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Estimating the Energy Demand of the Residential Real Estate Stock in Hungary Based on Energy Performance Certificate Data*

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In our study, estimates are made for the distribution of the Hungarian residential real estate stock in 2020 by energy characteristics. In our calculations, which are novel in Hungary, a new database has been compiled by combining the energy certificates issued since 2016, the 2016 Microcensus and the housing construction statistics of the HCSO. Energy performance certificate data are assigned to the dwellings included in the Microcensus and to the 68,000 new dwellings built in the period since then. A statistical relationship is established between the characteristics and the energy demand of dwellings, which is then extrapolated to the stock as a whole. This is processed to present the estimated calculated energy consumption per square metre of the Hungarian residential real estate stock and the characteristics of the estimate by area and real estate type. Our results can support sustainable mortgage lending in the financial system.

Journal of Economic Literature (JEL) codes: G21, O13, Q40, R30

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1. Introduction

The Hungarian residential real estate stock will need to be almost completely renewed in terms of energy efficiency in the next decade or decades. Only a modern real estate stock with minimal energy demand can lead to achieving the country's 2030 "Fit for 55" climate targets and the 2050 goal of European climate neutrality,

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as set out also in Hungary's Long-Term Renovation Strategy (*ITM 2020*). To achieve this goal, it is essential to assess the current state of the stock, as well as to plan and calculate the costs and to set up an effective incentive system. However, even in the interests of achieving such an important goal, an energy audit cannot be carried out quickly on more than four million real estate units, and the conditions can only be characterised by estimations. In our study, we contribute to these estimations by creating a new database and by its statistical processing.

The renewal of the dwelling stock, as one of the largest energy consumers in the economy, is essential for an environmentally sustainable future. In this study, our calculations contribute to narrowly-defined, direct objectives. The focus of the projection at this time is on the EU Taxonomy target, as a priority for the financial sector, which establishes rules for sustainable finance that can only be derived from the stock as a whole. The primary objective of the study is to estimate the limit of the top 15 per cent of the Hungarian residential real estate stock in terms of energy consumption per square metre as at 31 December 2020. This requires an assessment of the energy quality of the entire dwelling stock.

According to Point "7.7 Acquisition and ownership of buildings" of Annex I of the European Commission Delegated Regulation (EU) No 2021/2139, from the perspective of the EU taxonomy, the following buildings are considered to contribute substantially to climate change mitigation: buildings constructed before 31 December 2020 which have at least a Class *A* energy certification. Alternatively, the building is in the top 15 per cent of the national or regional building stock expressed as an operational Primary Energy Demand (PED) and verified by appropriate evidence, which at least compares the performance of the asset to the national or regional stock built before 31 December 2020 and at least distinguishes between residential and non-residential buildings. In the case of buildings completed after 31 December 2020, the building complies with the criteria set out in Point 7.1 of the above Annex, relevant at the time of purchase. On the basis of the above, for the regulation, it is necessary to estimate the limit of the top 15 per cent from an energy point of view. Based on the projection to the total stock, this is of course also given. Although the Taxonomy does not specify a distinction by building type, both professional considerations and past practice justify the setting of limits by building type. Based on the results of this study, in the case of residential buildings, even the separation of detached houses and condominiums can be justified, as the results are significantly different in terms of energy demand.

The value estimated in our study, i.e. the lower limit of the best 15 per cent of residential real estate in Hungary in terms of energy efficiency, provides important considerations for the financial sector. The main reason for this is that the green finance attitude is gaining ground among regulators, central banks and profit-oriented actors as well (*Sági 2020*). From a real estate financing perspective, one of the key drivers is the issuance and trading of what are called green bonds. While green bonds may not only be linked to the real estate market (*Bokor 2022*), the mortgage lending market is a natural way to enforce a green finance attitude, both because of its inherently securitised nature and the high energy intensity of the underlying assets (residential real estate). While there is no universally agreed rule on what is considered "green" for residential mortgage lending, there is consensus that, in line with the EU regulation quoted above, a real estate unit must be in the top 15 per cent in the country in question regarding energy efficiency (*Ritter 2021*). Since a simultaneous and thorough expert assessment of all domestic real estate is essentially impossible, we believe it is necessary to develop a procedure that can provide an estimate of the distribution of energy demand of residential real estate in Hungary. Beyond supporting regulatory and prudential aspects, our calculation can also contribute to the development of financial products.

The limit of the top 15 per cent of the Hungarian dwelling stock in terms of energy is estimated as follows. As a first step, we process the database of energy performance certificates produced in Hungary between 2016 and 2020, which contain the primary energy demand of the built unit at building or dwelling level, calculated by an expert, and certain technical parameters of the built structure. Additional data is linked to these using the 2016 Microcensus of the Hungarian Central Statistical Office (HCSO). In the second step, statistical relationships between the energy demand of the residential real estate units and their characteristics as defined in the first step are estimated using two different methodologies. In the third step, since the database of energy performance certificates is not representative for the whole country in several aspects, such as age and location, the estimated correlation is extrapolated for the total dwelling stock of the country using the weights of the Microcensus.

To our knowledge, this study is among the first to perform this calculation for Hungary. The methodology of our work is cutting-edge, even in international comparison. Although the study of the relationship between the energy demand of buildings and their characteristics is a popular research topic, offering the possibility to use a wide variety of statistical methodologies, a large part of the studies focuses on the variation of energy use over time (e.g. within a day or a year).[1] There are far fewer works on topics that are more relevant for us and that look at the dwelling stock in a cross-sectional manner, using technical or other characteristics (e.g. age) to focus on a certain indicator of the distribution of the total stock (e.g. average, median or top 15 per cent). In our experience, a major and serious limitation in this area is the nature and quality of available data: in most cases, either the detailed energy demand of buildings or the distribution of the national building stock is not available to researchers.

There are several approaches to handling this problem in literature. Some studies ignore the problem: *Antonín* (*2019*) examines the dwelling stock in the

[1] For comprehensive summaries of these, see e.g. *Sun et al.* (*2020*) or *Al-Shargabi et al.* (*2022*).

