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Using Hotmaps Online Heat Atlas for Energy Planning in a Rural Area and the Influence of Spatial aspects on the Energy Mix – a Case Study of a Geographically Mixed Rural Area in Hungary

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ABSTRACT

Rationalising the production and use of thermal energy would be key to the energy transition. However, in most rural areas, heat planning and a just transition are challenging. Energy geography solutions such as innovative online heat atlases, like Hotmaps, are valuable tools for estimating household heat demand at the municipality level. The aim of this study was twofold: firstly, to compare the Hotmaps database to field-obtained actual consumption data and to determine its usability for local thermal energy planning in a Hungarian rural study area; Secondly, to investigate the influence of spatial aspects on the heating energy mix in a study area facing coal phase-out. The results confirmed that the investigated settlements with residential heat demand above 5,000 MWh/a could rely on the Hotmaps, however, complete local heat mapping can only be done by field data collection, especially where the ratio of solid fuels is over 50%. The heating energy mix can vary significantly even within a small geographical area. This underlines the importance of in situ rural energy mapping and highlights the need to develop such complex but replicable methodologies for heat planning in this research area.

Keywords

Rural heat planning;
Hotmaps;
Heat atlas;
Residential heat demand;
Heating energy mix.

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1. Introduction

Heat planning is a crucial element of the transition to a more sustainable and independent energy system, which is a desirable goal given that Central and Eastern Europe countries, especially *Hungary*, are highly dependent on imports. The country's energy dependence ratio exceeds 80% [1]. There is an urgent need to take steps towards energy autonomy, which can only be achieved with thorough energy planning studies [2]. Identifying sustainable solutions that are locally available and developing scenarios based on the current situation would be essential because long-term heat planning is vital for municipalities since heat cannot be produced and transferred in a vast national-level system.

1.1 Background of the research

EU Member States have had to create and revise National Energy and Climate Plans to forecast the improvements and future parameters of the energy system by 2050. These plans can be complemented by regional and municipal level Sustainable Energy Action Plans (SEAP), which are incentives that concentrate specifically on opportunities at a local level. Marinakis et al. (2017) underline the importance of the participatory approach in energy planning in the case of SEAP [3].

The revised Energy Efficiency Directive (EU/2023/1791) also recognises the importance of local heating plans, introducing a provision for developing local heating and cooling plans for at least those

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Abbreviations

CV: calorific value
DHW: domestic hot water
HEM: heating energy mix
RHD: residential heat demand

municipalities having a total population of more than 45,000. Small local authorities can also observe the need for such a strategy. In the framework of a LIFE-funded project, a municipality survey was conducted in *Bulgaria, Hungary and Romania* [4], 74,8% of the 1,500 respondents, covering 20% of the municipalities in *Hungary* and *Romania*, and 15% in *Bulgaria*, do not have a local climate mitigation strategy, but they intend to develop one.

Furthermore, integrated spatial and energy planning (ISEP) can be another tool for reaching sustainable development goals, namely “clean and affordable energy.” The concept of ISEP is embedded in a formalised spatial planning system as an integral part that holistically addresses the spatial dimensions of energy demand and supply [5].

Heat atlases have been coming to light to map and analyse local heat demand and supply possibilities [6]. They could be essential in heat planning because they cover areas where no other studies are available. In most countries, there needs to be a proper database, which does not allow the heat demand to be calculated in a bottom-up heat planning model [7]. In *Denmark*, a national database contains the most important building energy data needed for this purpose, as well as individual addresses and geographic identifiers. The accuracy of these databases was also investigated, confirming that such atlases can effectively support energy planning processes [8].

One of the international developments in this field is Hotmaps [9], an open-source heating and cooling toolbox that aims to provide a starting point for planning. Hotmaps provides data even at the municipal level. This will help local authorities, which typically lack human capacity and specialised knowledge, to identify, analyse, model and map resources and solutions to meet the energy needs of their area in a relatively simple way. Furthermore, the database could facilitate the development of energy strategies and action plans such as SEAPs on local, regional and even national scales [9].

The situation in *Hungary* is similar to the European average; unfortunately, a thorough knowledge of the thermal energy consumption of municipalities at the building level is not available. Our 10-year research, described in this article, aims to partially fill this gap. Using the data collected, we continued our work with the comparison with Hotmaps and heating energy mix mapping. This offered a useful opportunity, as we considered it worthwhile to investigate the extent to which it could be applied to the situation of small rural settlements in *Central Europe*.

1.2 Literature review

An important step in taking spatial aspects into account was the GIS-based research in which Nielsen (2014) applied a methodology to assess the potential for district heating extensions [10]. The first heat atlases were developed in *Denmark* using GIS. The Danish Heat Atlas, the predecessor of Hotmaps, has been subjected to very thorough comparative studies using measured data firstly from the buildings in the region of *Mid-Jutland* [6], and secondly from 1 million residential buildings all over the country [8].

One of the first continental-level heat atlas, Pan-European Thermal Atlas (PETA) developed within the framework of the Heat Roadmap Europe project, Möller et al. (2018) presents a thermal atlas of *Europe* at a resolution of 100 metres [11]. As an important part of the project, the analysis by Möller et al. (2019) is a huge step forward in assessing the potential of excess heat in *Europe* [12].

Hotmaps is a project with a significant spatial dimension, providing a toolkit for strategic heating and cooling planning [13]. The toolbox is meant to be used mainly by public authorities, energy agencies, and urban planners on all scale [14,15]. It incorporates handbooks with guidelines and open-source software that functions without any other commercial tool. The Hotmaps contains building-related information, such as heat and cooling demand densities, gross floor areas, and building volumes [16]. Pieper et al. (2022) compared the Hotmaps heat demand density map to the National GIS database in the *Pärnu region of Estonia* [17]. Pezzutto et al. (2019) developed the method of the Hotmaps project, which was tested in the pilot areas, such as *Aalborg, Bistrita, Frankfurt, Geneva, Kerry County, Milton Keynes, and San Sebastian* [18]. However, the top-down method used in the Hotmaps could be further tested in regions, particularly in rural areas with residential buildings characterised by low energy efficiency and a lack of access to affordable clean fuels.

Due to rural communities' socio-economic and sustainability characteristics, a combination of resources and methods may help study energy consumption [19]. According to Peng et al. (2019), the presence of solid fuels in the heating energy mix (HEM) of rural areas makes planning more difficult due to the need for more reliable statistics on consumption [20]. This research group conducted a field survey covering approximately 17,000 rural households in *China* to obtain data on solid fuel use patterns. Researchers found that actual energy consumption was 62% more than reported. The $PM_{2.5}$ emissions from household coal usage were also underestimated. Furthermore, the national total biomass consumption was 50% lower than reported. Their findings highlight the importance of field surveys in energy planning [20].

Ma et al. (2022) utilised a questionnaire survey to understand the energy consumption habits in rural households in *central China* [21]. Collected data was used to calculate the direct carbon emissions from related energy use. The authors suggested that behavioural change would be crucial in reducing carbon emissions.

