification category. This is the so-called prebound.

Calculating all reasonable combinations, Fig. 5 summarises the results. As mentioned, the CC energy certification class (101 kWh/m^2a < Ep < 130 kWh/m^2a) was defined as a renovation target. The results in Tables 6 and 7 are the *averages of* each quintile *income's averages* for a certain dwelling type. Fig. 5 visualises the data of Tables 6 and 7 Again, we mention that the calculations had not been done for the households situating in house by rating CC.

Considering that 1.5% of the households are renovated in all categories, and the average savings are thought, 120 kt/year of CO_2 emission could be avoided by the energy saving of 580 GWh/year, on natural gas basis calculation at the national level.

4.2. *Costs of renovation*

Estimating the costs of investments to improve energy efficiency is not easy since the construction sector prices are affected by many factors. For example, in which region the investment is made which region the contractor comes from. The development of prices is also influenced by seasonality, especially in works where the entire year is not available (e.g., weather requirements) for construction work. Many sources are trying to provide information on construction and material prices, yet it is difficult to determine actual and acceptable costs. Designers have a variety of software available to prepare budgets, and the database's status affects its relation to the actual costs (is it sufficiently recent or not).

The purpose of determining specific costs is not to determine the costs of investments in individual cases, but to determine the nationally summarised resource demand, therefore the costs of energy renovation of a dwelling are determined by specific characteristics and data (location, size, etc.) may differ from the result obtained by multiplying the specific values by the area in a ± direction.

The specific costs of renovation (HUF/m^2) in 2015 were investigated in detail by ÉMI (2015). The cost-optimum level renovation means that the investment cost in the case of the construction or renovation of residential buildings and the operating cost (heating and maintenance) is a minimum of 30 years (EU Comission, 2012). From a cost-optimum point of view, the price of the materials to be installed (thermal insulation) and heating system significantly affects the optimal conditions. In addition, there are regulated thermal transmittance (U) values associated with the cost-optimal requirements (Table A4). If any parts of the building's energy characteristics fail, the requirements must be subject to renovation. In that context, the works may vary according to the pre-renovation status, but for the inefficient buildings, generally, the new windows, doors, insulation works and renewal of the heating system must be done.

We accepted these values as a base and modified them according to the changes in the HCSO report. Table 8 summarises the increase in the building sector's cost indexes in Hungary for the last five years and Fig. 6

Table 5
Calculation results for a single-family house (FH 45–79).

EQ =	4	Floor =	80 m^2	Expenditures covering the base comfort, 20 °C					
		Heating costs, Ft/month							
Quintiles	Certificate	Minimum	Maximum	CC	DD	EE	FF	GG	HH
Q1	HH	13 076	17 320	7584	9755	13 000	17 091	22 022	29 260
Q2	HH	14 887	14 887						
Q3	HH	15 154	18 978						
Q4	HH	15 482	17 885						
Q5	HH	17 709	20 044						
		Income	%	Monthly expenditure reduction, Base: Minimum					
Q1	HH	148 522	8,80	5492	3321	76	−4015	−8946	−16 184
Q2	HH	214 432	6,94	7303	5132	1887	−2204	−7135	−14 373
Q3	HH	237 302	6,39	7570	5399	2154	−1937	−6868	−14 106
Q4	HH	288 419	5,37	7898	5727	2482	−1609	−6540	−13 778
Q5	HH	420 977	4,21	10125	7954	4709	618	−4313	−11 551
		Income	%	Monthly expenditure reduction, Base: Maximum					
Q1	HH	148 522	11,66	9736	7565	4320	229	−4702	−11 940
Q2	HH	214 432	6,94	7303	5132	1887	−2204	−7135	−14 373
Q3	HH	237 302	8,00	11 394	9223	5978	1887	−3044	−10 282
Q4	HH	288 419	6,20	10 301	8130	4885	794	−4137	−11 375
Q5	HH	420 977	4,76	12 460	10 289	7044	2953	−1978	−9216

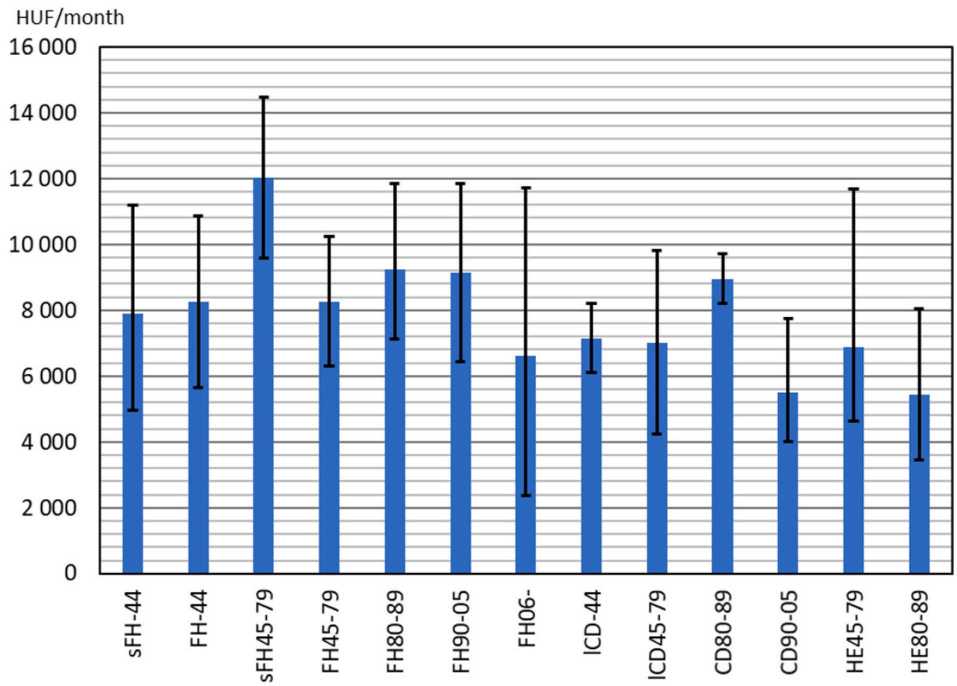

Fig. 5. Heating expenditure reductions (The values are averages of averages, and the maximum and minimum average values are also indicated.).

