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Spatial analysis of renewable-based rural district heating possibilities – a case study from Hungary

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ABSTRACT

This research work investigates the possibilities of establishing renewable-based district heating (DH), including "hybrid district heating" (HDH) applications in a peripheral rural area of Hungary, the *Bükkalja*. HDH, or multi-source systems, use a reasoned combination of energy sources, which is still unusual practice in Eastern Europe. This particular *Bükkalja* region struggles with import dependency, energy poverty, and serious air pollution. Considering natural and social capabilities, potential sites for rural district heating developments were examined. Door-to-door field surveys, residential heat demand, GIS-based renewable energy potential calculations, detailed supply-demand and statistical analysis were applied to reveal DH development possibilities. Most of the results have a tight correlation with the relevant values of Pan-European Thermal Atlas (PETA 4.3), however, in case of suggestions, there are considerable differences. The outcomes also highlight that current biomass utilization far exceeds the sustainability limits within the area. The screening proves that the capabilities of seven rural settlements are suitable for DH developments. This investigation supports the decision-making process and its proposed projects could play a significant role in the local energy transition. This study underlines that rural DH developments could have the same relevance as similar projects in urban circumstances.

Keywords:

District heating;
Rural energy transition;
Heat demand estimation;
GIS;
Renewable energy;

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1. Introduction

Almost a decade ago in and around the Bükk Mountain, local governments, small enterprises, social organisations, and individuals decided to create a LEADER community (as an EU-wide development programme and method to engage local actors) focusing on sustainable energy solutions [1]. Their main goal was to approach energy independence. One of the motivations behind this research work was to give a new momentum to this unfortunately stalled local energy transition initiative. The results of this research work can contribute in the formulation of regional planning policies. In a broader sense, this study proposes a methodology based on local data collection in combination with geospatial analyses, which can be applied to similar rural regions with limited data availability. According to the OECD [2] and the EEA [3], immediate action is inevitable, especially in peripheral regions such as the study area. Besides the ongoing climate change, the other apparent reason is the heating-origin air pollution which causes the early death of 937,6 people per million inhabitants every year in Hungary. This is the worst value among the European OECD countries [2,4]. This problem is tightly linked to the harmful residential heating habits, the inefficient building stock and heating devices. Solving this problem, DH developments should be considered, but

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Abbreviations

DH:	District Heating
DHW:	Domestic Hot Water
GIS:	Geographic Information System
HD:	Heat Demand
HDD:	Heat Demand Density
HDH:	Hybrid District Heating
LEADER:	Liaison Entre Actions pour le Developpement de l'Economie Rurale
PETA:	Pan-European Thermal Atlas
PM:	Particulate Matter
RHD:	Residential Heat Demand
SDH:	Solar District Heating

this technology is generally not accounted for in the case of villages and smaller settlements in Eastern Europe.

The hypothesis of the research is that DH systems can also be developed even in rural Hungary. Therefore, the following points were investigated:

a) The current situation regarding residential heating energy mix and the level of fuel consumption.
b) The average Residential Heat Demand (RHD) and heat density of the settlements in the study area.
c) The amount of local renewable energy sources available for sustainable heat production.
d) Relevance of developing rural DH systems in the study area and most suitable settlements.
e) The correlation between the outcome of this research work and the latest results of the PETA 4.3, presented in the Heat Roadmap Europe, a project mapping and modelling the heating and cooling sector in 14 EU Member States [5,6]. PETA was used for comparison due to its detailed open database on heat demand which includes the study area.

1.1. Research philosophy

This preliminary research contains a careful investigation of residential heating habits, fuel demand and heat utilization. Its main goal was to identify suitable settlements within the study area to reveal possibilities and limiting factors of potential DH developments. The importance of such studies in providing information for regional planning is highlighted in heat atlases [7].

As for the research philosophy, the principle of "strong sustainability" was used: the environmental aspects were considered the most important elements, which were followed by the social and economic considerations [8]. It is time to change the approach and primarily to find clear answers to the global ecological crisis [9,10], even if such actions may have higher costs in the short run. At the household level, state-of-the-art heating technologies provide crucial solutions for increasing energy saving thus decreasing environmental burden [11].

Thus, the research work is a kind of sustainable energy potential analysis. This statement can be supported by the focus on renewable sources, which is far from the general practice of DH systems in Hungary that utilise mainly imported natural gas [12]. However, the approach of this research work made it necessary to also map the HDH possibilities, in order to reveal synergies between different renewable-based technologies ensuring the careful utilisation of sensitive resources, such as biomass.

1.2. Literature review

A significant number of DH-related papers focus on spatiality, mainly on national, sub-national levels and urban areas, using precise GIS and CAD operations as research methods [13,14] including optimization of systems in densely populated areas [15]. Many of them, however, are case studies and are approaching from an engineering viewpoint with technical feasibility purposes focusing mainly on the demand side. Lately heat atlases have been coming to light in order to map and analyse heat supply and demand [7]. The accuracy of these databases in Denmark was also investigated, confirming that such atlases can support energy planning [16].

Another main issue is the energy mix of DH systems. Even though several studies focus on the potential of locally available resources, most commonly biomass [17] and waste heat [18], not many studies were found evaluating the possibilities of multiple sources in rural settings. However, considering several alternatives (e.g. biomass, geothermal heat, ground-source heat pump, industrial waste heat) throughout the planning of the heat supply would contribute in the transition to cleaner energy [19]. Some of the systems utilize a combination of sources. They are usually composed by one main production plant and supported by satellite plants [20, 21].