The study of Yu et al. (2024) takes the municipality of *Holbæk in Denmark* as a case study to examine the potential of rural heating systems, taking into account local fuels, excess heat, and individual heating technologies [22].

Based on the literature, the Hotmaps online heat atlas could benefit from an analysis of its application in a rural area with different geographical aspects that the pilot areas used to validate the tool. The literature also suggests the benefits of combining resources and methods for energy planning in rural communities. Considering the gap in knowledge of applying heat atlases in a rural setting and the value of combining heat atlases with other methodologies. There for specific research aims were defined in 1.3 Subsection.

1.3 Scope

As mentioned above, most rural municipalities face significant knowledge (data and expertise) and resource (human and financial) gaps, which cause a considerable burden in implementing heat planning and climate mitigation actions. Therefore, many local authorities would be willing to act [4], since the predominantly solid fuel heating causes PM_{10} air pollution that often exceeds the limit value during the heating period [23]. However, the above-mentioned barriers threaten the achievement of long-term climate and emission targets. There are four specific aims of this research:

1. To create a comprehensive database for the 20 municipalities in the study area, which can be used for bottom-up heat planning.
2. To examine the accuracy of Hotmaps for heat planning in rural settlements. The online heat atlas was tested by comparison to the results of a thorough field survey focused on residential energy consumption, including actual heat demand calculations. As a hypothesis, it was assumed that Hotmaps is a reliable source of residential heat demand (RHD) for heat planning in rural settlements. At the same time, we need to know the limitations of its use within the study area. The following research questions have risen:
   - How can this tool be beneficially used for energy planning purposes in a geographically diverse, Hungarian rural research area where the investigated settlements have vastly different characteristics and land uses?
   - How do the size of the settlements and the HEM, especially the difficult-to-calculate solid fuel ratio, affect the practical accuracy and reliability of the tool?
3. To develop a methodology to help bridge the statistical gap in heat planning in our rural study area.
4. To investigate the influence of spatial aspects on the heating energy mix by focusing on the solid fuel ratio in the residential sector. The most important additional research questions in this regard were:
   - What does the residential HEM look like and what is the exact spatial pattern of it within the study area?
   - What is the correlation of inescapable energy geographical factors such as the existing open-cast lignite mine, large expanses of protected forest or intensive suburbanisation with the residential HEM pattern?

A key element of our research is the comparison between Hotmaps and the BÜKK dataset (the latter will be referred to by this abbreviation throughout the paper). The BÜKK dataset contains the results of our extensive field research based on the household energy questionnaire detailed in Chapter 2. Through this, we sought to understand the applicability and limitations of the Hotmaps in a typical Central European rural area. Beyond this, we also intend to use our methodology and results to support and accelerate the implementation of energy transition within the study area.

2 Materials and Methods

The first part of the analysis estimates the RHD. The applied methodology of the RHD calculation was based on our earlier analyses [23,24]. The study area of this paper is composed of 20 settlements. Fifteen out of 20 currently investigated settlements' RHD information was available; however, the current study area contains 5 new municipalities with radically different characteristics.

The database gained from the field survey questionnaire was used for these calculations. Then, the RHD calculation results for the field database were compared with those of the Hotmaps database. During the RHD comparison, the HEM of the municipalities provided a reference for interpreting possible anomalies.

The main inputs are

a. statistical data on population;
b. statistical data on natural gas consumption;
c. heating pattern and thermal comfort expectations;
d. "actual energy billing data" (incl. the type, quantity and quality of utilised fuels);
e. building insulation condition and stock of heating appliances.

Extensive in-depth surveys in the study area collected data on b), c), and d) official statistics complemented the database created from the surveys [25]. The results for each settlement are compared to the Hotmaps (Figure 1).

There are settlements within the study area with vastly different energy resource use patterns. Therefore, this work can serve as a basis for further analyses and energy planning projects that aim to increase the share of local renewable energy use in *Hungary* and other *European regions*. One of the findings of our previous analysis underlined [24] that there were 18 communities out of the investigated 20, where renewable based residential heat self-sufficiency could be reached. The detailed questionnaire on household energy consumption patterns is available in Appendix 1.

2.1 Description of the study area

The 20 investigated settlements of the *Bükkalja region* are situated in the southern part of the *Bükk Mountain*. The study area has geographically diverse natural and economic characteristics, covering plain and mountainous areas and their borderline. One of the biggest opencast lignite mines in *Europe* is located here [26] and there are also dense protected forest ecosystems (*Bükki National Park*), massive geothermal potential, e.g., active thermal wells and abandoned hydrocarbon test wells, and vast areas of arable land [27,28]. The settlements vary from

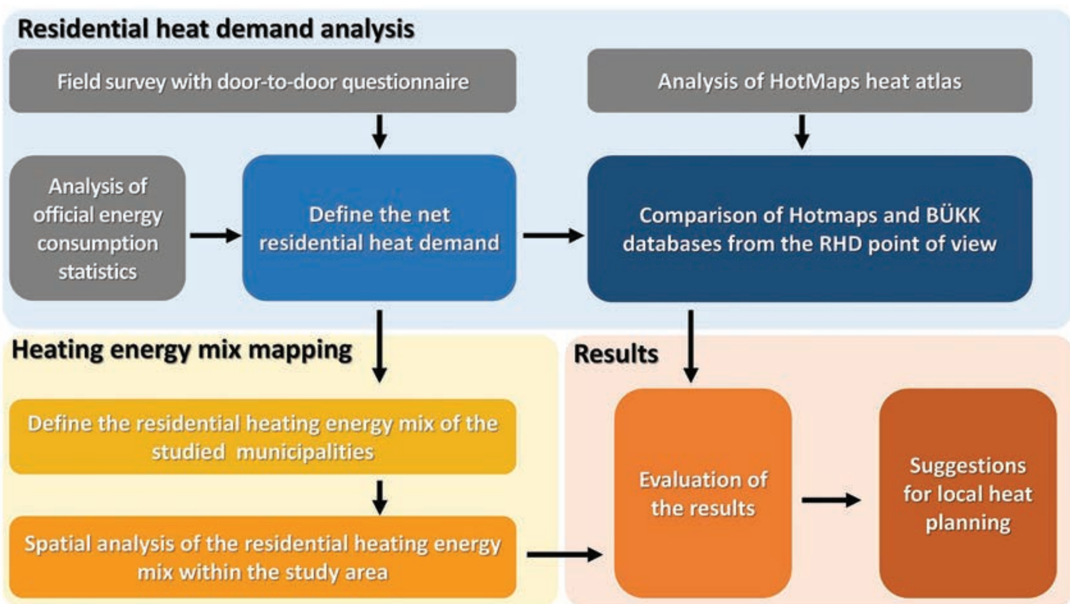

Figure 1: The input data sources and the utilised methodological steps of the study.

remote small villages to bigger, more developed agglomeration municipalities between 276 to 5,030 residents. These factors make the study area a uniquely diverse test field for the heat atlas and spatial HEM analysis (Figure 2). In 2023, the overall population of study area was 32,983 inhabitants in 15,021 households.