Table 6
Energy expenditure saving for family houses.

Average, minimum, and maximum expenditure reductions due to renovation, HUF/month							
	sFH-44	FH-44	sFH45-79	FH45-79	FH80-89	FH90-05	FH06-
Average	7882	8265	12 026	8267	9253	9146	6613
Max	10 795	10 877	14 473	10 237	11 378	11 865	10 853
Min	4969	5653	9579	6297	7128	64 26	2372
Uncertainty, %	+27/-37	+24/-32	+17/-20	+19/-24	+19/-23	+23/-30	+39/-64
Primary energy saving MWh/month (2593°-days)	76.2	79.9	116.3	79.9	89.4	88.4	63.9
Number of houses	275 559	310 990	423 211	844 137	387 822	219 188	227 648

Table 7
Energy expenditure saving for condominiums and housing estates.

Average, minimum, and maximum expenditure reductions due to renovation, HUF/month						
	lCD-44	lCD45-79	CD80-89	CD90-05	HE45-79	HE80-89
Average	7153	7024	8961	5501	6866	5449
Max	8194	9823	9711	6990	9110	7450
Min	6112	4225	8211	4011	4621	3449
Uncertainty, %	±15	±40	±8	±27	±33	±37
Primary energy saving MWh/month (2593°-days)	69.1	67.9	86.6	53.2	66.4	52.7
Number of households	242 287	329 225	187 428	141 097	515 350	185 256

Table 8
Labour and materials cost-index (HCSO, 2020c).

Period		Construction cost index	Section	
year 2015 = 100.0%			Labour	Materials
2016.	Jan–Mar	98.5	95.5	101.1
	Apr–Jun	101.3	101.7	101.4
	Jul–Sep	101.5	101.5	101.5
	Oct–Dec	104.9	109.9	101.3
2017.	Jan–Mar	104.6	107.4	102.7
	Apr–Jun	108.0	114.3	103.4
	Jul–Sep	108.2	114.5	103.6
	Oct–Dec	113.4	126.3	103.9
2018.	Jan–Mar	109.4	113.3	106.5
	Apr–Jun	113.2	120.8	107.6
	Jul–Sep	114.2	120.7	109.4
	Oct–Dec	120.8	133.6	111.4
2019.	Jan–Mar	119.4	126.9	113.8
	Apr–Jun	123.1	133.0	115.7
	Jul–Sep	127.0	136.7	120.0
	Oct–Dec	133.2	148.1	122.4
2020.	Jan–Mar	131.6	139.1	122.7

visualises the changes. Table A3 in Appendix shows the cost-optimum renovation level expenses for three dwelling areas to achieve rating CC. In Table A3, the non-relevant variations are blank (single-family houses and condominiums where the characteristic area is less than 100 m^2).

5. Financial aspects

Under financial aspects, we study two phenomena. Firstly, we examine how the creditworthiness of households and the bank credit

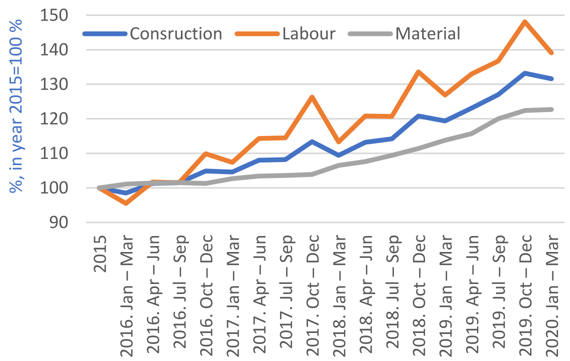

Fig. 6. Labour and materials cost-index changes (HCSO, 2020c).

supply determine the credit available for energy efficiency investments. Households might face two credit constraints: 1) whether they can take a loan at all; or 2) if they can take a loan, the typical loan amount would be enough to cover the cost-optimum renovation expenses (Table A3). Secondly, relying on our results of expenditure reduction calculations (Chapter 4.1), we could calculate how the energy expenditure reduction would decrease the credit risk by increasing households' disposable income. We call this effect the income/PD channel of credit risk.

5.1. The credit availability

The income situation of consumers also affects (energy) consumption through access to credit. After all, in the absence of credit facilities, households cannot make enough investments for energy efficiency. This chapter deals with this problem.

The liquidity constraint is an essential issue in the literature describing household consumption patterns. There are two types of this: (1) there is a hard liquidity constraint when some consumers do not have access to credit at all; (2) a soft liquidity constraint is when consumers face high credit costs and are unable to get the level of financing needed to optimise their consumption trajectory (in this case, their energy investment). The liquidity constraint (insufficient supply of credit) results in consumers consuming or investing less overall (e.g., in energy projects) than their income trajectory would allow.