Czech Republic, and although he uses detailed energy demand data from energy certificates, he does not adjust them for the potentially different distribution of the dwelling stock across the country, and basically he gives the lower limit of the top 15 per cent of available energy certificates. A similar approach is used for Italy by *Nidasio et al.* (*2022*). Others face a partial lack of data in relation to the energy demand of residential real estate. In this case, the authors make some kind of simplifying assumption most of the time. For example, the estimate of the Irish Central Statistical Office (*ICSO 2019*) uses the letter code of existing certificates instead of the energy demand which is not available to them and extrapolates it by location, building type and year of construction for the whole country, in order to determine the best 15 per cent in terms of energy. Of course, in this case, the 85th percentile (the lower limit of the best 15 per cent) is not a numerical annual energy demand, but the letter code of the category in which the (calculated) 85th percentile of residential real estate falls in terms of energy demand. This greatly simplifies the calculations in some cases: in some countries, the recent introduction of stringent energy efficiency standards for new-build real estate means that a good starting point is to take a count of the real estate units built since the restrictions were introduced, determine their share of the total real estate stock and compare this ratio to the 15 per cent. Studies we are aware of use this approach with minor or local modifications in Norway (*Multiconsult 2021*), Denmark (*Jyske Realkredit 2022*) and the Netherlands (*CFP 2022*).[2]

Where these data or regulatory changes are not available, researchers have to use other types of information to approximate energy demand. In France, *Florio and Teissier* (*2015*), instead of using a distribution of the letter codes of energy certificates, assigned so-called type buildings from a European catalogue of thousands of types of buildings to a large sample of French residential buildings with many technical characteristics, and then combined these data to estimate the annual energy demand and energy efficiency class for each residential unit in the sample. The common European type building system (the result of the so-called EPISCOPE/TABULA project) is also used by *Csoknyai* (*2023*), who defined the energy efficiency of the Hungarian building stock using a bottom-up method. In an earlier work, *Csoknyai et al.* (*2016*) made similar calculations for several countries in the Central and Eastern European region.

Of course, studies that perform calculations very similar to the present paper on the dwelling stock in Hungary should be mentioned separately. In this regard, we highlight two works. On the basis of detailed data from Hungarian energy certificates, *Ritter* (*2022*) – after concluding that the lower limit of the best 15 per cent for energy efficiency in Hungary falls into the *CC* category – estimates the exact value from the distribution of energy demand in 2016–2019. Presumably due to

[2] It is worth noting that these studies, probably due to the relative simplicity of their methodology, have typically not been published as academic papers, but as public material for public policy or market actors (banks and investors).

the limitations of data on the dwelling stock and the scope of the study, the author does not address the fact that the composition of energy certificates and the total dwelling stock may differ (e.g. the certified stock is newer and therefore on average more energy efficient than the entire stock in the country).

The approach of *Kovács et al.* (*2021*) is different. In the framework of an earlier, large research programme, they defined twenty-three so-called type buildings representing Hungarian residential real estate, and based on these, they selected a statistically representative sample of two thousand buildings from the Hungarian stock, which they assessed in more detail from an energy point of view. This allowed for an empirical determination of the energy demands of type buildings, from which a weighted lower limit of the best 15 per cent per type can be derived.

The closest methodological approach to our study in the literature is that of *Hettinga et al.* (*2023*). In this study, the authors produce a predictive algorithm that can estimate the letter code of the certificate for all residential real estate in the Dutch real estate register, based on data from energy certificates in the Netherlands. According to the authors, this algorithm predicts the energy efficiency class much more accurately than by assigning the energy consumption of the TABULA model buildings developed for the Netherlands to the data in the land register and determining the energy efficiency levels on that basis. In the present study, we also use a large number of energy certificates, from which a statistical relationship between the characteristics of the residential real estate and energy efficiency is estimated. There are two main differences in our methodology. On the one hand, we do not have a register of the Hungarian real estate stock as in the Dutch case, and thus we must use the Microcensus for the national extrapolation. On the other hand, in this study we focus not so much on the energy efficiency class of the best 15 per cent of the residential real estate stock, but on its actual (calculated) energy demand. We see three advantages of this decision. First of all, this is a more accurate measure of the underlying physical processes to be modelled (the amount of energy consumed by the country's residential housing stock) than the category indicated by the energy efficiency class, since the latter can easily be changed by regulation from time to time. Secondly, this methodology, even with the inherent uncertainty of statistical estimation, can give a more accurate estimate of the 85th percentile than the letter-coded energy efficiency class. In the literature we processed it is typical that the best 15 per cent falls somewhere in the upper part of the rather broad *C* category, but since we have no more information beyond this, we are forced to stop here or to interpolate in some simple way between the category boundaries. Thirdly, to achieve a *BB* or better category, it is necessary to meet criteria other than the primary energy indicator – i.e. renewable energy production. Thus, estimates for letter codes would require the use of more uncertain categorical estimates rather than ordinal ones. The much more detailed database of energy certificates that we use allows us to work more accurately, which is pioneering in the international literature.

2. Research methodology

The energy characteristics of the Hungarian dwelling stock are the subject of a research programme that has been ongoing for several years. In addition to the intensive background work on data collection and data processing, a study on the correlation between the energy performance and price of detached houses (*Ertl et al. 2021*) has also been published, which was joined by a central bank survey with a calculation among new dwellings (*Hajnal et al. 2022*) and a publication on the summary data of certificates (*HCSO 2023*). Our research to estimate the condition of the residential real estate stock consists of three parts. Firstly, the data from the 2016 Microcensus of the residential real estate stock and the new dwellings survey were merged with the energy performance certificates. The result is a database representing the residential real estate stock at the end of 2020 with 68,000 dwellings. Secondly, a statistical correlation was estimated between data for the energy consumption per square metre of the energy certificate and the dwelling characteristics surveyed in the Microcensus. This estimation was performed separately for houses and flats. Finally, using this relation, an energy demand was assigned to each real estate unit that was part of the Microcensus stock but could not be linked to an energy certificate. This results in an estimated energy consumption per square metre for each residential real estate unit in Hungary for 31 December 2020. The results of this approach are presented below.

The real estate units can be ranked according to their energy consumption per square metre, so that the limit value for the best 15 per cent can be determined. Ranking is also possible by type and geographical location. Our methodology can also be updated annually to integrate newly built real estate units.

The estimate itself offers many interesting things which show the relationship between energy consumption per square metre and housing characteristics. The construction period and certain masonry and building engineering characteristics are assigned partial coefficients in the OLS -prediction, which show the overall change on the energy consumption per square metre.

Since the main goal of our work is to estimate the characteristics of the stock, this is in fact a prediction task. We therefore considered it appropriate to also use a prediction method that does not explicitly represent partial effects. The correlation between the energy consumption per square metre and the dwelling characteristics was also performed using the random forest method.

Accordingly, we first present our baseline database and the merged database, and then the statistical estimations performed on the merged database. Our results are presented in the following section, where projections for the whole stock are presented.

2.1. Databases used

2.1.1. Database of energy performance certificates

Based on the European Union guidelines, the energy certification of buildings in Hungary is regulated by Decree 7/2006 (24. V.) TNM on *the determination of the energy characteristics of buildings* and Government Decree 176/2008 (30. VI.). The former determines the calculation method itself, and the latter describes the certification process and the certificate. In the present project, the data of the completed certificates were received by the HCSO for statistical processing from the Lechner Knowledge Center, which manages them. Our research focuses on certificates issued between 2016 and 2020. The calculation methodology changed in 2016, and thus the data before 2016 cannot be compared with the data after 2016. Since, from the aspect of the EU Taxonomy, our aim was to observe the situation at the end of 2020, we used the data after 2016. For the same reason, although post-2020 certificate data is also available, only certificates issued up to 2020 were considered. However, our methodology can also be applied by extending the time horizon.