Deliberate energy planning of residential heating would be essential in the study area, as it is highly dependent on imported natural gas and locally mined poor-quality lignite. The EU's Fit55 and its RepowerEU descendant require the Member States to move away from natural gas. The area is also affected by the EU's Just Transition Mechanism [29] and the "coal regions in transition" initiative [30]. These need to lead to a significant change in the source structure of the heat sector for several neighbouring settlements, which would be particularly justified in starting the heat planning processes. A detailed RHD analysis should accompany this, but this data is unavailable at the desired scale in *Hungary*.

Socially, is one of the most deprived regions in the country. The indicator of overall satisfaction with life was one of the worst in the country in 2023 [31]. The net income per capita indicator (~4,750 EUR/capita/year) was the lowest in *Hungary* [32].

These are the main reasons why the illegal burning of waste is not uncommon and using outdated, unmaintained heating devices is standard in the study area. Many local households suffer from different depths of energy poverty. The lignite opencast mine still determines the socio-economic situation of the area but the planned mine closure until 2030 could temporarily worsen this situation. On the other hand, the EU's energy and climate policy, as coal phase-out could accelerate the region's just (energy) transition.

In *Hungary*, as part of the "utility cost reduction programme", the government kept energy prices artificially low for nearly 10 years [33], before raising them significantly after the outbreak of the energy crisis in 2022. Households and local authorities responded by considerably reducing their energy consumption, but in an ill-conceived and poorly planned way. This highlighted several problems, namely that there was no motivation to improve

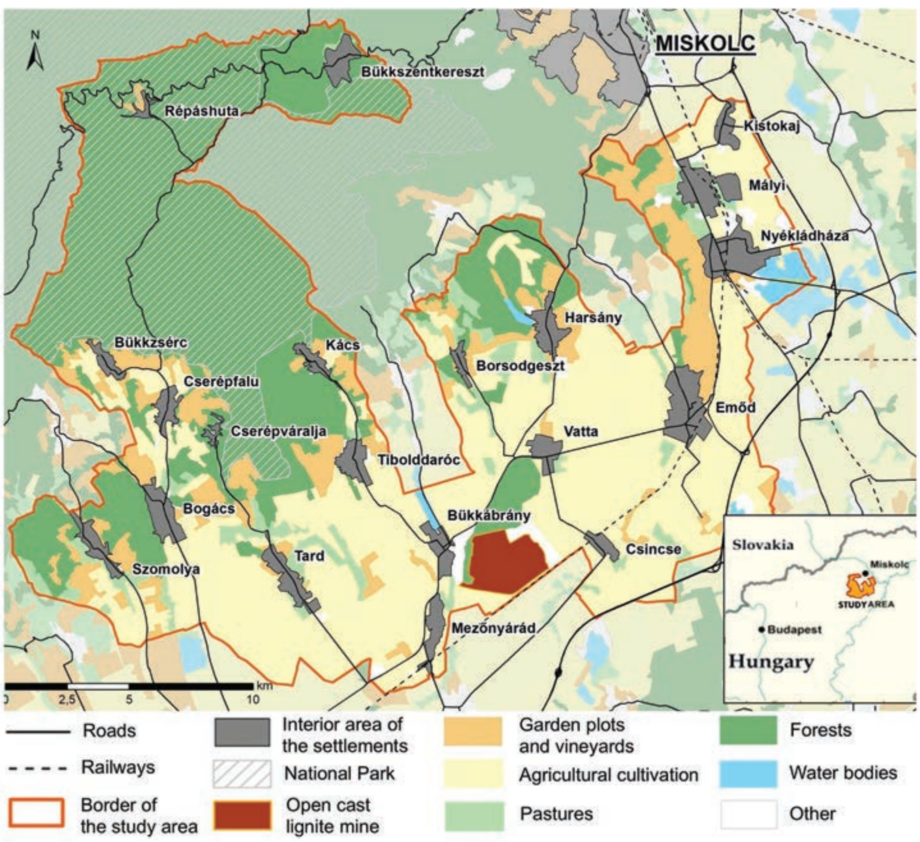

Figure 2: The study area is located in the *Bükkalja region*, *Hungary* - the colour codes used in the labels are valid only for the study area; outside the study area colours are faded (edited by Tamás Soha and Csaba Csontos).

the energy efficiency of the residential building stock; families had no intention of saving energy and the general energy awareness was low too [34].

2.2 Residential heat demand estimation based on field surveys

The residential heat demand estimation was based on previously developed extensive door-to-door surveys [23,24], which included actual billing data collection. In this process, 10% to 35% of the occupied dwellings in each municipality within the study area were visited. In light of our previous fieldwork, we put more emphasis on getting a higher proportion of responses to reduce the anomalies caused by the small number of samples.

2.2.1 Methodological background of the field survey

Specially trained university students and researchers interviewed the residents using a complex questionnaire (Appendix 1), resulting in a vast dataset with more than 2.5 million data points from 2,500 households of 20 investigated settlements. The database contains information on the main parameters of the energy performance of buildings and energy consumption patterns, such as

- the condition of buildings, including the heating system, insulation, windows and doors;
- the quantity and quality of fuel used;
- heating habits and indoor climate requirements;
- the production of domestic hot water;
- details of electricity consumption.

Surveys took 20 to 40 minutes per household and were carried out between 2015 and 2021. Home visits were prepared in collaboration with local authorities; thus, inhabitants were generally open to cooperating. The survey was conducted on weekdays and weekends to increase the response rate and representativeness, including the diversity of the Respondents' age, family, and financial status. The research aimed for the most extensive possible geographical coverage to avoid the distorting effects of social and wealth differences within the investigated municipalities. When it was possible, the interviewers made visual inspections of the heating system and energy-related elements of the building, taking notes that were used in the qualitative analysis. After collecting qualitative and quantitative data, detailed spreadsheet and statistical analyses were carried out.

2.2.2 Input data regarding heat supply from statistics

Besides onsite data collection, official national databases were used for the estimations, i.e. municipality-level annual natural gas consumption. Based on these values, mean natural gas consumption data for 2015–2019 was considered to eliminate the anomalies of yearly weather fluctuations. Due to the COVID-19 pandemic and the subsequent energy crisis in 2022, residential energy consumption patterns substantially changed. Khalil and Fatmi (2022) suggest that residential energy consumption, in some cases, may have increased by 29% during the pandemic [35]. Therefore, statistical data between 2020 and 2023 was not considered.