The liquidity constraint prioritises credit supply as a fundamental reason for insufficient lending. However, this may be coupled with demand or regulatory factors as well.

Another general feature of the credit market is that pricing is often secondary. The development of bank credit supply is primarily explained by non-price factors, which means banks' creditworthiness standards and lending conditions. Lending standards are internal banking rules that determine which customers, groups of customers (by sector, area, size, financial indicators, etc.) and types of credit (covered, investment, current account, etc.) are provided by the bank. Lending conditions may be price or non-price. Non-price lending conditions (e.g., income requirements, debtor's commitments, maximum loan/credit limit size, etc.) are specific contractual terms and conditions, with the bank only willing to disburse the loan. Non-price factors in the credit supply vary considerably over time, depending on banks' expectations, lending capacities, competitive situations, etc.

As with the supply of credit, the demand side varies over time and depends on many factors: household preferences (including experience), income conditions, expectations, subsidised home loan schemes, etc.

The indebtedness legislation – mainly the Hungarian National Bank's so-called debt brake rule – limits the room on both the supply and demand sides. There are two main elements of this rule:

- Debt service to income ratio (DSTI): limits the maximum repayment burden in a specified proportion of the borrower's regular official income in case of a new loan.
- Loan to value ratio (LTV): limits the new loan amount in proportion to the coverage value of collaterals (real estate).

The specific value of the above limits also depends on the type (housing/consumer), currency denomination (HUF or EUR) and interest rate setting (fix or float) of loans. Since we do not have statistics on the value of collateral by income quintiles, we consider the DSTI rule an effective limit (Fig. 7).

The debt brake rules, as we present, are only a cap on indebtedness. On average, household demand (based on their income, expectations, etc.) and/or banks' risk-taking is lower in specific household segments.

According to the latest statistics of the Hungarian Central Bank (MNB), the average annual percentage rate of new mortgage loans is 4.8%, and the average maturity is 18 years (February 2020 data). These values are 13.5% and 6 years for personal loans, respectively. In block-I of Table 9, the maximum monthly repayment and loan amounts permitted by the debt brake rules are included in addition to the above credit parameters. These amounts are rather theoretical for several reasons. Firstly, not all income types can be included in DSTI calculation. Secondly, already indebted households could get lower new loans due to the DSTI rule. Thirdly, for low-income quintiles (work and other income combined), these maximum values based on debt brake rules are unrealistic. Typically, these households cannot use 35% and 50% of their income to pay off loans since the basic cost of living does not allow this.

Furthermore, the credit supply of this customer segment is also likely to be very weak, as Fig. 8 illustrates. Only 2% of home loans fall into the bottom and 5% in the second quintile on a loan number basis. On this basis, we can say that there is virtually little home lending in the bottom two quintiles. However, this is not the case with personal loans.

In block-I of Table 9, we consider the loan amounts as effective, which could limit energy investments. Statistics on mortgage loan goals (new/used home purchases, renovation) per income quintile are not publicly available. We note that households could not take the same credit amount for renovation as they would for buying a home. This is particularly true if the household already has another loan (e.g., purchasing a home). But this is already a demand issue that goes beyond the scope of the current study.

Table A3 shows the average expenses of a "Cost Optimal" technical renovation for each type of dwelling calculated by the updated costs for 3 different housing sizes (50, 75, and 100 m^2) (see Fig. 9).

Fig. 9 contains the comparison of Tables 9 and A3. The energy efficiency investment required for all categories, from third-income quintile households, can be achieved at the necessary 'cost optimal' level. For large and medium-sized families, row and condominiums built before 1944, the number of mortgages for households with incomes in the 3rd quintile is less than the renovation costs, but the difference is not very large. Some interest rate reductions would increase the available loan amount in these cases. The 1st and 2nd quintiles are not presented in Fig. 9 since mortgage loans are deficient.

Note that larger personal loans are also available on the market, even specifically for home renovation purposes. More minor renovation needs can also come from personal loans, although banks likely prefer mortgage-based financing for more significant loan amounts.

To summarise, besides the prebound and rebound effects, the characteristics of the credit market might limit the efficiency of a nationwide energy renovation program because of the credit constraints (availability). For less creditworthy clients, a government subsidy program, in case of insufficient loan amounts, some interest rate reduction could ease these credit constraints.

The next chapter of our study examines the justification of preferential interest rates from a risk perspective. However, the reduced interest rate may also result from a more favourable refinancing of banks.

	Method for the interest of the chosen loan					
	Interest rate period is longer than 10 years		5 years ≤ Interest rate period < 10 years		Interest rate period < 5 years	
	Certified monthly income (HUF)					
	less than 500 000	Above 500 000	Less than 500 000	Above 500 000	Less than 500 000	Above 500 000
	Maximum ratio of DSTI					
HUF loan	50 %	60 %	35 %	40 %	25 %	30 %
EUR loan	25 %	30 %	25 %	30 %	15 %	20 %
Other currency	10 %	15 %	10 %	15 %	5 %	10 %

Fig. 7. DSTI limits for mortgages with a maturity of more than 5 years (Source: MNB, 2022: Pénzügyi Navigátor Füzetek (trans: Financial Navigator Booklets) 16. szám: Hitelfelvétel tudatosan (trans: No 16, Borrowing consciously) pp6. available: https://www.mnb.hu/letoltes/hitelfelvetel-tudatosan.pdf. Accessed: 5 February 2022).