The analysis of financial aspects also plays a decisive role in the scientific debate. Hendricks et al. estimates the economic feasibility of DH developments in rural communities and reveals cost-effective possibilities for villages with high density of heat demand [22]. Hansen et al. compare yearly heat prices of typical Danish buildings supplied with different heating systems. It was proved that DH is the most cost-efficient option in densely-built settlements, however, individual heating could be cheaper in rural circumstances [23]. Another important way of DH development could be the extensive excess heat utilisation using an effective price regulation. Its main source could be the industry contributing to even a tenfold lowering of the carbon footprint in urban areas [24]. However, DH planning from the investors' perspective is mainly restricted to short term economic factors, while comprehensive examinations (considering social attitude; environmental constraints; supply alternatives; the quantity of heat demand and its future changes) play a minor role. Focusing on the cost aspect, demand side management possibilities are also investigated [25].

After some hundred years of evolution, DH can be one of the most energy-efficient ways of production and distribution of heat. In the 21 century it is an integral part of the energy system, as - due to heat storage - it can help to manage intermittency of wind and solar PV [26] In Northern and Western Europe 3rd generation DH systems are common, and the 4th generation is on the threshold. Supplying lower temperature heat to buildings, integrating heat sources and developing smart systems represent the transition to modern technologies [27]. Moreover, these solutions contribute to establishing sustainable community energy systems as well [28].

In Europe some of the most innovative rural DH systems can be found in Denmark and Austria. In Denmark, the number of multi-source Solar District Heating (SDH) systems has risen nearly ten times over the last decade [29]. With this progress, the total surface area of such systems could exceed 1.5 million m^2 by 2019, and their combined heat capacity could reach 900 MW_{th} [30]. The world's largest such facilities were also built in Denmark; however, this technology was also implemented extensively on a smaller scale [31]. In this research the Danish SDH model was mainly used for the solar thermal potential calculations.

The "*Güssing energy model region*" is one of the peripheral rural regions in Austria, lacking even natural gas infrastructure. This was one of the reasons for the recent establishment of several small-scale biomass-based multi-source systems that operate in the vicinity of *Güssing*, covering the Heat Demand (HD) of households in the scale from a few dozen to several hundred. A new direction is the biogas utilisation in CHP-connected DH systems [32].

These examples were used as a benchmark for this research providing not only empirical and methodological background, but also highlighting the characteristics of existing systems in rural settings.

2. Materials and methods

The spatial preconditions of introducing DH can be divided into three main areas: i) RHD estimation; ii) available (local) energy sources; iii) distribution routes. Regarding the energy sources, geothermal and excess heat; biomass; and solar thermal were considered.

The following input information was collected:

a) statistical data on the population and on natural gas consumption of the settlements [33];
b) main structural attributes of settlements, i.e. size of the inhabited area, spatial distribution of road network (using OpenStreetMap);
c) household-level heating patterns and thermal comfort expectations, "actual energy billing data" (type, quality, and quantity of utilised fuels) which represents the highest confidence level according to the literature [34], and personal acceptance regarding possible DH developments;
d) main attributes of residential heat consumption, which include building envelope insulation conditions and stock of heating appliances in every investigated household;
e) experiences on small-scale DH projects – collected by interviews with local decision-makers and technical staff in the study area, *Güssing* region and Denmark.

Data on c) and d) were collected between 2015 and 2019 by in-depth surveys in the study area exploring at least 10% of the households, complemented by the official national database [33].

The analysis was implemented with ArcMap 10.2.2. and MS Excel and it can be structured as shown in Figure 1.

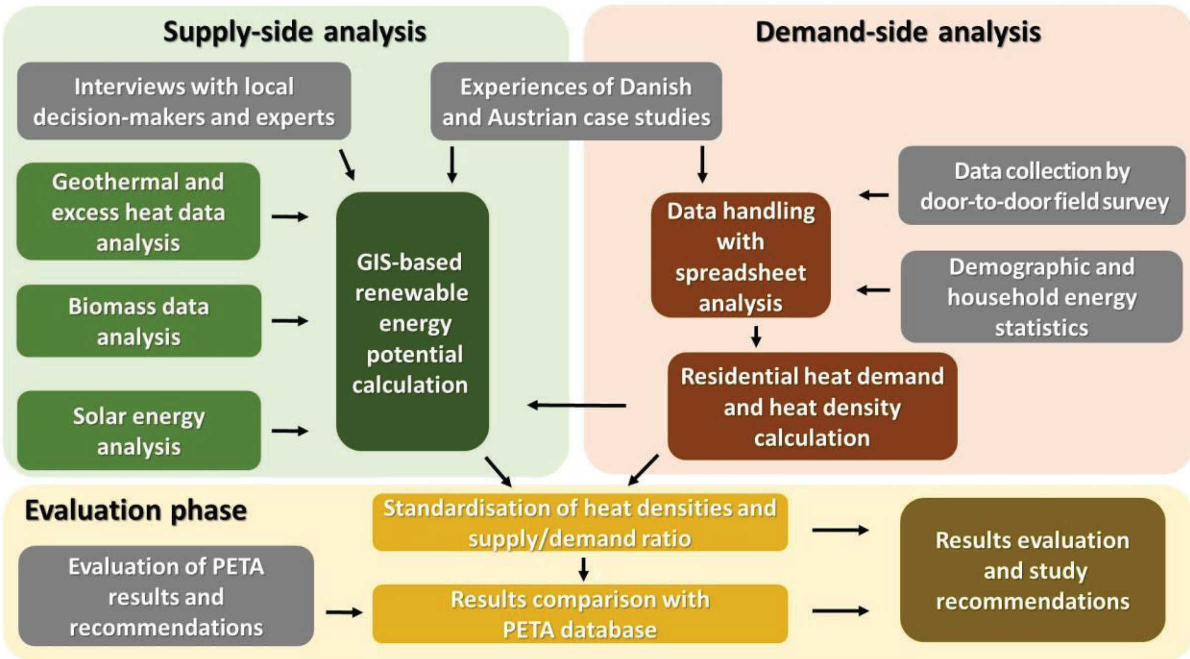


Figure 1: Outline of the research methodology

2.1. Study area

In a broader context, most DH systems are still stuck at lower technology levels in Hungary. 95 municipalities operate DH systems, which supply ~17% of the households [35]. Almost all of them can be classified as 2nd generation without any heat storage and operating with significant heat loss. In most cases, the controllability is limited, which explains the bad reputation of DH. Most of the affected settlements are cities [36].