2.2.3 Efficiency of the heating equipment

The RHD estimation considered the calorific value of the region's commonly used fuels and the efficiency of the heating appliances (Figure 3). The fuel consumption

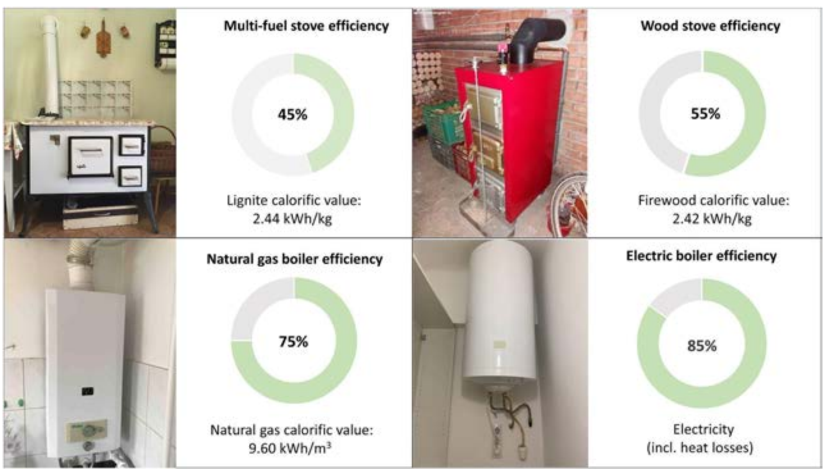

Figure 3: The typical types and efficiency of heating equipment and fuel calorific value (CV) in the study area. Efficiency indicators represent the average efficiency of stoves and domestic hot water (DHW) systems include measured heat losses [37,38].

estimation and efficiency calculations resulted in each household's average annual RHD. Most of the heating equipment identified in the surveyed households was outdated, more than 25 years old, low-efficiency gas boilers (ave. efficiency 75%), solid fuel stoves (ave. efficiency 45%) and multi-fuel boilers without heat storage (ave. efficiency 55%) or buffer tanks. The efficiency of the calculations was based on the categorisation of the Hungarian housing stock reported by Csoknyai et al. (2016) [36].

2.2.4 Residential heat demand calculation formulas

The energy demand from natural gas consumption was calculated:

$$Ng = \Sigma\left(Cg * cal * \eta g\right) * ep \tag{1}$$

where N_g = the net energy demand from natural gas in MWh; C_g = natural gas consumption (m^3); cal = average caloric value (kWh/m^3) of the residential natural gas; η = average gas combustion efficiency; ep = extrapolation factor (T/n) for the whole settlements Eq. (1).

The energy demand from firewood consumption was calculated:

$$Nc = \Sigma\left(C * cal * \eta l\right) * ep \tag{2}$$

Where N_f = the net energy demand from firewood in MWh; F = firewood consumption in m^3; d = dryness factor (%); cal = caloric value of firewood with different levels of moisture content (kWh/m^3); ηb = average solid biomass combustion efficiency; ep = extrapolation factor (T/n) for the whole settlements Eq. (2).

The energy demand from lignite (coal) consumption was calculated:

$$Nc = \Sigma\left(C * cal * \eta l\right) * ep \tag{3}$$

Where N_c = the net energy demand from lignite in MWh; C = lignite consumption in tonnes; cal = average caloric value (kWh/tonne) of lignite from Bükkábrány's mine; = average lignite combustion efficiency; ep = extrapolation factor (T/n) for the whole settlements Eq. (3).

The domestic hot water (DHW) demand from electricity consumption was calculated:

$$N_{DHW} = \Sigma\left(E * \eta l\right) * ep \tag{4}$$

Where N_{DHW} = the net energy demand from electricity in MWh; e = electricity consumption of average size (120 litres) DHW boiler in MWh; = average DHW boiler efficiency including heat losses; ep = extrapolation factor (T/n) for the whole settlements Eq. (4).

Heating with electricity is not widespread in the study area. Some households use electricity as an additional heating source to heat one or two rooms (most typically the bathroom); however, this amount of energy is hardly quantifiable since neither statistical nor actual billing or measured data are available. Therefore, this negligible consumption has yet to be considered. The distribution of heat pump-based or fully electrified heating systems is less than 1% in the study area (but in recent years, the number has been growing substantially). In these cases, the actual billing data-based electricity consumption has been added to the DHW demand produced by electric boilers.

2.3 Spatial analysis of residential heating energy mix

In the heat demand survey, the amount and relative proportion of heating fuels used by the sampled households were counted for each municipality. In each case, the data collected from the survey were extrapolated to the settlement as a whole and, more specifically, to the number of households occupied. The obtained results can be used to estimate the HEM in each municipality. The differences resulting from the diverse land use of the sample area and the different physical and social geography of the settlements were visualised using GIS software (Figures 2 and 8). Then, the spatial patterns were analysed to determine the exposure to fossil fuels (energy dependence), the use of solid fuels and the role of electricity in heating and DHW supply.

2.4 Comparison of Hotmaps to the BÜKK database from the RHD point of view

The net RHD estimation results for each settlement, referred to as the BÜKK database, were compared to Hotmaps. The hectare scale resolution was applied to the software (Figure 4) to gain all necessary information on the investigated municipalities. The selection tool was used to define the exact RHD of the interior area of the settlements. Thus, the accuracy of the results was increased, and the number of anomalies was reduced. Subchapter 3.2 discusses the results.

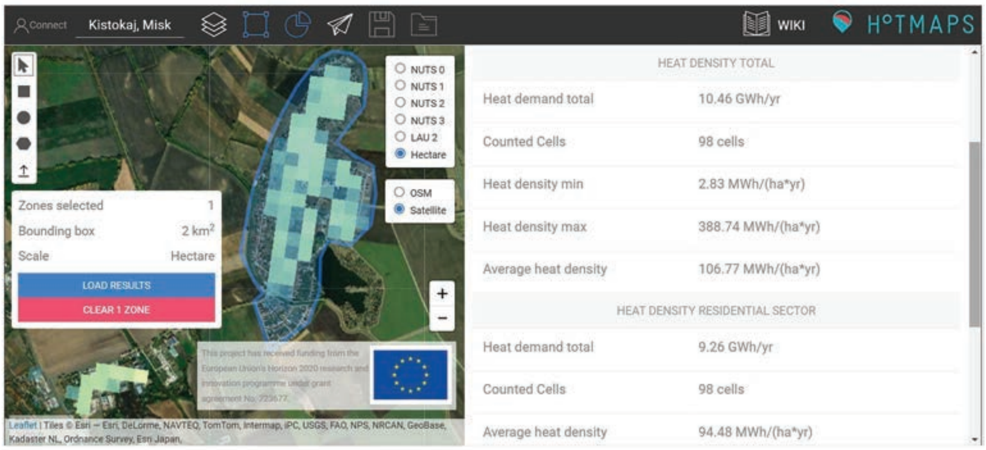

Figure 4: Web clipart from Hotmaps software, *Kistokaj*'s RHD, one of the investigated settlements of the study area [39].

3 Results of the Analysis

In this chapter, the main findings of the study are summarised concerning the comparison of Hotmaps RHD with the BÜKK database and the results of the spatial analysis of the HEM in the study area.