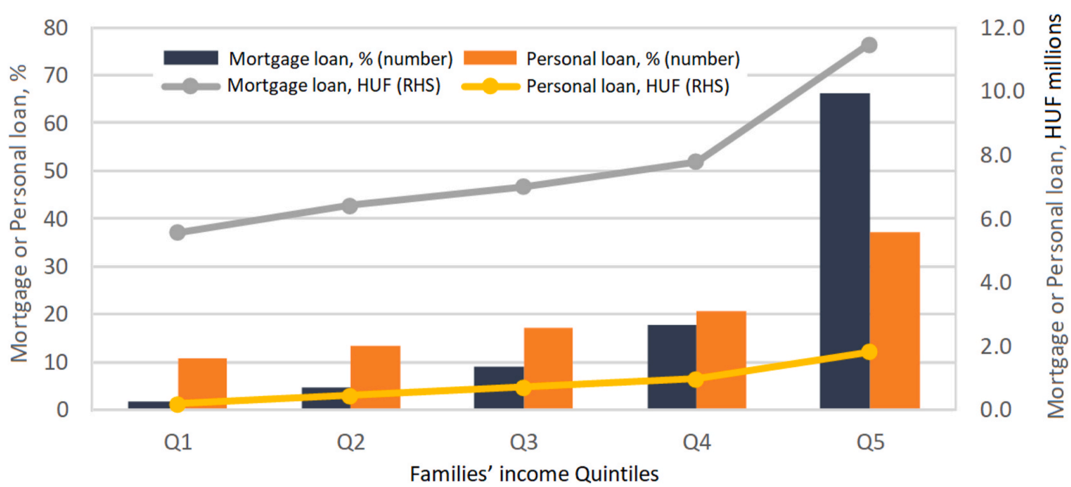

Fig. 8. Distribution and the average amount of new loan contracts by income quintile.
Note: Loans issued by credit institutions and financial undertakings in the first half of 2019. Income quintiles are based on the incomes of the entire domestic population. (Source: MNB, 2019: MNB Financial Satbility Report 2019 December, page19. Available: https://www.mnb.hu/letoltes/financial-stability-report-2019-december.pdf).

Table 9
Loan amounts and repayment burden by income quintiles.

HUF	I Average new loan amounts, and the calculated monthly repayment charges					II Maximum loan amount and monthly repayment burden allowed by debt break rules			
	Households total monthly net income per quintile	Monthly repayment - mortgage loan	Monthly repayment - personal loan	Average loan amount - mortgage loan	Average loan amount - personal loan	Maximum monthly repayment - mortgage loan	Maximum monthly repayment - personal loan	Maximum loan amount - mortgage loan	Maximum loan amount - personal loan
Quintile 1	148 406	38 726	4206	5 594 006	206 799	51 942	74 203	7 503 060	3 648 328
Quintile 2	214 770	44 360	9946	6 407 771	489 023	75 169	107 385	10 858 234	5 279 766
Quintile 3	237 436	48 417	14 825	6 993 817	728 890	83 103	118 718	12 004 175	5 836 974
Quintile 4	288 030	54 185	20 018	7 826 973	984 223	100 811	144 015	14 562 090	7 080 749
Quintile 5	425 342	79 698	37 763	11 512 338	1 856 699	148 870	212 671	21 504 210	10 456 323

Sources: income - 2018 household budget and living conditions survey, OSAP 2153; 2154; MNB, own calculation

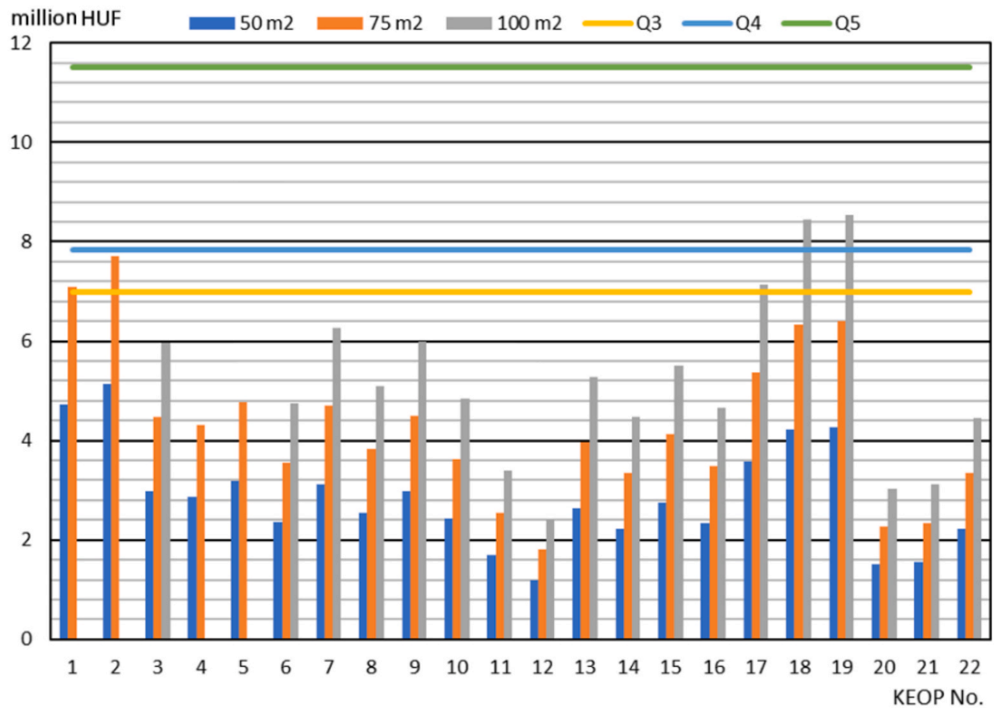

Fig. 9. Estimated renovation amounts for 50,75, and 100 m^2 and average mortgage loan amounts for Q3, Q4, Q5 income.