The study area is composed of 18 villages and 2 small towns in the *Bükkalja* region, Hungary, situated in the southern slopes of the Bükk Mountain. Specific natural and economic attributes make the subregion coherent from a geographical point of view (Figure 2). The population is 36,296 inhabitants in 13,014 households. The total area is 564.07 km^2 resulting in a density of 64.3 inhabitants/km^2 [37].

As for the land use, the area's 52% is covered by dense, mainly protected forests (Bükk National Park), while 29% is cropland [38] (Figure 2). The region is rich in geothermal energy: the study area is located above a medium enthalpy (>60˚C) and relatively low depth (<3 km) geothermal reservoir [39]. Furthermore, in the foreground areas of the Bükk Mountains, there are numerous abandoned hydrocarbon wells, which could be redeveloped for geothermal energy purposes [40].

Socially, this is one of the most deprived regions in the country. GDP/capita value is 60–70% of the national average. The unemployment rate is 42% higher than the Hungarian average (3.6%) and the mean net income is in the lower quartile [42].

Consequently, residential heating is highly influenced by energy poverty [43]. Illegal burning of waste or the usage of outdated heating devices are not unusual in the region. Due to the geomorphological and climatic circumstances, atmospheric inversion is a frequent winter phenomenon in *Bükkalja*. It results in the harmful concentration of Particulate Matter (PM) [44]. During the heating season, the daily PM values regularly exceed the yearly average health threshold (25–40 μg/m^3) defined by the European Union [45,46]. The consequent external effects and costs of air pollution are significant and must be considered in economic analyses of heat supply. Therefore, low-emission DH systems could effectively mitigate the complex problems in the study area.

2.2. Residential heat demand analysis

Creating a detailed HD-analysis was inevitable since this kind of dataset is not available in Hungary on the preferred scale. Basing this research solely on European level databases would not be sufficient either. As most of the investigated settlements are economically situated in a peripheral zone, the industrial and service sectors have a negligible share of the heat market. Generally, no significant business units are operating, the only exception is a brick factory in *Mályi*. Municipal and community buildings were also out of scope.

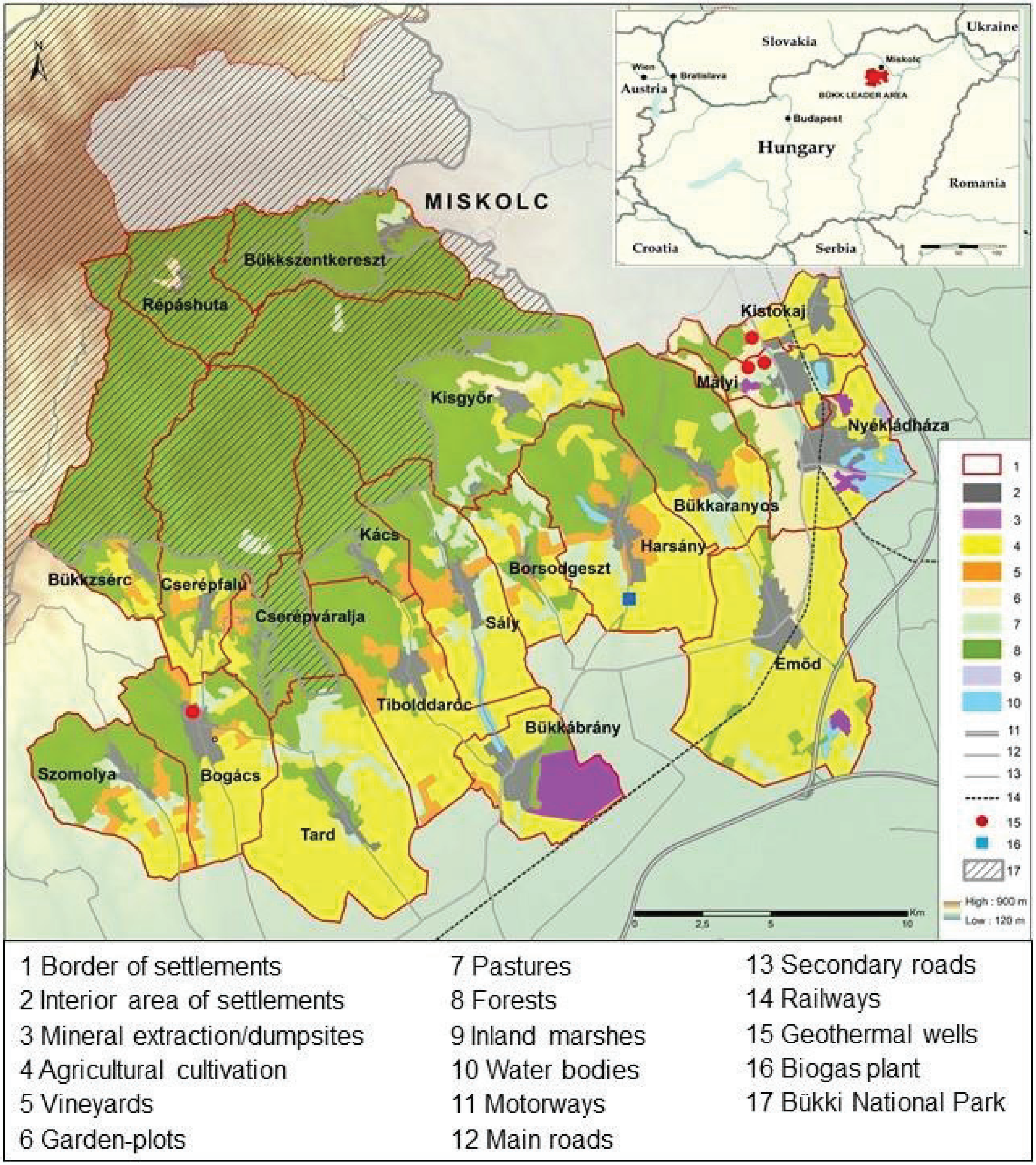


Figure 2: Land use in *Bükkalja*. Data sources: [38,41]