3.1 Residential Heat Demands in the Study Area

As expected, the total net RHD based on the field survey aligned with the number of households in the given settlements; larger settlements have a higher total RHD. Within the study area, RHD varies between 1,000 and 23,400 MWh/a (Figure 5). The RHD of the three most populous municipalities (small towns) is above 15,000 MWh/a. Due to the smaller settlements, the net RHD of most municipalities is in the range of 4,000 to 10,000 MWh/a. The RHD in the case of the five smallest villages is less than 3,000 MWh/a. The share of solid fuel in the municipalities studied is related to the size (RHD) and geographical location of the municipality (Figure 5).

3.2 Results of the Hotmaps - BÜKK databases' residential heat demand comparison

The BÜKK database generally correlates with the Hotmaps database in terms of RHD. Both analyses produced similar results for municipalities with an RHD of 5,000 MWh/a or higher. However, in those municipalities where RHD is under this threshold, higher discrepancies and, in some cases, significant anomalies were detected (Figure 6).

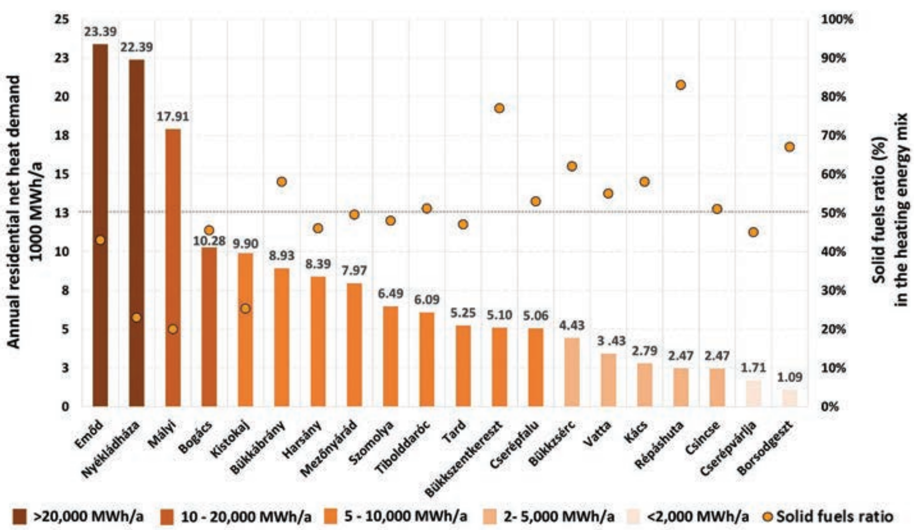

Figure 5: The RHD of the settlements and their solid fuel ratio in the HEM.

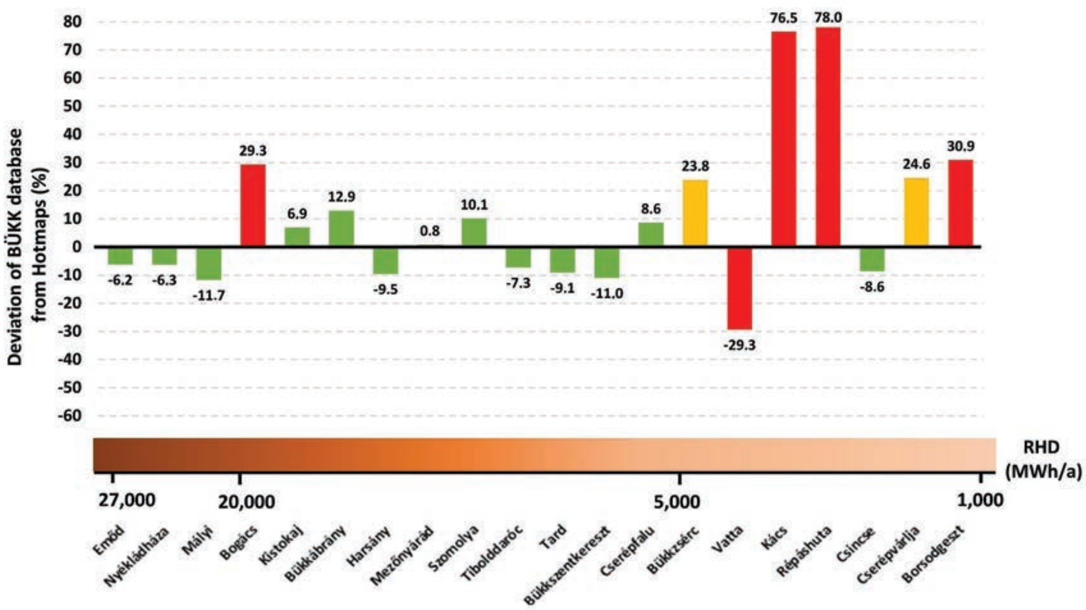

Figure 6: RHD comparison of the Hotmaps database and BÜKK database. Legend: green = deviation within 15%, yellow = deviation between 15-30%, red= deviation is over 30%; (light brown = low RHD, dark brown= high RHD).

Anomalies have been investigated between the two data sets. According to the y-axis (Figure 6), the theoretical "0%" means that the software-based heat demand estimation is in complete agreement with the field-survey-based data. In the case of 13 out of 20 municipalities, values showed less than 15% anomalies between the two calculation methods, which indicates that Hotmaps heat demand estimation can be used for spatial planning in most cases.

However, the comparison showed a deviation of more than 15% in seven cases. In five out of seven of these municipalities (than 5,000 MWh/a RHD), the anomaly exceeded 25%. These more significant deviations could be partly explained by the fact that the HEM of three municipalities (*Kács, Borsodgeszt, and Vatta*) was dominated by solid fuels. In these cases, according to BÜKK survey results, solid fuel ratios exceeded 55% (Figure 6).

On the other hand, the accuracy and reliability of heat atlases such as Hotmaps decrease below a certain settlement size. According to this study, the critical turning point in cases of the given pilot area can be defined as around 5,000 MWh/a.

In the case of *Bogács*, the strikingly large discrepancy is not due to the size of the settlement. This could be because the village has a thermal spa, which boosts all-year-long tourism and causes additional heat demand. This case also highlights the importance of in-depth settlement-specific heat mapping and planning.

3.3 Spatial patterns of the heating energy mix

The HEM comprises four main sources: natural gas, firewood, electricity, and lignite in the region. It is strongly influenced by the natural and socio-economic environment of each municipality and the land use patterns of the area. Natural gas and firewood combustion are the most common (Figure 7). The 20 investigated settlements have been sorted into four clusters:

- The Foresty (zone) cluster includes four settlements: *Bükkszentkereszt, Répáshuta, Kács, and Bükkzsérc*. In these cases, firewood consumption exceeds 50%.
- The Transitional (zone) cluster has altogether nine municipalities such as *Bogács, Tard, Szomolya, Cserévváralja, Cserépfalu, Borsodgeszt, Tibolddaróc, Harsány, and Emőd*. The HEMs were relatively balanced between firewood and natural gas.
- The Lignite mine (zone) cluster contains four traditional mining municipalities within 5 km of the open-cast lignite mine. In *Bükkábrány, Mezőnyárád, Csincse, and Vatta*, the lignite ratio exceeds 20%.
- The Suburban (zone) cluster includes three settlements with the most suburban characteristics. *Kistokaj, Mály, and Nyékládháza* have a solid (more than 60%) natural gas ratio.