Table 1 shows the number of energy certificates processed. The table on the certificates issued shows that many certificates worse than *FF* are also issued. At the same time, every year there are more and more real estate units that are at least modern and have been awarded *AA–BB* certification.

Table 1
Number of energy certificates issued for residential buildings for certifications completed between 2016 and 2020, by letter of classification

		2016	2017	2018	2019	2020
AA++	Minimal energy demand	521	398	348	354	453
AA+	Outstandingly energy efficient	0	702	840	445	594
AA	Better than zero energy requirements	0	0	0	342	639
BB	In compliance with zero energy requirements	372	1,505	2,040	3,293	4,869
CC	Modern	16,299	27,062	28,879	30,875	37,639
DD	Close to modern	11,840	18,203	17,950	16,447	15,156
EE	Better than average	12,616	19,631	19,313	17,333	15,123
FF	Average	12,346	18,255	18,761	16,842	14,371
GG	Close to average	11,260	17,218	17,917	16,261	13,645
HH	Poor	14,517	21,143	22,172	21,149	17,362
II	Bad	11,191	15,892	16,931	15,805	13,251
JJ	Extremely bad	5,749	8,149	8,579	7,909	6,550
	Total	**96,711**	**148,158**	**153,730**	**147,055**	**139,652**

Source: Calculated on the basis of the database of the Lechner Knowledge Center, processed by the HCSO

Looking at the purpose of certifications, most of the energy analyses are linked to the sale of real estate (*Table 2*), which is understandable given the legal obligations of the seller. It can be seen, however, that in these years the proportion of new dwellings within certified real estate (certificates prepared for occupancy authorisation) rose to over 10 per cent. Overall, the second most frequent reason for certification is tendering. The category of certification for own use may reflect more than one of the above purposes, which have not been identified by the client for the energy professional. Where several certificates were prepared for the same real estate unit, the one closest to the year of the survey was taken into account (for dwellings surveyed in the Microcensus, the one closest to 2016, for new dwellings the one closest to the year of construction).

Table 2
Number of energy certificates issued for residential buildings for certifications completed between 2016 and 2020, by purpose of certification

Reason of certification	2016	2017	2018	2019	2020
Sale of real estate	83,201	119,047	120,906	106,401	88,645
Tender	3,958	10,720	13,611	17,134	19,740
Occupancy authorization	4,295	8,632	8,946	11,982	18,531
Renting of real estate	1,962	2,579	2,449	2,654	1,542
Obligation imposed	197	86	54	38	87
Public building, state-owned	8	29	6	19	16
Own use	3,090	7,065	7,758	8,827	11,091
Total	**96,711**	**148,158**	**153,730**	**147,055**	**139,652**

Source: Calculated on the basis of the database of the Lechner Knowledge Center, processed by the HCSO

The geographical distribution of available certificates is important for the territorial representativeness of the database. This is shown – by region – in *Table 3*. It can be seen that the database covers a wide area of the country: in our research, we were able to draw on tens of thousands of data points from all regions.

The proportion of certifications carried out in relation to the stock by region and type of settlement is shown in *Table 4*. The highest rate is found in the cities of Pest County, where the share of certificates is 19 per cent of the total, while the lowest rate is found in the municipalities of the Southern Great Plain.

Table 3
Number of energy certificates issued for residential buildings for certifications completed between 2016 and 2020, by region

Region	2016	2017	2018	2019	2020
Budapest	27,635	39,868	38,114	33,593	27,829
Pest county	11,873	19,622	20,641	20,159	18,619
Central Transdanubia	10,685	15,438	15,873	15,607	15,798
Western Transdanubia	9,475	14,361	14,921	14,896	15,491
Southern Transdanubia	8,371	11,628	12,592	12,470	12,451
Northern Hungary	7,928	13,580	14,892	14,974	14,636
Northern Great Plain	9,853	17,603	19,187	18,516	18,431
Southern Great Plain	10,891	16,058	17,510	16,840	16,397
Total	**96,685**	**148,158**	**153,730**	**147,055**	**139,652**

Source: Calculated on the basis of the database of the Lechner Knowledge Center, processed by the HCSO

Table 4
Share of energy performance certificates issued for residential buildings (2016–2020) as a proportion of the dwelling stock in 2020, by region and type of settlement

Region	County seat	Town	Rural municipality	Total
	(%)			
Budapest	18			18
Pest county		19	17	18
Central Transdanubia	17	16	15	16
Western Transdanubia	17	15	15	15
Southern Transdanubia	16	15	11	14
Northern Hungary	15	13	11	13
Northern Great Plain	18	12	10	13
Southern Great Plain	18	12	9	13
Total	**17**	**15**	**13**	**15**

Source: Calculated on the basis of the database of the Lechner Knowledge Center, processed by the HCSO

2.1.2. The Microcensus Dwelling Questionnaire

After the energy performance certificate database presented above, we briefly present the contents of the "Microcensus 2016" database for the dwelling stock, which are described in more detail elsewhere (*HCSO 2017; HCSO 2018*). In 2016, the seventh Microcensus was carried out, with some 440,000 addresses listed in 2,148 municipalities across the country. The selection of addresses was based on stratified sampling and participation was mandatory. This sample – taken between the two censuses – is therefore representative of the residential real estate stock in Hungary. The Microcensus Dwelling Questionnaire is also presented in *Annex 1* of our study. The following data is available from this source:

− exact address of the flat/house,
− area of the flat/house,
− period of construction of the flat/house, roughly by decade,
− masonry type of the flat/house,
− type of heating of the flat/house
− nature of renovation works completed on the flat/house after 2005,
− number of dwellings represented by the flat/house in the Hungarian dwelling stock.

The data was linked to the energy certificates based on the precise address and/or topographical lot number of the real estate.

Technical data of the real estate can play an important role in its energy performance. Some of them directly: type of masonry, type of heating, insulation, replacement of windows and doors. Some of these are indirectly related to the energy demand, such as the period of construction in relation to the materials and construction technology used at that time. We therefore hypothesised a detectable correlation between these characteristics and the calculated energy demand, which we tested statistically. Naturally, we are aware that many other criteria can have a significant impact on the energy performance of dwellings, but in this research we had to rely on the information available in the Microcensus.