Bond issues of banks with a high ESG rating may have a lower cost of funding (Nanayakkara and Colombage, 2019).

5.2. Income/PD-effect estimation

From a credit risk perspective, two possible channels might decrease the credit risk of green mortgages: i) increasing disposable income of borrowers due to the energy-efficiency improvements (income/PD channel); ii) due to the energy-efficiency investment increase in dwelling value and marketability decreasing the LGD (value/LGD channel). In our study, we evaluate the income/PD channel.

According to the banking regulation and practice, banks calculate expected credit losses, which should be priced to customers (risk cost) and covered by provisioning. The bank capital should counterbalance the unexpected losses (in excess of expected losses). Both expected loss and capital requirement calculations have two common parameters: the probability of default (PD) and loss given default (LGD). The expected loss is the product of PD and LGD.[5]

Our final research question is to assess the sensitivity of PD to changes in heating cost. Home energy efficiency improvements decrease the monthly heating expenditure, which would increase the disposable income (income effect) to cover the monthly loan repayment instalment and other expenses. The expected monthly heating expenditure reduction was estimated in chapter 4.1. The sensitivity of PD to disposable income changes depends on several factors: level of disposable income, the number of the family, other fixed expenditures, etc.

There is no public data available for the whole Hungarian household lending market for long-term PDs and LGDs. As an indication of the LGD level, we present the numbers of a significant players in the Hungarian retail banking market (K&H Bank, 2019):

- Mortgage: average LGD: 31.75%.
- Other retail (consumer loans): average LGD: 48.39%.

There is a relatively recent sector level assessment on the income sensitivity of households (Balás et al., 2015). According to this study, repayment capacity is not only affected by loan instalments but also by households with higher other (non-repayment) expenditure obligations (food, housing costs, etc.) and the probability of default is also higher: HUF 10 000 higher expenditures ceteris paribus increases long-term PD by 0.21 percentage points. In this study, the long-term PD is 14% for mortgage loans that we are using.

Firstly, we calculate the yearly expected credit loss (risk cost) effect of the reduced risk emerging from green mortgage finance. According to Table 10, the expected loss effect (ΔPD*LGD) is very limited since the monthly saving from home energy efficiency improvements is limited (6000–12,000 HUF).

Secondly, we investigate the unexpected loss effect and the decrease in minimum regulatory capital requirement. The Capital Requirements Regulation (Article 154)[6] determines the formula, which shall be used to calculate the risk weighted (RW) exposure amounts for retail exposures.

Table 10
Calculation of room for an interest rate reduction based on the decreased expected loss.

Calculation steps		Values
Duration of the loan	b	10
Long-term PD	c	14%
Yearly PD calculated from the long-term PD	$a = 1\text{-}(1\text{-}c)^{(1/b)}$	1.5%
Reduction of long-term PD (%point)	d	0.21%
New long-term PD	e = c-d	13.790%
Yearly PD of the new long-term PD	$f = 1 - (1\text{-}e)^{(1/b)}$	1.47%
Yearly PD decrease (%pont)	g = f-a	−0.024%
LGD	h	31.75%
Room for interest rates reduction (%pont)	i = g·h	**−0.008%**

Note: there are different methods to calculate long-term PD. We use the simplest version, supposing a stable yearly PD.

[5] In this presentation of expected loss and capital requirement we use some simplifications, but these are not material form the study perspective.

[6] EU Regulation No 575/2013.

Table 11
Calculation of the reduction in minimum regulatory capital requirement due to the decreased PD.

Calculation steps	Values	
LGD	31.38%	31.38%
PD	1.00%	0.98%
RW (using function of Article 154)	0.542	0.537
Capital requirement	4.34%	4.29%
Change in capital requirement (%point)	**−0.045%**	

The capital requirement is the product of RW and 8%. Table 11 summarise the calculation steps.

Overall, preferential interest rates for green household loans could not be justified based on credit risk's income/PD channel due to the limited positive effect on expected loss and capital requirement.

6. Conclusion and policy implications

6.1. Conclusions

The research aimed to identify the aggregate effect of different constraints on housing energy renovations. We calculated the energy performance gap (prebound and rebound effects), renovation costs, and credit constraints of housing energy renovations. We computed how the energy expenditure reduction would decrease the credit risk by increasing households' disposable income. Thus, the study used a multidisciplinary approach to consider technological, social, and financial effects.

Several research projects were aimed to establish the state of the country's building stock, the extent of justified energy renovations, and their cumulative impact over the past decade. The documents describing these results could be used as sources of research. These are essential elements of the study: the typology matrix representative of the residential building stock, the values of the energy indicators, and the technical content of investments that increase possible and justified energy efficiency.

In natural measure defined energy indicators (kWh/m^{2}a) transposition into financial indicators (HUF/month) is the second corner element of our approach. The technical indicators generally are known for the typology matrix elements. It is plausible to extract the heating expenditures from the national data set and assign the actual household living costs in the representative buildings' elements. The data was obtained and presented in different ways. In our opinion, the results are without precedent in complexity and content.