2.2.1. Heat demand calculations

A custom database was created by implementing surveys that involved 1,354 households in 15 settlements. The well-prepared and trained interviewers made a door-to-door survey, using paper-and-pencil interviewing (PAPI) technique. The interviewers had to cover every street and collect information about at least 10% of the occupied dwellings at the given settlements. Thus, the gained database represents a wide range of households including singles, pensioners, regular, wealthy families and those who have many children or live in energy poverty. In the case of direct surveyed settlements, the information was used for building a spreadsheet-based model of the study area. The results were extrapolated to the 5 remaining settlements in order to overcome the human and financial implications of surveying. During the extrapolation process, the principle of similarity was used, and data were gained from the closest similar settlements.

Even though data of natural gas consumption were collected by the survey, the official national database was preferred for accuracy reasons. Moreover, since no official data on biomass and lignite consumption were available, the natural gas database was used for validation of the total RHD calculation. To eliminate the anomalies of the weather fluctuations, the average of the period 2013–2017 was considered.

Fuel properties and data on heating appliances were collected (Table 1). The aim was to estimate heat demand and establish a comparison with the PETA database [5,47]. Most of the equipment identified in the surveyed households are old and/or low-efficiency gas boilers, wood burning stoves and multi-fuel stoves. The efficiency values are estimated based on these observations and typical appliances reported by Csoknyai et al. [48] and Lucon et al. [49].

The average annual HD of a single household was calculated by multiplying the fuel consumption (derived from actual energy billing data) by the average efficiency of the conversion processes. Electricity use for space heating is not common in the area and was considered exclusively in Domestic Hot Water (DHW) production.

2.2.2. Heat demand density calculations

Heat demand density (HDD) and linear HDD were calculated for each settlement using the results of the RHD-calculation and satellite images. These were used as the first and second input factors in the standardization phase of the demand-side analysis. Higher HDD was associated with more feasible DH projects [14].

The first step of HDD evaluation was defining the built-up area of each settlement. This calculation was based on a digitization process, considering only the built-up area of the settlements instead of using the available statistical datasets. RHDs and the area of the defined polygons determine the HDD for each settlement.

For the linear HDD calculations, the road network of the settlements was intersected by the aforementioned built-up area polygons, assuming that new distribution pipelines would be placed parallelly to the streets of the existing road network. The linear HDD was determined by dividing the total length of the settlement's road network by the RHD. This calculation considered a 100% DH coverage for every settlement.

2.3. Supply-side analysis

Due to the diversity of the local renewable resources, and their distinct accessibility conditions, it was important to evaluate all of them for each settlement to suggest the proper energy mix. Existing geothermal and excess heat sources were preferred because of sustainability and lower investment costs. Furthermore, excess heat utilization is the most apparent and effective way to accelerate the green transition within the heat sector [53]. However, a badly chosen excess energy source, e.g. a coal power plant, can affect the efforts to decarbonise the heat sector, therefore climate-neutral sources are preferred. In the case of those settlements where geothermal sources could cover the whole demand, other main sources were not considered, therefore accounted as a conventional, single-source DH system. In this case, a peak load system (e.g. boiler system) would be required to complement the baseload. The settlements' biomass potential was the second source investigated in the priority order.

Solar energy potential was calculated in two cases: a) where the aforementioned potentials were found insufficient to cover the total RHD or b) where the amount of available biomass would be sufficient, but the consumption would be higher than the sustainability limit.

In the final step, considering the technical constraints and geographical characteristics of the settlements, network heat-loss was assumed to be 20% [54].

2.3.1. Geothermal and biogas excess heat

There are three active production and one reinjection geothermal wells in the study area. The thermal energy

Table 1: Conversion and efficiency factors used in the BÜKK analysis [50,51,52]

Fuel type	Values	Units	Appliance	Efficiency
Firewood	2.42	MWh/m^3	wood stove	0.55
Natural gas	9.60	kWh/m^3	boiler	0.75
Lignite	2.44	kWh/kg	multi-fuel stove	0.45
Electricity	1	kWh	water heater	0.85

of wells in *Kistokaj* and *Mályi* (30+30°MW_{th}) are utilised outside the region since it is distributed to the county's capital, *Miskolc*. However, the volume and temperature of the return fluid would be high enough for further utilisation. Potential calculations were based on this return temperature (approx. 65°C) and water discharge (1,080°m^3/h) data. The difference between the supply and return temperature is 25°C, consequently, the reinjected water is not colder than 40°C. In this calculation, two factors were considered: a) the baseload heat demand with the degree-day factor (182.5 days); b) annual domestic hot water demand [55]. The energy potential was calculated, as:

$$N_t = \Sigma \frac{(c * V * \Delta t) * DDF}{Q} \tag{1}$$

where N_t = energy potential in MWh; c = specific heat of water; V = water volume in m^3; t = water temperature in °C; DDF = degree day factor in hour; Q = distribution heat loss in °%.

Regarding *Bogács*, where the geothermal well provides hot water (70°C; 1,112°m^3/day) for a local spa, a similar methodology was used to calculate its heat potential. In this case, the difference between the supply and return temperature was defined as 30°C.

The only biogas plant of the area operates in *Harsány*. Even though the capacity of the plant is 1.19 MW_p and 1.12 MW_{th} [56], its excess heat is only used for heating up the digestion tanks. In the potential calculation the capacity factor (80%), the plant heat self-consumption (30%), and the degree-day factor were considered [57]. The energy potential was calculated, as:

$$N_t = \Sigma \frac{P * Cf * DDF * E_{sc}}{Q} \tag{2}$$

where N_t = energy potential in MWh; P = heat output in MW; Cf = Capacity factor in %; DDF = degree day factor in hour; E_{sc} = heat self-consumption in %, Q = distribution heat loss in %.