2.1.3. New Dwelling Questionnaire

New residential real estate units built between 2016 and 2020 were included in the database on the basis of the OSAP 1078 dwelling construction survey. With the exception of renovation characteristics, which are not relevant for new dwellings, the same data are available as in the Microcensus. When extrapolated to the national stock, these dwellings represent themselves, i.e. they are assigned a weight of 1. This database contained data on 83,000 residential real estate units. The data was linked to the energy certificates based on the precise address and/or topographical lot number of the real estate.

2.1.4. Merged, weighted database

For our analysis, we used the 2016 Microcensus dwelling stock as a basis and linked the energy certificates issued between 2017 and 2020 to these records. The linking variable was the address identifier available from the address register of the HCSO, which was assigned to the energy certificate using the general address cleaning service. In this process, it was possible to match on a sub-registry level address identifier for almost 70 per cent of the nearly 480,000 certificates of which 22,300 dwellings could be identified in the Microcensus database.

In the next step, we looked for energy certificates for dwellings occupied between 2016 and 2020 available from the OSAP 1078 data collection. Since the exact sub-registry level address of these dwellings is not known, only that of the building, the set of certificates for 2016–2020 was narrowed down to those issued for the entire building. This is also deemed justified because it is common practice to prepare an energy performance certificate for the entire building for the occupancy permit. The linking variables were the topographical lot number of the building and the year of occupancy, and the certificates were only taken into account if the whole building was classified in a single energy class and the certificate was issued in the year of occupancy or the year before. In this way, certificates could be linked to 56.5 per cent of the dwellings occupied between 2016 and 2020. In total, 22,300 energy performance certificates were associated with the 386,000 dwellings in the Microcensus, while 46,700 were associated with the 83,000 new dwellings. The question may arise why the data linkage was not complete for new dwellings, since the issuance of a certificate is mandatory at the time of occupation. The main reason is that the exact address details were often not yet known when the occupancy permit for each real estate unit was issued, which is when the statistical census is taken, so the information needed to make the link was not always available.

The energy distribution according to the resulting aggregated database is shown in *Table 5*. In total, we obtained access to 69,000 individual records where the calculated energy demand of the real estate and the characteristics of the dwellings are available. This stock, based on the weights of the Microcensus, represents 300,000 residential real estate units of the national stock.

Table 5
Number and distribution by energy category of data with dwelling characteristics linked to energy performance certificates

	Number of dwellings in the merged database	Share (%)	Number of dwellings represented in the merged database	Share (%)
AA++	640	0.9	658	0.2
AA+	1,703	2.5	1,886	0.6
AA	682	1.0	793	0.3
BB	5,744	8.3	6,839	2.3
CC	34,087	49.5	63,424	21.0
DD	5,300	7.7	30,547	10.1
EE	3,409	4.9	33,575	11.1
FF	3,344	4.9	33,578	11.1
GG	3,277	4.8	32,778	10.9
HH	4,694	6.8	44,042	14.6
II	4,104	6.0	36,554	12.1
JJ	1,944	2.8	16,802	5.6
Total	**68,928**	**100.0**	**301,476**	**100.0**

Source: Calculated from the merged database

After presenting the newly created database on which our calculations are based, the next section describes the estimations made on the database between the real estate characteristics and the calculated energy demand.

2.2. Regression fitting

Fitting was performed with the following variables, where the explained variable was the calculated aggregated primary energy consumption per square metre (“E_p”). The regression specification is similar to the hedonic regression used for dwelling prices, which is used in a number of statistical analyses, including the Technical Manual on Owner-Occupied Housing and House Price Indices (*Eurostat 2017*) and the HCSO Dwelling Survey for dwelling price indices (*HCSO 2016*). While in the case of explanations of dwelling prices, the simple specification has a deep economic content behind it in terms of demand (*Kain – Quigley 1970*), in this case we can assume a relationship between the explained and the explanatory variables on the basis of technical connections. As the full technological properties were not available, we included geographical proxy variables similarly to the regressions explaining dwelling prices. A separate model was estimated for detached houses and condominium flats (buildings with at least three flats). In the regressions, we weighted the observations based on the Microcensus. For both, the following explanatory variables were considered:

Geographical variables:

- 7 regions
- 4 settlement sizes: regional centre (Debrecen, Pécs, Szeged, Győr, Miskolc); towns with county rights; city; rural municipality
- the proportion of taxpayers with a tax base of over HUF 5 million in 2020 in the municipality (the reason to include this is that the presence of higher income households increases the chances of having high quality residential buildings)
- personal income tax base per resident in the municipality in 2020

General variables for the building:

- floor space
- building era:
  - built before 1919
  - built between 1920–1945
  - built between 1946–1960
  - built between 1961–1970

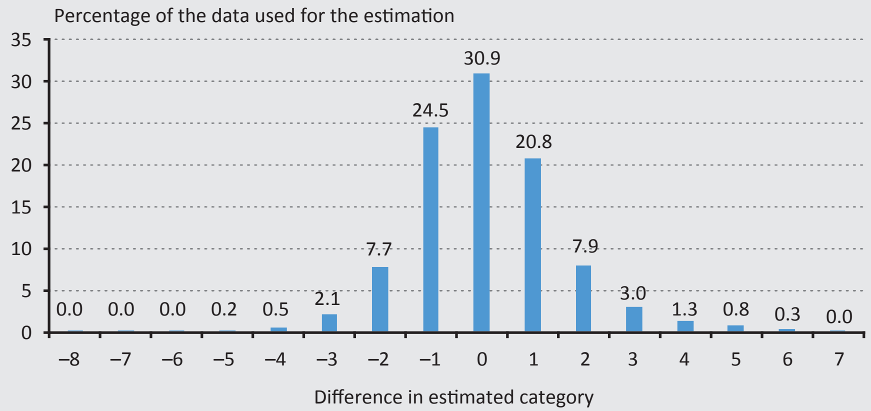
- built between 1971–1980
- built between 1981–1990
- built between 1991–2000
- built between 2001–2011
- built between 2012–2016
- built after 2016

Variables related to the energy of the building:

- Has there been any renovation? (As renovation those works were identified where insulation, window replacement or heating system retrofitting was carried out in the real estate in the ten years prior to 2016, according to the Microcensus, i.e. the answer to Question 13.3, 13.6 or 13.12 of the questionnaire in *Annex 1* was Yes)
- Masonry type: brick, concrete, concrete panel, other
- heat pump, air conditioning, solar panel, existence of centralised ventilation, use of alternative energy
- heating system: separately for each room, one dwelling heated by boiler (central, circle) or other device, more dwellings of a building heated by boiler (central, circle) or other device, district (block) heating
- air conditioner: according to the Microcensus, the owner had an air conditioner installed during the ten years before 2016 (Yes to Question 13.8 of the questionnaire in *Annex 1*)
- heat pump: according to the new dwelling survey, a heat pump was installed in the real estate.