The general underheating hypothesis was identified earlier, but our study verifies by data for all building categories first time in Hungary. Furthermore, the income situation was not examined previously, and the first time concerning renovations was assigned to the typology elements of the building stock, with expenditures being given together with the quintiles of total household income. This combines the building categories' technical characteristics, the actual income and the actual expenditure of the households living in it. The results show that the heating expenditure is not necessarily proportional to the household's income situation and/or the dwelling's technical characteristics. Actual expenditure and actual savings are determined together with the energy state by sociological characteristics (use of dwellings, lifestyle, comfort needs, etc.). We have determined the reduction in expenditure that can be reached by raising the dwelling to CC according to the building's energy certificate. Between the thus defined state and the baseline, the reduction in expenditure was determined by the actual expenditure and not the category's comfort-level expenditure was taken into account, but in the CC state, we assumed a comfort-level release. The combination of income quintiles and housing areas shows a very mixed picture of reducing expenditure and, typically, higher monthly savings rates for smaller dwellings.

Moving to the financial aspects, firstly, we investigated the creditworthiness of households and the loan availability for energy efficiency investments. We found some credit constraints in the lowest two quintiles of Hungarian households. From quintile 3, the energy efficiency investment can be fully financed at the necessary 'cost optimal' level. A government subsidy program (some interest rate reduction) could ease these credit constraints for less creditworthy clients.

Secondly, we examined the preferential interest rates of green mortgages from the income/PD channel of credit risk. We call the income/PD channel the following: home energy-efficiency improvements decrease the monthly heating expenditure, increase the disposable income to cover the monthly loan instalment and other expenses, decreasing the credit risk (PD). The expected monthly heating expenditure reduction was limited, according to this study. Therefore, we found a very limited positive effect on expected credit loss and a regulatory capital requirement on home energy-efficiency improvements.

Further research topics are the value/LGD channel of credit risk and the effect of preferential funding. The first means that an energy-efficiency investment might improve the value and marketability of dwellings, decreasing the loss of the bank in the case of customer default. According to the second, a favourable green bond issuance might reduce the cost of funding, allowing a preferential interest rate for green mortgage products.

6.2. Policy implications

Hungary has a unique energy policy related to the residential overhead costs as gas, electricity, water, and waste handling have been fixed since 2013. At first sight and from the viewpoint of the consumers, it is a favourable condition, but the fixed energy tariffs were higher than the retail prices until the enormous energy inflation was started a year before. Until the 2021 autumn, there were no financing issues related to gas and electricity, but the water and waste handling service companies continuously suffered losses. If the observed energy inflation trends are going on, financing low household energy prices puts an excessive burden on the budget. The overall negative impacts are treated in detail by Weiner and Szép (2022) in the recently published study, and the author's recommendation is: "on the one hand, to eliminate the utility cost reduction programme and instead provide support to those in need through pricing and social programmes, and on the other, to give priority to energy efficiency." Our findings harmonise (Weiner and Szép, 2022) statements.

The households of first- and second-income quintiles pay a higher percentage of their income for heating, and the higher energy consumption of third-, fourth- and fifth-income quintiles receive more support. The low energy prices for everyone mean undifferentiated support. The income-independent support for everyone seems fair, but it is **not** since it transfers more support to those who consume more. This is the opposite of the good support policy, as it takes resources from the lower-income category and distributes it to those who do not need them.

The fixed prices do not transmit market processes to the population, discouraging higher-income earners from saving energy. The energy prices significantly different from actual market prices distort the real economic potential of renovations. In this situation, without public support programs, housing energy investments do not pay off economically. The reintroduction of market prices would make energy efficiency investments of the higher-income households more economical, reinforcing such investments. In this case, the subsidy intensity of existing housing energy renovation programs could also be reduced, as renovations would become more economical, saving fiscal funds. Higher market prices are also likely to reduce the rebound effect, increasing renovations' energy savings. The fiscal funds released could support investments in energy efficiency improvements in the lower-income groups. Overall, a higher volume of renovation, less primary energy consumption, and lower CO_2 emissions would mean.

More vital support for energy efficiency investments in the lower-income groups would also be needed because financial constraints are tough for these groups in many cases. They are not, or only less, creditworthy, which is a potential barrier to energy efficiency investments. Regarding climate mitigation, the low energy prices for everyone preserve high energy consumption and the associated CO_2 emission.

CRediT authorship contribution statement

Gyula Gróf: Conceptualization, Methodology, (engineering), Writing – original draft. **Béla Janky:** Investigation, Formal analysis, Writing – review & editing. **András Bethlendi:** Conceptualization, Methodology, (finance), Writing – review & editing.

Declaration of competing interest

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

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Appendix

Table A1
The elements of the building typology matrix (ÉMI, 2015).