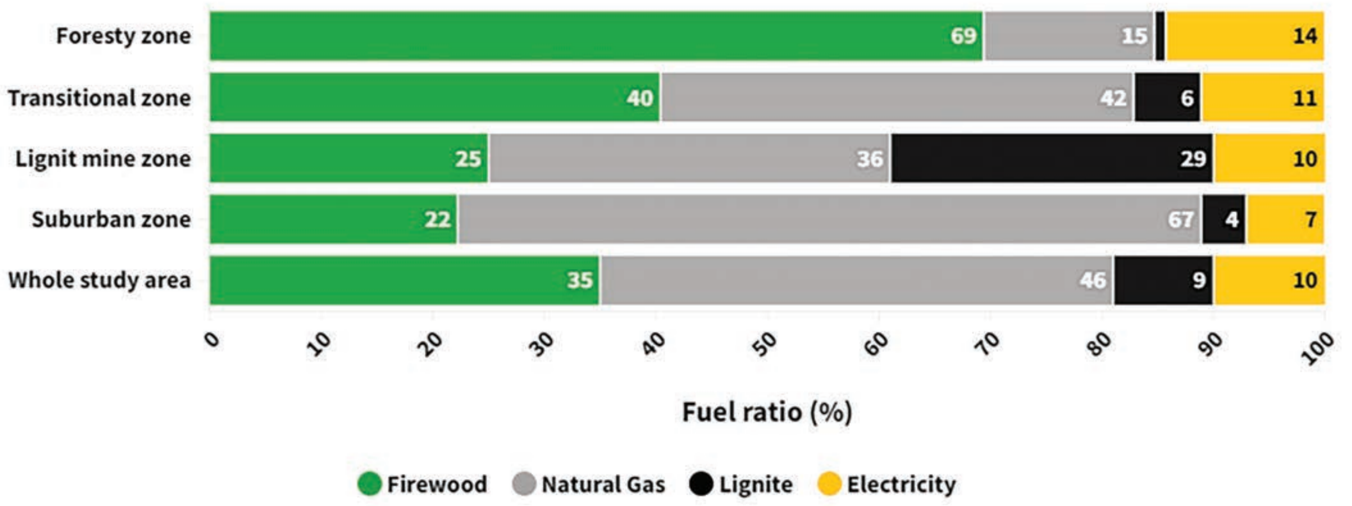

Figure 7: HEM patterns within the clusters in the study area (n = 20). Foresty zone (n = 4), Transition zone (n = 9), Lignite mine zone (n = 4), Suburban zone (n = 3).

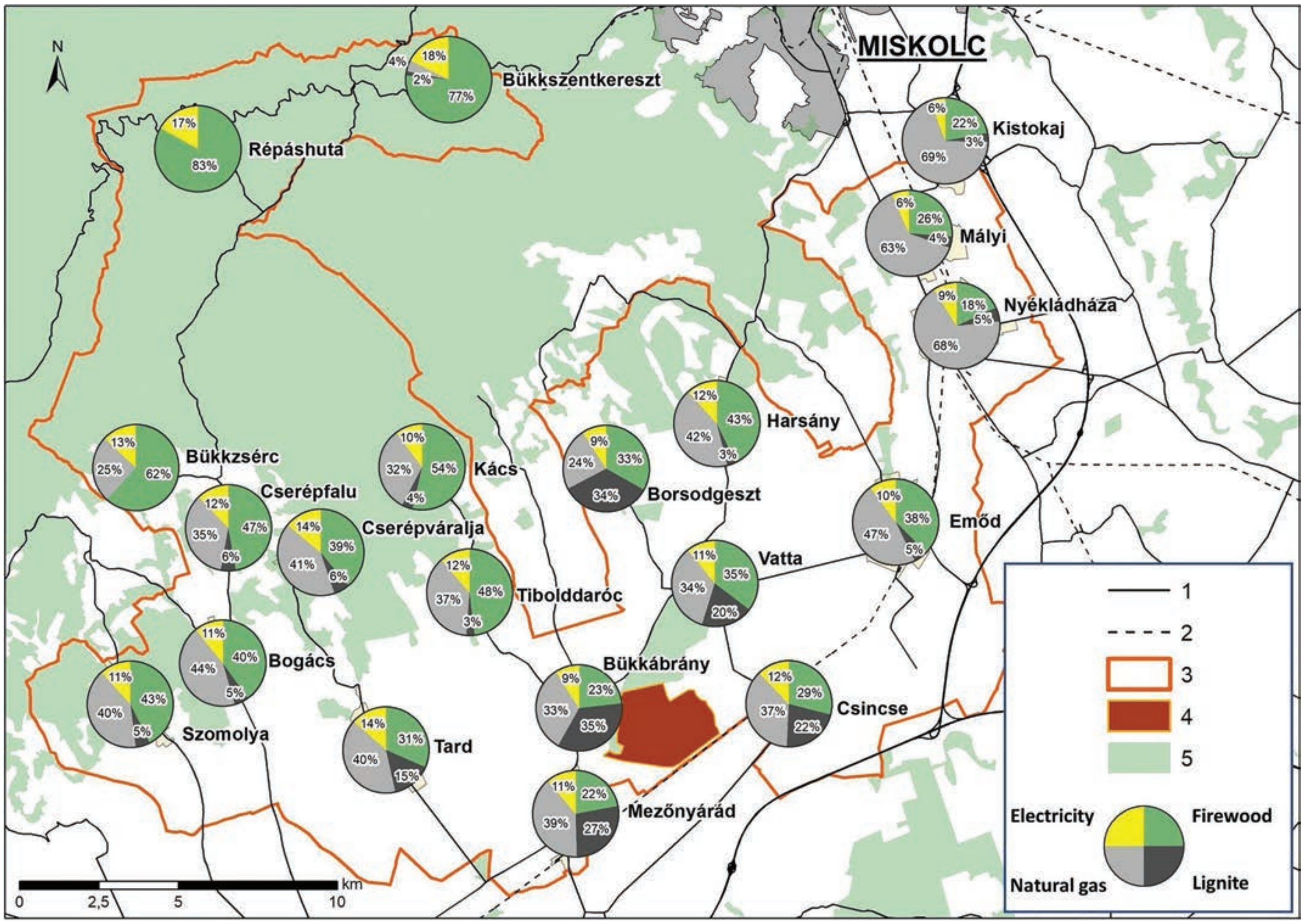

Figure 8: Spatial pattern of the HEM within the study area. In the case of *Bükkszentkereszt*, instead of natural gas, the figure displays PB gas consumption. 1 = roads, 2 = railways, 3 = border of the study area, 4 = open cast lignite mine, 5 = forests (Edited by Tamás Soha).