In the regression, we also used cross products in relation to the implementation of the renovation, whose coefficients were found to be significant. The coefficients were estimated using level OLS estimation based on the specificity of the real estate characteristics on the energy demand. According to more traditional fitting indicators, the Adjusted R^2 was 73 per cent for detached houses and 65 per cent for condominiums. By fitting the regression, in addition to the traditional indicator, we also examined how much (by how many categories) the energy category defined on the basis of the predicted energy consumption per square metre differs from the actual rating. This connection is shown in *Figure 1*. In 76 per cent of the cases, our model is at most one category wrong.

Figure 1
Errors of the OLS regression explaining energy consumption per square metre by category difference



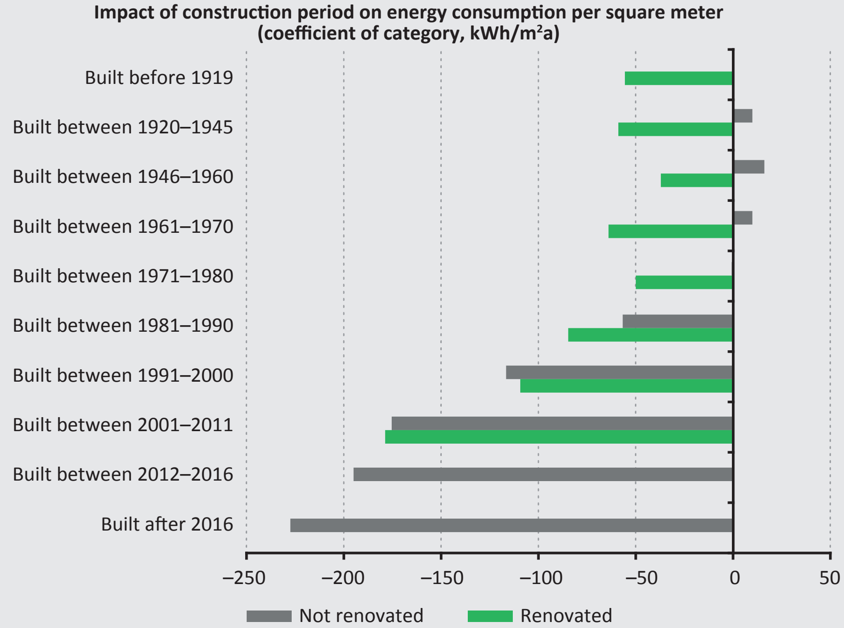
Note: Positive numbers: the energy consumption per square metre predicted by the estimation is in a worse category than the actual certificate (AA++, AA+, AA and BB categories are combined).

Source: Calculated based on the merged database

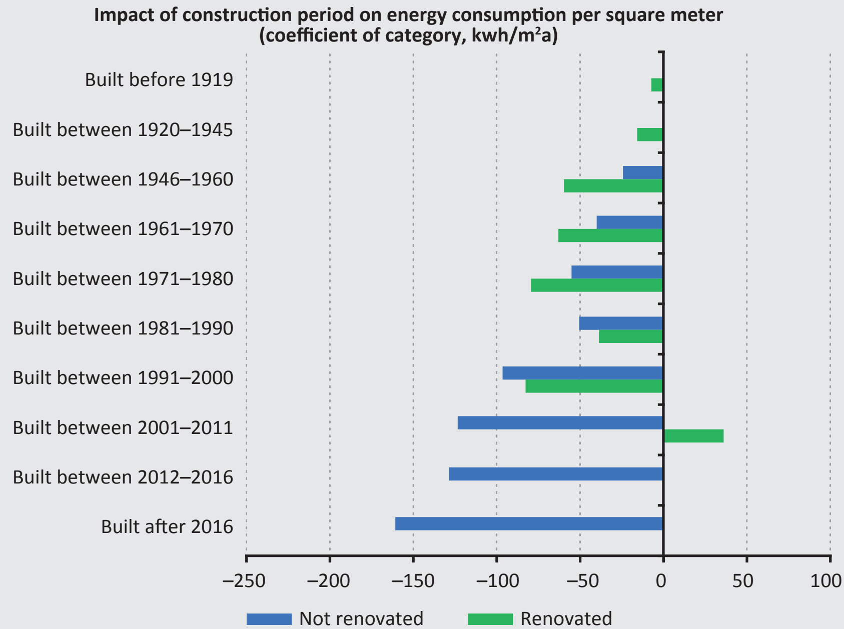
Beyond the general fitting characteristics, it is worth highlighting the magnitude of some estimated coefficients. In the building typology used in the Long-Term Renovation Strategy, the period of construction of buildings plays an important role. The coefficients for the periods defined in the Microcensus were also significant in our estimation (see *Figure 2*). The energy consumption per square metre of modern buildings can be up to 200 kWh/m^{2}a lower than that of old buildings. The differences are slightly larger for detached houses than for condominium flats. Renovated dwelling units show a 50–100 kWh/m^{2}a lower energy consumption compared to non-renovated units. This estimated impact is larger if the building is older and more outdated, and statistically almost negligible in our database if the building is post-2000. For condominiums built after 2000, the coefficient is not significant due to the low number of units.

Figure 2
Estimated coefficients for the year of construction in the OLS regression explaining energy consumption per square metre

a) Detached houses



b) Condominiums



Source: Calculated based on the merged database

In terms of geographical variables, it is worth highlighting the higher energy consumption of real estate in the Northern Hungary and Northern Great Plain regions compared to other regions. It can be assumed that the unobserved real estate characteristics in these parts of the country are also worse than in other regions, because the owners have less money to spend on construction and maintenance. These coefficients explain an average difference of about 35 kWh/m^{2}a between the categories.

Condominiums built with panel technology require around 20 kWh/m^{2}a less energy than the average condominium.

The energy demand of homes without hot water supply from pipeline is much higher, reflecting the impact of other factors such as outdated construction and neglect. The proportion of dwellings without hot water in the sample is 4.5 per cent of the total dwelling stock.

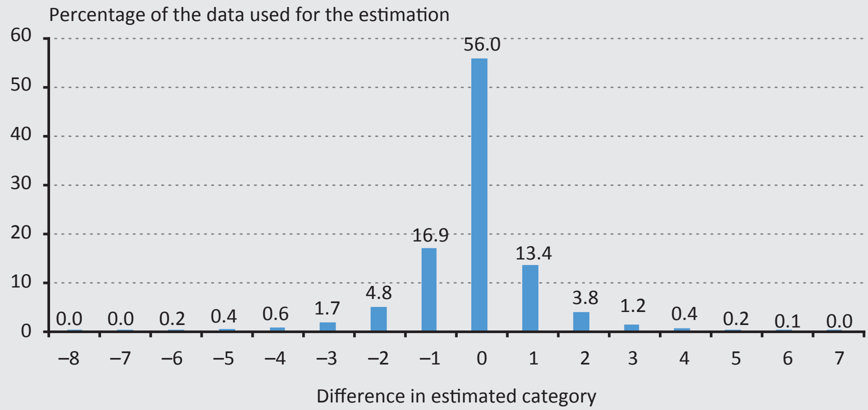
The coefficients of the regressions and the standard errors of the estimates are given in *Annex 2*.