2.3.2. Biomass

The assessment of the forestry biomass potential is based on the National Forestry Database. It was assumed that the prospective DH system would operate at least until 2050. Therefore, tree species within the subcompartment with projected logging date beyond 2050 were excluded. The ones which are under logging restriction because of nature protection were also excluded. The energy potential was calculated, as:

$$N_t = \Sigma\left(\left(S + t_l * i\right) * R_{fw}\right) * U \tag{3}$$

where N_t = energy potential in MWh; S = forestry stock in m^3; t_l = time left until planned logging in years; i = yearly increment in m^3/year; R_{fw} = firewood ratio; and U = energy density. Reflecting the forest management practices and the volume of different tree species, firewood ratio of 0.4 [58] and energy density of 2.8 MWh/m^3 [51] were used.

The sustainable cereal straw potential was calculated with the method developed by Weiser, C. et al [59], which considers aggregated humus-balance value, from those technically available residues not used by livestock [58]. It was based on agricultural statistical and soil quality data within 1×1 km resolution raster of arable land.

Energy yields for forestry polygons were allocated to the settlements, in relation to the calculated RHD of the settlements (section 2.1) with ArcMap "Location-allocation tool", using the road network. Since the Energy Return of Investment (EROI) and the carbon emission of the biomass value chain is highly sensitive to the transportation [60] and the size of the study area is small enough, the maximum range of 20 km was considered. Based on [61], for the biomass DH, total system efficiency of 65% was used, including the efficiency of boiler and heat loss of the pipeline.

2.3.3. Solar thermal

The solar thermal potential calculation has three main steps:

a) Annual energy yield calculation
The calculations were carried out using empirical experiences of Danish SDH systems and solar irradiation data for Hungary. In practice, ~400°kWh/year solar heat production is available per effective aperture m^2 in Denmark [62]. In Hungary, 500°kWh/m^2 production would be achievable annually with similar technology due to higher irradiation [63]. According to the collector spacing and other spatial parameters, the achievable annual heat production per land area was calculated to be ~143°kWh/m^2. According to [62], 3.5 m^2 of land is needed for 1 m^2 of collector area.

b) Available land analysis
Environmental aspects were the focus of this step and only brownfields, grasslands, and other less valuable unbuilt areas were investigated (mineral extraction sites, dump sites and pastures) [37]. 500-meter buffer zones were drawn around the borders of the built-up area of each settlement, according to [62]. The suitable areas were intersected with these buffer zones, allowing to identify the closest potential areas and minimise heat losses.

c) Solar fraction and heat storage calculation
The maximum solar fraction of the existing Danish solar-biomass HDH systems with seasonal pit storage is ~40–45% and around 20% with diurnal storage [62]. In the next phase, due to the heavy capital cost of seasonal heat storage, only diurnal storage was counted, and the solar fraction was limited to 20% of the annual heat supply [64].

2.4. Supply-demand relations

Supply-demand relations have been defined after the demand-side analysis and the supply-side potential calculations. The final calculation contains and allocates the aforementioned available renewable energy sources (in MWh/year). The supply-side potential was divided by the RHDs to determine the supply-demand ratio. In this case, 100% means that all the RHD could be attended with a renewable-based DH system. The result was inserted as a third factor in the standardization.

2.5. Standardization

In order to compare different dimensions and values, a standardization process was used. The final evaluation was based on the so-called "complex parameters" of indicators, and the average of these indicators defined the final result (Appendix 1). The mean of the following criteria was used: HDD; linear HDD; supply-demand ratio. For the process of standardization, the following equation was used for each factor:

$$z = \frac{\chi - \mu}{\sigma} \tag{4}$$

where z = standard score; χ = each value in the dataset; μ = mean of all value in the dataset; σ = the standard deviation of a sample.

These indicators were chosen, thereby the environmental, social, and economic aspects of sustainability would be represented in the calculation. It also allowed both sides (supply and demand) to be equally weighted parts. The results were divided into five groups, most recommended (z>1), recommended (0<z<1), recommended with limitations (–0.31<z<0), recommended with strong limitations (–0.50<z<–0.31), not recommended (z<–0.7). After evaluation, the results were compared to DH development recommendations of PETA [5].

3. Results

Firstly, the main findings of the field surveys are presented followed by the results of the heat demand and supply-side analyses. Results of the standardization, possible developments and social acceptance are found in the second part of this chapter.

3.1. General results of household heating

The average fuel utilisation was calculated as 18.3 MWh per household. The average heated area is approximately 90 m^2/household and the value of the mean specific HD is around 132 kWh/m^2 per year. This consumption shows that the condition of the investigated building stock is substandard [65]. This claim is highlighted by the findings of the door-to-door survey:

a) half of the building stock does not have any kind of insulation;
b) the existing insulations are mostly partial and not sufficient;
c) the average age of doors and windows is higher than 20 years.

Currently, natural gas (107,450 MWh/year), firewood (92,400 MWh/year), and lignite (15,960 MWh/year) are the most common primary heating energy sources in the study area. As regards electricity for heating, the diffusion of air-to-air heat pumps and the usage of auxiliary electric devices are negligible. Electricity, however, is frequently used for DHW production (in 66% of the households), it represents 10% (24,100 MWh/year) of the energy mix (see Figure 3).

Energy mix slightly changes year by year, influential factors could be e.g. actual price of firewood, weather conditions, demographic processes, etc. Moreover, the regional energy mix hides the differences among the settlements.