KEOP N°.	Illustrative picture	Building type	Building time	The materials of the outer walls
1		detached or terraced house (1–3 flats) sFH-44	- 1944	adobe wall with foundation
2		detached or terraced house (1–3 flats) FH-44	- 1944	adobe wall without foundation
3		detached or terraced house (1–3 flats) FH-44	- 1944	brick, stone, masonry block
4		detached or terraced house (1–3 flats) FH45-59	1945–1959	brick, stone, masonry block
5		detached or terraced house (1–3 flats) FH60-79	1960–1979	brick, stone, masonry block
6		detached or terraced house (1–3 flats) FH60-79	1960–1979	brick, stone, masonry block
7		detached or terraced house (1–3 flats) FH80-89	1980–1989	brick, stone, masonry block

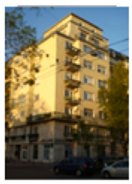
(*continued on next page*)

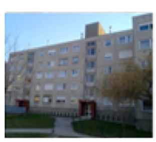
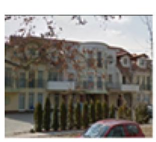
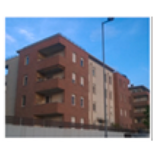
Table A1 (*continued*)

KEOP N°.	Illustrative picture	Building type	Building time	The materials of the outer walls
8		detached or terraced house (1–3 flats) FH80-89	1980–1989	brick, stone, masonry block
9		detached or terraced house (1–3 flats) FH90-05	1990–2005	brick, stone, masonry block
10		detached or terraced house (1–3 flats) FH90-05	1990–2005	brick, stone, masonry block
11		detached or terraced house (1–3 flats) FH06-	2006 -	brick, stone, masonry block
12		detached or terraced house (1–3 flats) FH06-	2006 -	brick, stone, masonry block
13		house with 4–9 flats CD-45	- 1945	brick, stone, masonry block
14		house with 4–9 flats CD45-89	1945–1989	brick, stone, masonry block
15		house with 4–9 flats CD90-05	1990–2005	brick, stone, masonry block
16		house with 4–9 flats CD06-	2006 -	brick, stone, masonry block

(*continued on next page*)

Table A1 (*continued*)

KEOP N°.	Illustrative picture	Building type	Building time	The materials of the outer walls
17		house with 10 or more flats lCD-44	- 1944	brick, stone, masonry block
18		house with 10 or more flats lCD45-79	1945–1979	brick, stone, masonry block
19		house with 10 or more flats lCD-79	- 1979	medium or great block, concrete

KEOP N°.	Illustrative picture	Building type	Building time	The materials of the outer walls
20		house with 10 or more flats HE-79	- 1979	concrete panel
21		house with 10 or more flats HE80-89	1980–1989	concrete panel
22		house with 10 or more flats HE90-05	1990–2005	brick, stone, masonry block
23		house with 10 or more flats HE06-	2006 -	brick, stone, masonry block

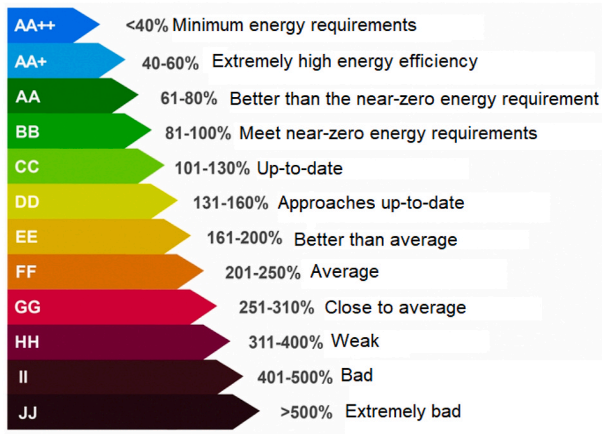


Fig. A1. Energy certificate classifications (NFM, 2008).

Table A2
The energy indicators and CO_2 emissions of the typology matrix elements (ÉMI, 2015).

KEOP N°	Ep kWh/m^{2}a	Certificate classification	CO_2 emission[7] kg/m^{2}a	Thermal envelop (A) Conditioned volume (V) Shape factor (A/V) 1/m
1	452.7	II	72.8	1.34
2	444.0	II	110.4	1.30
3	412.3	II	64.9	1.17
4	398.4	HH	64.8	1.15
5	423.6	II	97.6	1.21
6	339.2	HH	58.1	0.97
7	349.0	HH	54.3	1.09
8	255.1	GG	44.0	0.90
9	245.1	FF	45.0	1.14
10	185.3	EE	36.6	0.90
11	164.0	EE	28.1	1.23
12	153.7	EE	27.4	1.00
13	327.6	HH	60.1	0.75
14	271.6	GG	48.7	0.77
15	181.7	EE	36.6	0.78
16	112.7	CC	22.5	0.62
17	258.6	GG	52.7	0.44
18	226.6	FF	47.7	0.53
19	216.9	FF	45.8	0.50
20	174.7	EE	40.6	0.41
21	168.6	EE	39.0	0.45
22	126.4	CC	26.4	0.52
23	110.9	CC	21.9	0.62

[7] The different biomass percentage use effects on the CO_2 emission data.

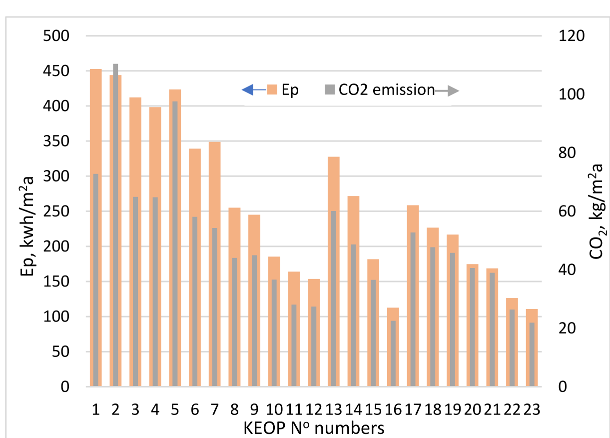


Fig. A2. The energy indicators and CO_2 emissions of the elements of the typology matrix (1–12 Family houses, FH; 13–16 Condominiums, CD; 17–23 Housing estates HE).