The dominance of natural gas is evident in the case of small towns close to the county capital, *Miskolc* (pop. ~150,000), namely *Kistokaj, Mályi, and Nyékládháza*. The reason is the agglomeration effect [40], which includes the higher purchasing power of the population living in this area. During the suburbanisation over the past decades, natural gas has generally been more expensive than firewood. In addition, people moving out of the city have become accustomed to the convenience of natural gas service. Therefore, in these settlements, the share of solid fuels was 30% or less, while natural gas usage was over 60%. In peripheral settlements further away from *Miskolc*, the share of solid fuel was higher; in some cases, it exceeded 60%.

Firewood consumption was significant in those settlements, that are surrounded by forests, located at the edge of the *Bükki National Park* (e.g. *Bükkzsérc, Kács*). Where the natural gas network was unavailable (*Bükkszentkereszt, Répáshuta*), firewood was the most dominant fuel source, and the electricity ratio was relatively high (approx. 15%).

An open-cast lignite mine (approx. 1,000 ha) is located in the southern part of the study area. In the vicinity of this mine, the role of low-quality lignite for residential heating is still evident today. Its economic impact is significant in the HEM of the surrounding municipalities. According to our survey, lignite corresponded to 20-35% of the HEM of settlements located in the close vicinity of the mine (e.g. *Bükkábrány, Mezőnyárád, Csincse, and Vatta*). However, the share of lignite in the residential HEM of the settlements decreases as the distance from the mine increases (Figure 8).

The share of electricity in the local HEM shows a tight correlation with solid fuel combustion. The higher the share of solid fuels, the higher the ratio of electricity. According to the field survey results, electric boilers for DHW production were the most common solutions in homes using solid fuels for space heating. Typically, electric boilers have higher energy efficiency than other common heating appliances in the study area. Furthermore, the heavy limescale effect and lack of regular maintenance can significantly increase their actual consumption. Natural gas-heated homes often use joint systems providing room heating and DHW. Therefore, electricity had a lower ratio in the HEM in suburban areas where natural gas consumption is dominant (Figure 8).

4 Discussion

Heat planning would be vital in rural municipalities with fewer resources, limited equipment, and a lack of internal expertise and energy consciousness [41]. The risk of energy poverty is also higher due to fewer jobs, lower income, less energy efficiency, and poor maintenance of building stock. That is why the reliability of freely available heat atlases and data is crucial for these rural communities to bridge the knowledge gap and successfully develop and implement tailor-made thermal energy action plans. Heat atlases can be used to identify vulnerable areas and even buildings across the country, allowing decision-makers to anticipate the potential impact of certain regulatory changes on affected households [6].

The comparison of Hotmaps and BÜKK databases revealed that data from an online heat atlas could be a reliable starting point for long-term rural thermal energy planning in this specific rural area of Hungary. Considering our study area, Hotmaps is a helpful software for the settlements (with RHD above 5,000 MWh/a) for rapid preliminary analysis, as the data series show a relatively small mismatch compared to the BÜKK field survey. Therefore, combining detailed field surveys with the online atlas could significantly increase the quality of the heat energy assessment of municipalities in the study. To get a completer and more generic picture of the applicability of Hotmaps in rural areas, similar field research and comparisons should be carried out in several other European regions. The results and experience gained could be used to improve the overall efficiency of energy planning and the related policy framework and the better allocation of the required resources at regional, country and even EU levels.

It is also important to stress that even though open-source tools can fill the missing data and statistical gaps, more is needed to define the settlements' HEM. In many HEM cases, detailed field surveys and additional calculations are required to determine the households' overall energy efficiency, and the inhabitants' energy consumption patterns. In rural areas, mapping the share of solid fuel consumption is crucial, as these data are difficult or impossible to obtain in official statistics. The HEM can also be an essential information for local decision-makers to develop energy and climate strategies for municipalities and address local environmental or socio-economic problems such as winter air pollution (high PM_{10} and $PM_{2.5}$ emissions) and energy poverty. In this context, we suggest that the theoretical and practical knowledge of how to burn firewood with low PM_{10} emissions should be disseminated. Residential heat storage also can support cleaner firewood combustion, which requires long-term national funding programmes such as ECO1-4 Government Scheme in the UK [42].

It should be noted that RHD and the solid fuel ratio are not constant over time since they can be influenced by many factors, but mainly the changing prices of different energy sources, which can cause 15-20% or even higher heating energy consumption fluctuations between heating seasons [43]. This paper also revealed that the HEM, even for a small geographic area, can vary significantly due to the diversity of available resources and energy infrastructure. We recommend the regular monitoring of HEM to keep the municipal (heat) energy transition on track. Furthermore, we want to highlight the need for tight cooperation among neighbouring settlements to maximise the renewable energy ratio in their residential HEM.

Complementing the online database with field surveys would aslo be beneficial, particularly in settlements where solid fuels account for more than 50% of the HEM. Notably, the authors of this paper invested considerable energy in implementing research findings by visiting local authorities on several occasions to consult with decision-makers and attend village gatherings. Moreover, the research team submitted and implemented a project with a local community (*Bükkszentkereszt*), which was involved in the analysis, to improve its air quality and reduce energy poverty. [44].

5 Conclusion

This paper applied the Hotmaps online atlas and compared its results to the BÜKK database developed from an extensive field survey for heat energy planning in a Hungarian rural area. The research also discussed the influence of spatial aspects on the HEM of the area. The hypothesis of this paper has been confirmed; despite the two databases being built up from different approaches they are mostly in agreement with each other. However, in those settlements where residential heat demand is less than 5,000 MWh/a, Hotmaps shows its limitation within the investigated municipalities, since below this threshold, the values were significantly divergent, which underlines the importance of tailor-made, in situ heat mapping. To define whether this reliability threshold is general, further investigations based on similar methodology need to be conducted in different rural areas across *Europe*.

It has also been shown that field surveys can be an essential complement to the use of open-source heat atlases, as the field surveys can reveal the actual HEM and the influence of spatial aspects not covered in the heat atlas. This is particularly true for municipalities where solid fuel combustion is dominant. The spatial analysis has shown that even in a 488.57 km^2 area, significant differences can arise in the HEM of municipalities. Therefore, tight cooperation and thoughtful energy planning are needed for a just energy transition in rural areas. The applied methodology of this paper can support this process since it is replicable and adjustable to most of the rural areas.

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Appendix 1: questionnaire of the field survey

Detailed household energy use questionnaire

used to create the BÜKK database

1. Characteristics of the building

1.1 How many m^2 is the *main building*? __ m^2

1.2 How big is the heated floor area ____ m^2

1.3 Is it possible to control the room temperature separately for each room? (thermostat)? □ yes; □ not; □ partly.

1.4 *What* type of building do you live in? □ detached

3. Information about the heating system and fuels

3.1 Energy sources: □ natural gas; □ propane-butane gas; □ firewood; □ coal/lignite; □ electricity; □ heat pump (e.g. air conditioning); □ household waste (paper, plastic).