3.2. Results of the demand-side analysis: Residential heat demand

Based on the spreadsheet analysis of household fuel consumption, the results of the settlements' average net

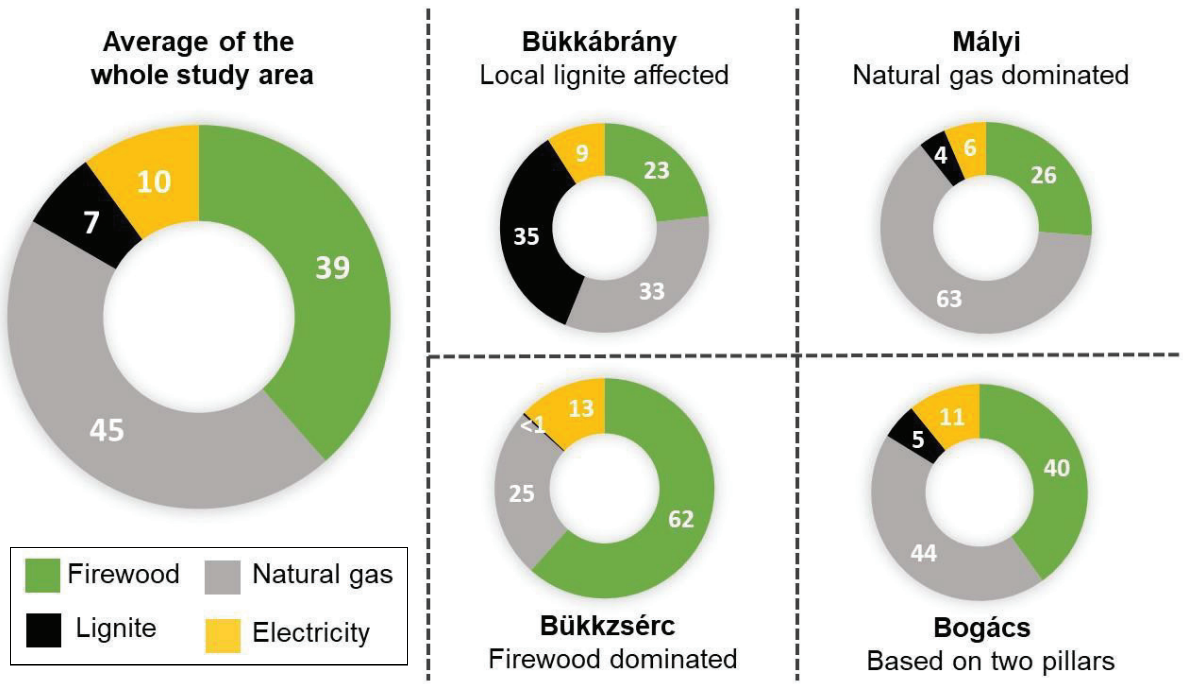


Figure 3: The estimated overall heating energy mix with some representative examples (values displayed in %)

RHDs ranged from 1,100 to 23,400 MWh per year – with error rate ± 25%, comparing the results to the official natural gas statistics [33]. The average RHD of the 20 municipalities is about 8,000 MWh/year.

a) Heat demand density
RHD-density represents the household-concentration of the built-up area. It is highly influenced by the structure of the settlements; thus, large unbuilt areas reduce these values. The study area mainly contains detached family homes, which also results in lower values. The average yearly value of the region is ~7,600 MWh/km^2 with a range between 3,500–12,500 MWh/km^2 (Figure 4).

b) Linear heat demand density
In the framing of future developments of DH systems, the linear HDD could also play an important role since the feasibility highly depends on this value. As a result, the average yearly value of the region is ~600 MWh/km with a range between 280–970 MWh/km (Figure 4).

3.3. Results of the supply-side analysis

This section presents the potential of the three investigated renewable energy sources to supply the DH developments.

3.3.1. Geothermal and excess heat potential

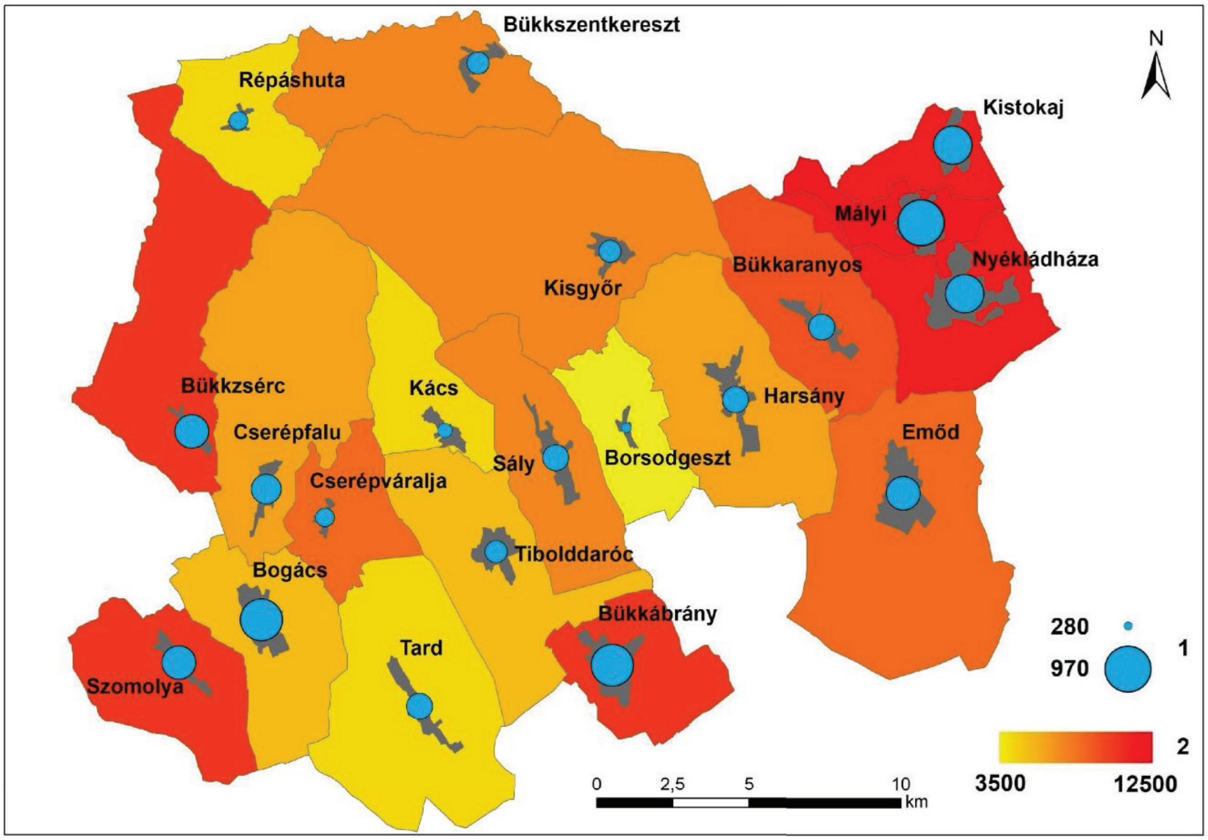
Regarding the geothermal potential, *Kistokaj* and *Mályi* have the best opportunity to use the return heat energy of *Miskolc*'s DH system. Approximately 110,000 MWh thermal energy would be available in the heating season (in Hungary usually from 15 October to 15 April), which far exceeds these two settlements' RHD. Due to the geographical proximity of the settlements, this value was divided equally theoretically by attributing ~55,000 MWh per heating season to each settlement.