2.3. Fitting a random forest model

Since the aim of our work is to estimate as accurately as possible the calculated energy demand based on the dwelling characteristics in the Microcensus, we also used a popular model in the field of machine learning. We chose random forest, which can capture more flexible relationships in terms of function shape and interactions than OLS. The model incorporates the explanatory variables listed in *Section 2.2.*

The algorithm grew 1,000 trees, with a minimum depth of 5 for each tree, and no limit on the maximum depth was set. The results obtained from the algorithm were tested on both teaching and test sets. The results of fitting are again presented in *Figure 3* based on the estimation of categories. Our model is at most one category wrong in 86 per cent of the cases.

Figure 3
Errors of the random forest model explaining the energy consumption per square metre by category difference



Note: Positive numbers: the energy consumption per square metre predicted in the estimation falls into a worse category than the actual certificate (AA–BB categories are combined).

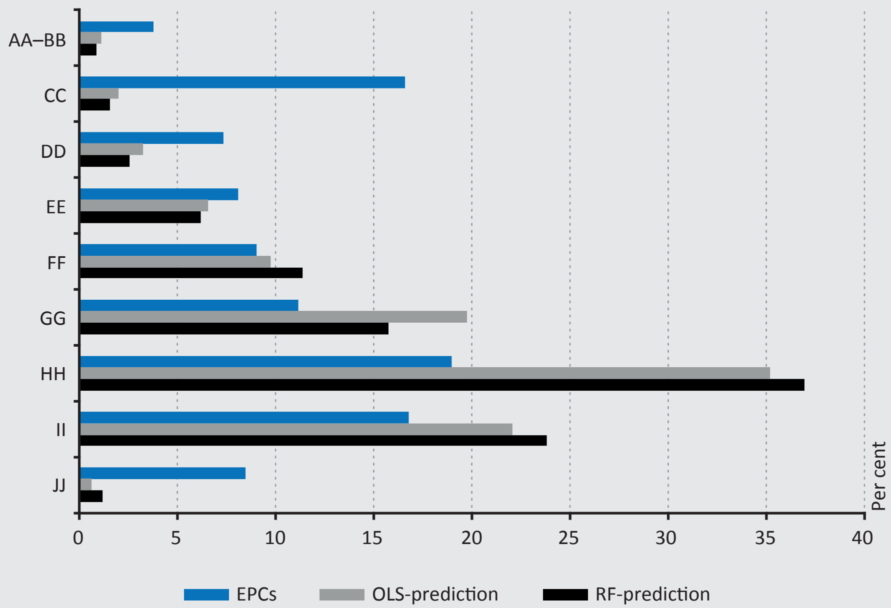
Source: Calculated based on the merged database

3. Results on the energy performance of the Hungarian dwelling stock

3.1. Estimates on the dwelling stock

After estimating the relationship between the energy demand and dwelling characteristics, the relationship was used to estimate the energy demand of dwellings for which no energy performance certificate data were available. Thus, using the original weighting of the Microcensus, an estimate was made for the energy consumption per square metre for the approximately 4.5 million residential real estate units in Hungary. The estimated distributions are similar for the OLS and random forest methods, but both show a less favourable picture than the certificates issued. This result is not surprising, as the real estate units that come on the market are generally better than the stock as a whole. This is mainly because energy performance certificates are issued for all new real estate, and roughly half of this (except for owner-occupied real estate) is put on the market. Another difference in the composition of certificates is that condominiums in large cities change hands more often and are therefore more likely to be certified than detached houses in small towns. However, our statistical method allows us to quantify this difference. While the most common category among the certificates issued is *CC*, the most common category in the stock is probably *HH*. This distribution is mainly the result of the dominant *HH* category among detached houses. In the case of detached houses, category *II* is also frequent, with an estimated number over 650,000 of such houses in Hungary, while the *GG* and *HH* categories include approximately 1.5 million houses out of 2.8 million detached houses. Although the *AA–BB–CC* category accounts for 20 per cent of the certificates, the projection for the stock shows that only 3 per cent of detached houses in Hungary are in the "modern" or better energy category (*Figure 4*).

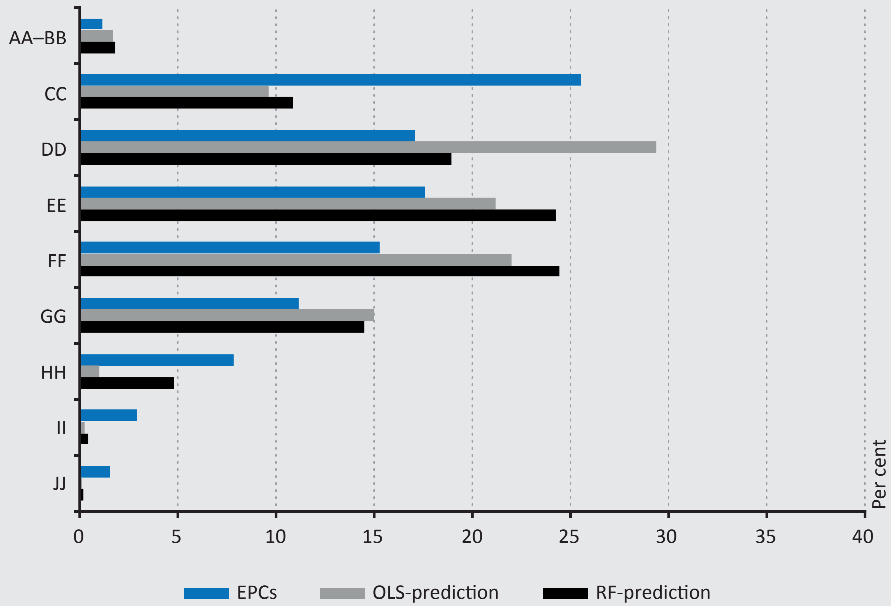
Figure 4
Estimated energy classification distribution of the Hungarian residential real estate stock, detached houses



Source: Calculated based on the merged database and the Microcensus

In the case of condominium flats, the estimation and the projection redraws the distribution shown by the certificates to a slightly less pronounced degree (*Figure 5*). The proportion of real estate that is at least "modern" (categories *AA++, AA+, AA–BB–CC*) can be estimated at over 10 per cent. The *DD–HH* categories show characteristics in lesser proportions. The difference between the OLS and the random forest procedure mainly appears in the *DD* and *HH* categories, which reaches 10 per cent in the case of *DD*. This surplus occurs at the expense of the *EE* and *FF* categories in the distribution of the condominium category.