3.2 □ *Central heater* □ *local (room) space heater*

3.3 If it is central, the *heat is distributed by…*

house; □ semi-detached house; □ row house □ condominium; □ other: ____

1.5 *When* was the building built?

□ Before 1944 □ 1945-1979 □ 1980-1989

□ 1990-2001 □ 2002-2012 □ 2013 or later

1.6 *How many floors* is *heated*? □1 □2 □3

1.7 Building Typological category: □
1.8 Does the building have *an energy certificate*?

□ yes, classification: _____ - __________kWh m²/year
□ no

1.9 Do you have a problem with poor air quality from heating in winter? □ not; □ sometimes yes; □ yes, many times

2. Energy consumption patterns

2.1 On a scale of 1-4, how *energy consciously* do you live (not at all = 1; fully = 4)? _________

2.2 At what temperature do you heat the *occupied rooms in winter?* ______°C

2.3 How cold will the building be *in the morning*? approximately _______°C

2.4 How do you feel in your home during the winter months?

□I usually I am cold; □ sometimes I am cold; □ I don't usually get cold.

2.6 *Windows are drafty, they close poorly*:

□ yes; □ partially; □ uncharacteristic.

2.7 How many degrees is in the building in *the summer heat*: _______°C

2.8 Do you record the *amount* of energy used?

□, yes, regularly; □, yes, sometimes; □ not.

2.9 Total number of hours stayed at home _____ hours/day (If 3 people are at home for 14 hours it should be recorded as 42 hours)

3.12 Is there any *heat storage in the system*? □yes, its size litters □not

3.13 Where *do you usually get* firewood from?
□ forestry; □ retailer; □ own resource; □ gathering branches from a forest; □ industrial waste; □ other;

3.14 After how much drying time do you usually use the firewood? □less than 0.5 years; □0.5 – 1 year; □1-2 years; □over 2 years old.

4. District heating and community energy

4.1 Do you plan to *switch to other type of heating*?

□yes; □not; □only if there was support for it.

If so, for what and why?

____

□ old type iron radiators; □ modern type flat panel radiators; □ low-temperature heating (floor, wall, ceiling heating).

3.4 How many years has the last maintenance of the heating system been? ____ *year*

3.5 How many years has the last cleaning of the chimney been? ____ *year*

Natural Gas

3.6 Average amount of *natural gas* used:

Quantity: A) ______ *winter monthly m³* ______ *summer monthly m³*

B) ______ annual total m³

Cost: C) Monthly flat-rate fee __________Ft

D) Annual cost ______Ft

3.7 Type of equipment: □ *boiler* (central) □ *convector* (local heater)

3.8 *Age:* □1-3; □ 4-8; □ 9-15; □16-25; □More than 25 years

Solid Fuel (firewood/lignite)

3.9 Please indicate the average amount of firewood/coal used by completing at least one of the following two options:

______ *quintal/year wood* _____ *quintal/year coal*

______ *stacked m³/year* ______ *m³/year*

_______ *€/year* (with delivery)

□ Split firewood; □ In logs; □ Another unit: ________

3.10 What combustion unit do you use?

□solid-fuel boiler; □pellet boiler; □tiled/mass stove; □iron stove/kitchen stove; □ fireplace; □ wood gasification boiler.

3.11 *How old* is the combustion unit? You can choose several answers: □1-3; □4-8; □9-15; □16-25; □More than 25 years

□ yes; □no; □can it be heated with it?

6.9 Do you use *electricity for heating?*

□ no; □ radiant heater; □ electric radiator; □ heating film or infrared panel; □ electric stove with heat storage; □ heat pump.

7. Energy efficiency

7.1 Does the building have *slab* insulation?

□ yes: ______ cm, its material: _______

□not, but *it is planned;* □not, *it is not planned.*

7.2 Does the building have *roof* insulation?

□ yes: ______ cm, material: ___________________

□not, but *it is planned*; □not, *it is not planned*.

4.2 If a state-of-the-art *district heating service* were in your area, would you *be willing to join* it?

□yes; □no; □if the old heating can be retained.

4.3 *Would you like to participate* in an energy community?

□ yes; □ no; Reasons: ______________________________

5. Domestic hot water

5.1 *What equipment or source* is used to produce hot water?

□ electric boiler; □ gas; □ solar collector; □ heat pump.

□ firewood; □coal, lignite.

5.2 If it is *electric boiler, its volume is* ______ Liters

Do you use controlled (cheaper) electricity? □ yes; □ no.

6. Electricity use

6.1 Please indicate the amount of *electricity* used by selecting any of the following options:

annual consumption _____kWh/year

monthly *flat-rate fee* ____ €/month

the annual monthly instalments _________€/year

6.2 *Do* you have a prepaid electricity service? □ yes; □ no.

6.3 What *kind of lighting do you* use?

____% incandescent (tungsten/halogen); ____% fluorescent lamp; ____% LED.

6.5 Do you have *a household PV system*? □ yes; ______ kW; number of panels: ______

□no, but *I plan to buy*; □no, *I don't plan to buy*.

6.6 Do you use *air conditioning*?

□ yes; □no, but *I plan to*; □no, *I don't plan to*.

6.7 Do you use the *air conditioning* system for heating?

7.3 Is there any insulation *on the façade*? □yes: _____cm; material: ______________ covers _____% of the façade.

□not, but *it is planned*; □not, *it is not planned*.

7.4 *Most of the windows are*: □ original jointed box-type window □ refurbished jointed box-type window (double glass, retrofitted with insulation) □ modern 2-layer window, age approximately ___ year □ 3-layer window.

7.5 *Do you plan to invest in energy efficiency in the following areas within 3 years*?

□ doors and windows; □ insulation; □heating system modernization; □no.

7.6 *How much support would you need* to invest in a major energy efficiency project? □ I would even do it *using only my own* resources; □ *with support* _____%; □ *in no case*.

8. Socio-economic dimension

8.1 How much of the household's annual income is spent on *heating* expenses?

□ <10%; □ 11-20%; □ 21-30%; □ over 31%.

8.2 How often do you not have the income to heat your home to the proper temperature?

□ never; □ rarely; □ regularly.

8.3 How often do you *fail* to pay your energy bills?

□ never; □ rarely; □regularly.

8.4 Have you ever had to heat with waste?

□ never; □ rarely; □ regularly.

8.5 Respondent's age: _______ year

8.7 Number of children/dependants: _____ pcs

8.8 Net monthly household income *per capita*:

□ < 125 €; □ 125 -250 €; □ 250-375 HUF; □ 500 HUF; □ 500-625 HUF; □ > 625 HUF.

8.9 *How many people* live in the household ______capita

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