In the case of *Bogács*, the existing geothermal well could provide 5,837 MWh of heat energy in the heating season. The biogas plant, which is operating in *Harsány*, could also provide at least 2,296 MWh excess heat (Figure 6).

However, the geothermal potential must be significantly higher, as the study area lies above geothermal reservoirs [66]. Nevertheless, in this research, drilling of new wells or redeveloping the abandoned hydrocarbon ones have not been considered due to high investment costs.

3.3.2. Biomass potential

The resulting potential of forestry and agricultural biomass residues are 63,158 and 35,185 MWh/year, respectively. Regarding the forestry area, only 39% of the territory has exploitable potential, this ratio in the case



1 linear heat demand density range (MWh/km);
2 heat demand density range (MWh/km²)
HDD were calculated for the inbuilt areas but displayed on the external lands of the settlements.

Figure 4: Linear heat demand density and heat demand density in *Bükkalja*. For detailed values see Appendix 2

of agricultural land is 96%. The potential of different forestry subcompartments and agricultural raster varies notably: while the standard deviation of the potential of different forestry subcompartments is 2.6 MWh/ha, in the case of agricultural areas it is 4.17 MWh/ha.

The result of the *location-allocation analysis* represents that there is no correlation between the number of allocated areas and the volume of the potential biomass source (Figure 5). Since the heat demand of two settlements could be completely covered by geothermal heat, the further calculation involved the remaining 18 settlements. Out of these, 14 villages could completely cover their RHD by biomass. 91% of the biomass was allocated successfully, the remaining available biomass could not be allocated to any settlements because of the 20 km transport limit.

3.3.3. Solar thermal potential

The *land availability analysis* resulted in the size of suitable areas for solar collector utilisation (Figure 6) to be significant as the theoretical possibilities are far higher than the heat demand. On the other hand, in cases of 6 settlements, due to the strict set of criteria, no proper sites were identified within their 500 m buffer zone, therefore this source was not considered in their heat potential calculation. Furthermore, *Mályi* was excluded from the solar thermal potential investigation because of its enormous geothermal potential.

The solar thermal potential calculation was linked to the available geothermal/excess heat and biomass potentials as the usable solar energy would depend on these sources. Therefore, the solar fraction was limited to 20%. Thus, in those 1 3 settlements where solar thermal utilization would be available, the required gross land size is between 1,800–17,250 m^2. According to the *land availability analysis*, only 0.5–25% of the expendable fields would be enough to implement the proposed solar thermal systems.