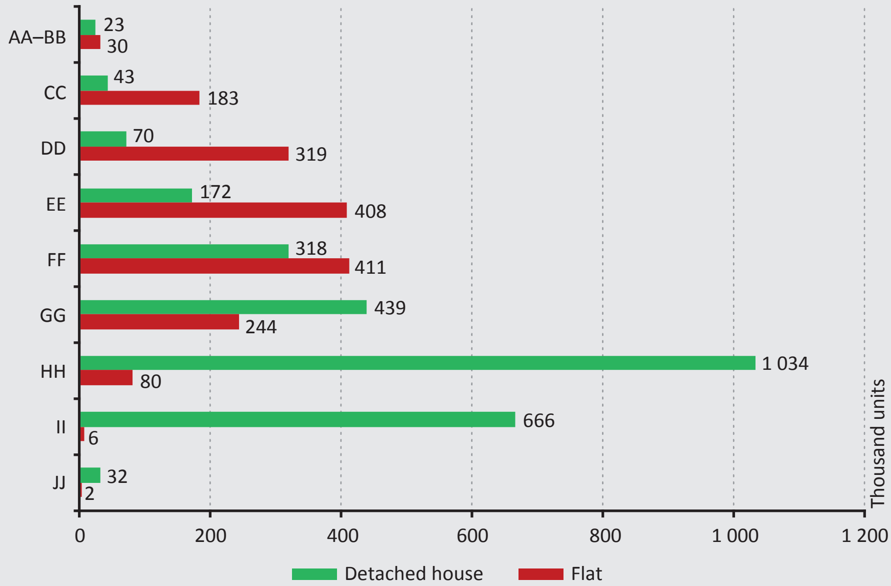
Figure 5
Estimated energy classification distribution of the Hungarian residential real estate stock, condominiums



Source: Calculated based on the merged database

According to the OLS estimation, the most common category for flats is *DD*, which is the "close to modern" rating. Based on the Random Forest procedure, the *EE* and *FF* categories are the most typical among condominiums (see *Figure 5*). The following *Figure 6* combines the RF estimates for the two property types. The distribution between categories shows a striking difference between houses and flats. It is instructive that we estimated 280,000 Hungarian residential real estate in the "modern" category (*CC* and above).

Figure 6
Estimated energy classification distribution of the Hungarian houses and flats



Source: Calculated based on the merged database

3.2. Estimates for the best 15 per cent limit

Since the projections assign an energy demand to every domestic residential real estate unit, the method is suitable for answering any question related to distribution. In the Taxonomy rules, the limit of the best 15 per cent plays an important role, so these data are published in *Table 6*. The OLS estimate puts the limit for the best 15 per cent of residential real estate slightly lower in terms of energy efficiency (total primary energy demand: 149 kWh/m^{2}a). While for flats the OLS and the random forest estimates predict almost identical limit values, for houses the OLS estimate is 9 kWh/m^{2}a lower.

There are differences also in the geographical distribution. The limit value for houses is the lowest in Budapest. For flats, Southern Transdanubia shows even lower values than the capital. The highest limit values for houses are shown in the table in Northern Hungary. The highest values for flats are in Northern Hungary (OLS) and Northern Great Plain (RF).

The difference between the lowest and highest values can be as much as 100 kWh/m^2 a for houses, while for flats it is around 20–30 kWh/m^{2}a.

Table 6
Limit of the lowest 15 per cent in terms of estimated energy demand in the Hungarian stock for the prediction based on OLS estimation and random forest (RF) (total primary energy demand, kWh/m2a)

Region	RF			OLS		
	House	Flat	Total	House	Flat	Total
Budapest	169.9	128.8	132.1	153.8	130.6	131.6
Pest county	178.0	132.0	163.0	174.1	129.4	156.0
Central Transdanubia	217.6	143.0	164.6	215.5	138.0	150.2
Western Transdanubia	198.4	143.7	161.5	186.5	137.4	150.5
Southern Transdanubia	251.6	112.8	164.0	233.6	119.9	142.3
Northern Hungary	264.2	144.7	186.8	263.7	148.2	182.6
Northern Great Plain	255.0	152.6	184.5	246.9	144.6	176.0
Southern Great Plain	262.0	135.0	185.7	247.1	136.8	169.0
Country level	222.9	133.3	160.3	214.0	133.6	149.4

Source: Calculated based on the merged database

4. Discussion

The estimates of the domestic building stock in the National Building Energy Performance Strategy and the Long-Term Renovation Strategy are based on 23 building types. Compared to this, in this study we have estimated the energy condition of domestic residential buildings using much more detailed estimation and statistical methods. A more detailed estimate also gives an idea of the relationship between the energy demand and some characteristics of the real estate. Projection to the whole stock is also suitable for displaying geographical and distributional characteristics.

Unfortunately, comparing our results internationally is very difficult. This is due to the limitations of the databases available to researchers, as explained in the introduction. This is particularly true for Hungary's neighbours, and more broadly for the countries that joined the EU in 2004, which we believe may provide a more relevant basis for comparison, both in terms of housing construction traditions and climatic conditions, than, for example, Scandinavian or Mediterranean countries. On the other hand, this fact underlines the innovative nature of our research and its contribution to the assessment of the energy status of the Hungarian residential real estate stock, and makes it suitable to inform domestic decisions on EU Taxonomy.

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Annexes

Annex 1: Microcensus 2016 – Dwelling Questionnaire

The questions and response options contained in the electronic Dwelling Questionnaire

The correct address of the dwelling

1. What is the type of the building?
− family house, 1–3 dwelling residential building
− residential building of 4 or more dwellings
− holiday resort
− not residential building (e.g. public institute, office building, factory building)

2. What is the type of the housing unit?
− dwelling (family house as well)
− holiday home
− other (e.g. shop, caravan)

3. When was the dwelling built?
− before 1919
− 1919–1945
− 1946–1960
− 1961–1970
− 1971–1980
− 1981–1990
− 1991–2000
− 2001–2011
− in 2012 or later
− not known

4. What was the dwelling built of?
− brick, stone, manual walling element
− middle or large block, cast concrete
− panel
− wood
− adobe, mud, etc. with solid basement
− adobe, mud, etc. without solid basement
− other
− not known

5. How is the dwelling used?
− habitually, for everyday life as a home
− seasonally only or as a second home
− for other purpose (e.g. office, doctor's office)
− vacant dwelling, no occupants

6. Owner of the dwelling:
− natural person(s) of Hungarian citizenship
− natural person(s) of foreign citizenship
− local government
− other institution, organisation (e.g. company, enterprise, church)

7. What is the total floor space of the dwelling?

Do not count the size of the cellar, attic, garage, open balcony or terrace. If the dwelling has more than one floor, consider all the floors.