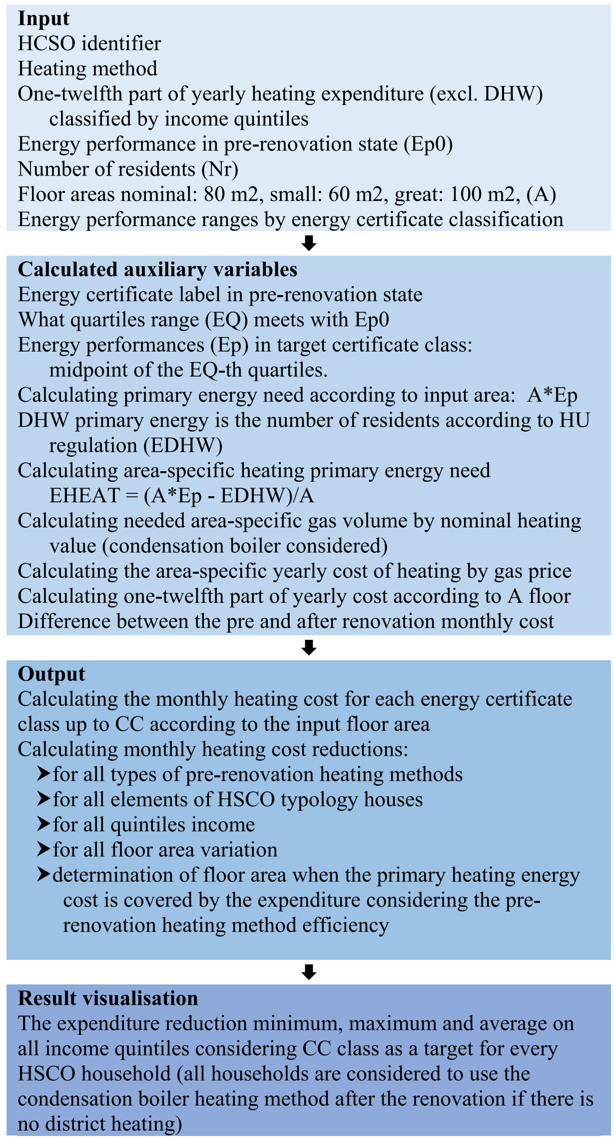


Fig. A3. The workflow of the calculation.

Table A3
Cost-optimum renovation expenses (updated for 2020).

KEOP N°	Cost-optimum renovation expenses Dwelling area		
	50 m^2	75 m^2	100 m^2
1	4 728 256	7 092 385	
2	5 144 178	7 716 267	
3	2 978 700	4 468 050	5 957 400
4	2 874 144	4 311 216	
5	3 179 653	4 769 480	
6	2 370 379	3 555 569	4 740 758
7	3 129 645	4 694 468	6 259 291
8	2 549 421	3 824 132	5 098 842
9	2 990 544	4 485 816	5 981 088
10	2 423 348	3 635 022	4 846 696
11	1 694 284	2 541 426	3 388 568
12	1 200 389	1 800 584	2 400 779
13	2 643 844	3 965 766	5 287 688
14	2 232 397	3 348 595	4 464 793
15	2 751 559	4 127 338	5 503 117
16	2 331 491	3 497 237	4 662 983
17	3 572 282	5 358 423	7 144 564

(continued on next page)

Table A3 (*continued*)

KEOP N°	Cost-optimum renovation expenses Dwelling area		
	50 m^2	75 m^2	100 m^2
18	4 221 860	6 332 789	8 443 719
19	4 273 776	6 410 664	8 547 552
20	1 514 255	2 271 383	3 028 511
21	1 563 342	2 345 013	3 126 684
22	2 228 185	3 342 278	4 456 371

Note: Type 23 (housing estate built after 2006) was omitted as a non-relevant category.

Table A4
Thermal transmittance values associated with cost-optimum renovation (NFM7/, 2006 & 2021).

Structure	Thermal transmittance U, W/m^2K
Outer wall	0.24
Roof (flat)	0.17
Ceiling	0.17
Heated space border walls	0.17
Glazed door, window (plastic, wood)	1.15
Floor (laying on the ground)	0.30

Table A5
Primary energy conversion factors by the Hungarian regulation (NFM7/, 2006 & 2021).

Energy source	Conversion factor
Renewable (solar, wind etc.)	0.0
Electricity (out of peak time)	1.8
Natural gas	1.0
Heating oil	1.0
Wood, pellets, biogas etc.	0.6
District heating	1.26

Table A6
Power factors of heating devices by the Hungarian regulation (NFM7/, 2006 & 2021).

Heating device	Power factor
Electrical heating devices	1.00
Tile stove	1.80
Fireplace	1.90
Gas convector (unregulated)	1.40
Gas convector (temperature regulated)	1.32
Gas convector (gas-air ratio regulation with chimney)	1.12
Gas convector (gas-air ratio regulation parapet)	1.07
District heating	1.01
Gas boiler (fixed temperature)	1.30
Gas boiler (fixed, low temperature)	1.08
Gas boiler (condensation)	1.01
Solid firing (coal, briquette etc.)	1.85
Wood-fired boiler	1.75
Pellet boiler	1.49
Wood gasification boiler	1.20

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