…m^2

8. Rooms of the dwelling:

Multi-purpose rooms must be divided by use (e.g. American kitchen into kitchen and room).

8.1. number of rooms over 12 m^2 (e.g.: living room, bedroom, dining room): …
8.2. number of rooms of 12 m^2 or smaller (e.g.: living room, bedroom): …
8.3. number of kitchens of 4 m^2 or larger: …
8.4. number of kitchenettes under 4 m^2: …
8.5. number of bathrooms: …
8.6. number of flush toilets (in bathroom or separately): …

9. Type of

9.1. water supply in the dwelling
− from public pipeline
− from private pipeline (e.g.: from well by pump)
− no piped water in the dwelling

9.2. hot water supply in the dwelling
− from pipeline
− from electric or gas boiler, kitchen water heater or other way
− no hot running water

10. Sewage disposal from the dwelling
− into a public sewer
− into private sewer (closed reservoir, cesspit)
− into another place or there is no sewage disposal

11. Heating
− separately for each room with convector, stove, etc.
− one dwelling heated by boiler (central, circle) or other device
− more dwellings of a building heated by boiler (central, circle) or other device
− district (block) heating
− no heating

12. Energy used for heating – Two answers can be given.
− piped gas
− LPG gas (container)
− LPG gas (bottle)
− wood
− coal
− electricity
− fuel oil
− alternative energy, namely (e.g. solar energy, geothermal energy): …
− other, namely: …

13. In the last 10 years what kind of maintenance, renovation or updating works have been done in the dwelling?

In case of a building of more dwellings, consider also insulation, renovation works on the building.

13.1. interior decoration, painting, wallpapering: yes/no
13.2. changing or repairing tile, floor-tile: yes/no
13.3. insulation (e.g. insulating walls, joist, floor): yes/no
13.4. exterior renovation (e.g. painting, whiting): yes/no
13.5. installing new meters (do not consider changing meters): yes/no
13.6. replacing mechanical installation (e.g.: radiator, electric boiler, air-conditioner): yes/no
13.7. installing air-conditioner: yes/no
13.8. installing public utilities (e.g.: gas, drainage system): yes/no
13.9. forming new rooms or other parts of dwelling (e.g. building bathroom, increasing the number or size of rooms, attic conversion): yes/no
13.10. changing doors, windows: yes/no
13.11. other renewing works in the dwelling, namely: …

Annex 2
Results of the OLS prediction

Explained variable: Energy consumption per square metre in the energy performance certificate

	Detached house		Condominiums	
	Coefficient	**Standard error**	**Coefficient**	**Standard error**
Constant	462.072***	1.842	433.484***	3.486
Pest county	–4.938***	0.699	–17.542***	1.014
Budapest	–33.199***	1.020	–27.720***	1.530
Central Transdanubia	–3.795***	0.746	–9.029***	0.759
Western Transdanubia	–14.608***	0.716	–6.188***	0.762
Southern Transdanubia	–22.252***	0.763	–24.679***	0.780
Northern Hungary	3.676***	0.693	1.577**	0.689
Northern Great Plain	–10.217***	0.702	–6.931***	0.751
Southern Great Plain	–4.047***	0.426	–5.062***	0.900
Built between 1920–1945	10.029***	1.303	–0.748	1.039
Built between 1946–1960	16.039***	1.249	–24.511***	1.092
Built between 1961–1970	10.027***	1.256	–40.108***	0.928
Built between 1971–1980	–0.864	1.322	–55.087***	0.865
Built between 1981–1990	–56.754***	1.378	–50.903***	0.941
Built between 1991–2000	–116.697***	1.460	–96.681***	1.170
Built between 2001–2011	–175.683***	1.417	–123.356***	0.941
Built between 2012-2016	–195.378***	3.023	–129.133***	3.791
Built after 2016	–227.622***	1.265	–161.130***	1.006
Built before 1919, renovated	–28.045***	2.381	–0.406	1.551
Built between 1920–1945, renovated	–41.298***	2.255	–8.169***	1.548
Built between 1946–1960, renovated	–25.855***	2.231	–28.685***	1.230
Built between 1961–1970, renovated	–46.569***	2.256	–16.455***	1.066
Built between 1971–1980, renovated	–21.577***	2.283	–17.909***	1.165
Built between 1981–1990, renovated	–0.363	2.389	18.856***	1.998
Built between 1991–2000, renovated	34.518***	2.452	20.296***	1.904
Built between 2001–2011, renovated	23.898***	4.876	166.359***	9.697
Concrete walls	–1.041	0.898	–6.310***	0.552
Other walls	2.752***	0.512	1.999	1.507
Panel walls	–89.733***	4.162	–20.631***	0.561
Heating separately for each room with convector, stove, etc.	–39.615***	0.460	–29.993***	0.515
More dwellings of a building heated by boiler (central, circle) or other device	–64.345***	1.227	–43.190***	0.629

Annex 2
Results of the OLS prediction

Explained variable: Energy consumption per square metre in the energy performance certificate

	Detached house		**Condominiums**	
	Coefficient	**Standard error**	**Coefficient**	**Standard error**
District (block) heating	–49.669***	2.459	–58.655***	1.035
Hot water supply from pipeline	–16.304***	2.471	–87.709***	3.144
Hot water supply from electric or gas boiler, kitchen water heater or other way	23.250***	1.024	–90.057***	3.104
Dwelling area	–0.538***	0.012	–0.379***	0.012
Square of dwelling area	0.001***	0.000	0.001***	0.000
Region centre dummy variable (Debrecen, Pécs, Szeged, Győr, Miskolc)	–24.567***	0.844	–21.186***	1.434
Towns with County Rights dummy (non-region centre)	–20.168***	0.682	–16.357***	1.419
City/Town	–8.629***	0.420	–8.269***	1.412
Renovated	–27.416***	2.042	–6.680***	0.917
Has air-conditioning	–25.318***	0.587	–2.959***	0.404
Heat pump	–24.445***	1.530	–26.355***	1.523
Centralised ventilation	–3.054**	1.239	3.511***	0.887
Solar panel	–0.141	3.503	13.538***	2.884
Alternative energy (solar energy, geothermal energy, other)	–31.003***	2.628	–28.681***	2.243
Percentage of residents with a tax base of over HUF 5 Million in the municipality	–1.091***	0.088	0.227**	0.104
Tax base per capita in the municipality	–0.002	0.001	–0.006***	0.002

*Note: Significance: ***: 1%, **: 5%, *: 10%*

Source: Calculated based on the merged database