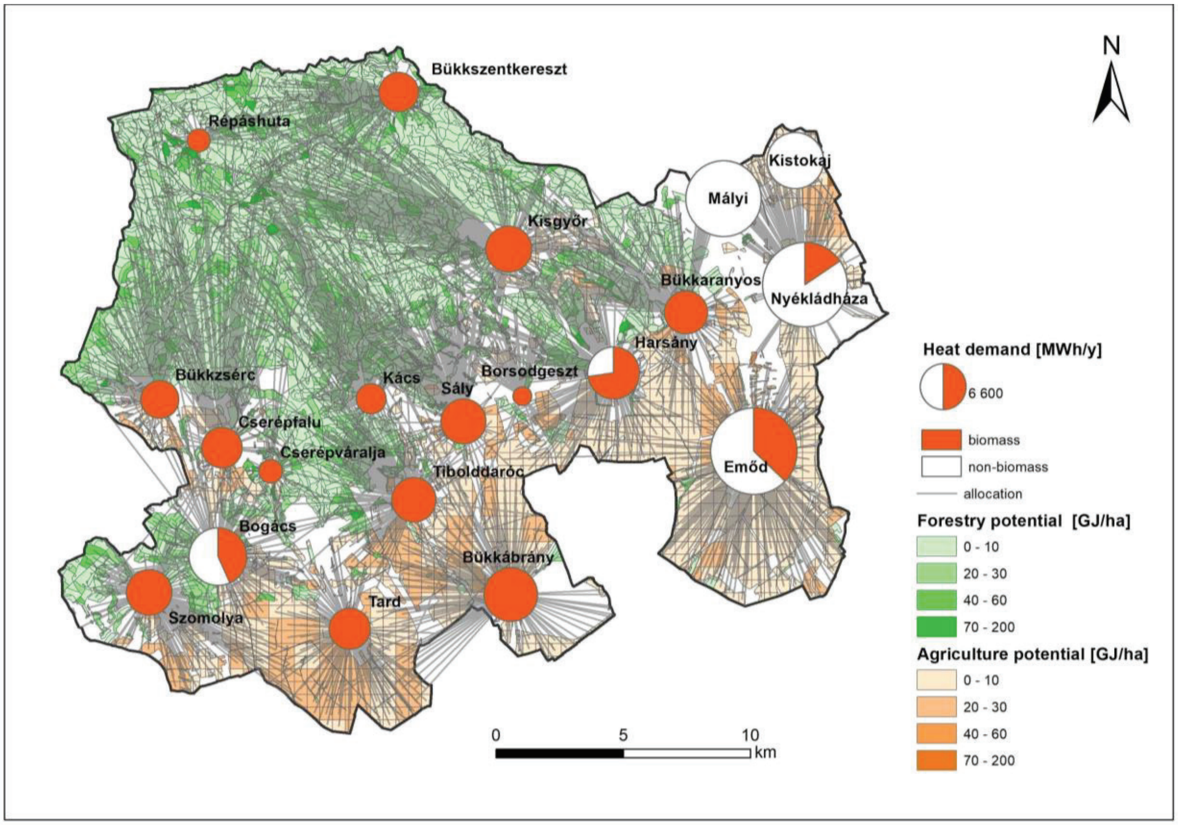


Figure 5: Available biomass resources and their optimal distribution within the study area. Allocation lines are only used due to visualisation, real biomass transport routes are not presented

3.4. Results of the supply-demand analysis

There are two settlements with far greater supply-demand ratio: *Kistokaj* could reach 554% and *Mályi* could reach 306% due to their huge geothermal stock. Most of the settlements have significant biomass sources, in fact, enough to cover their whole RHD. Regarding the DH possibilities, there are 18 communities out of the 20, where the heat self-sufficiency could be reached within the constraints of the sustainability criteria. There are only two settlements (*Emőd*, *Nyékládháza*), where the available renewable sources are limited, compared to the relatively high demand (Figure 7).

3.5. Results of the standardization – Possible DH developments in the Bükkalja region

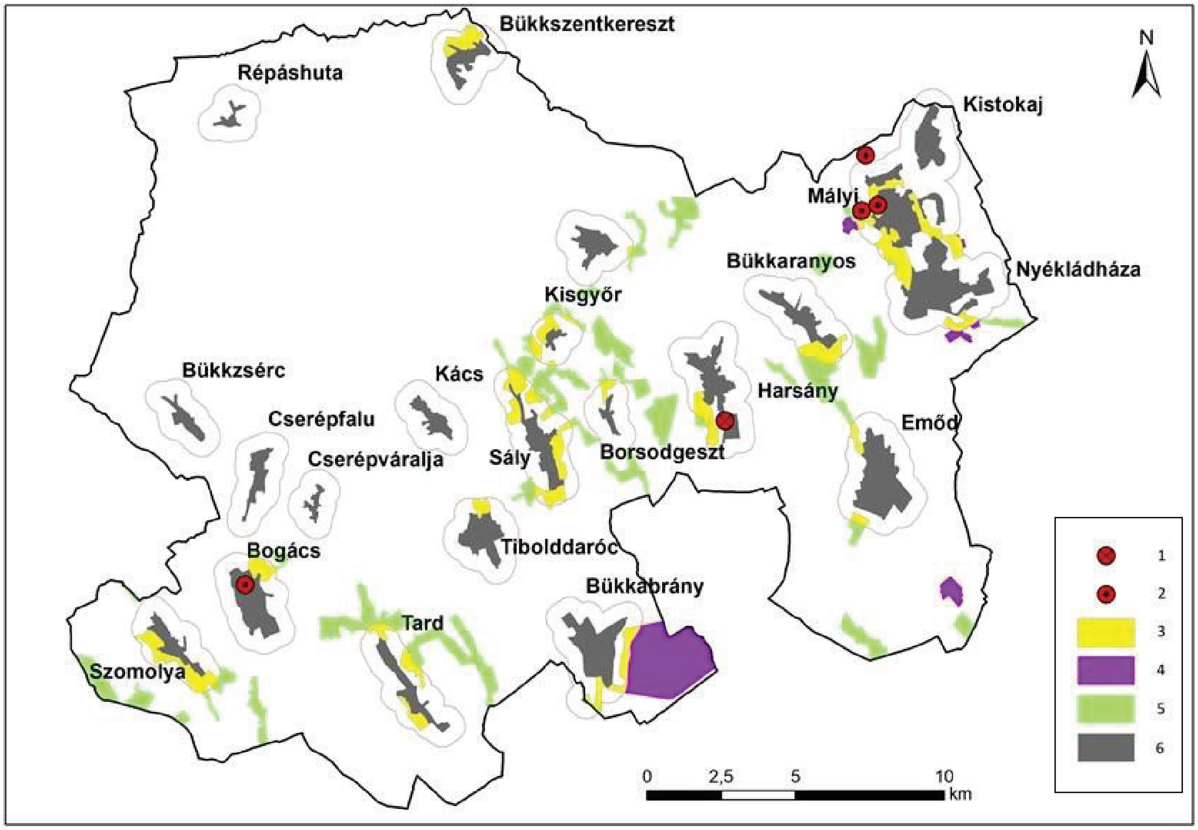
According to the results of the standardization, there are five groups of communities (Figure 8). The '*most recommended*' settlements for DH developments (above 2.0) are *Kistokaj* and *Mályi* due to a large amount of locally available renewable energy source, favourable RHD volume, and morphology. There are five other settlements with promising attributes '*recommended'* (above 0.0). Regarding the feasibility, it is important that three, *Mályi*, *Kistokaj,* and *Nyékládháza* are located within a 3.5 km radius.

In the so-called '*recommended with limitations*' category, there are six settlements with values between –0.3 and 0.0, showing limited capabilities for DH developments. Regarding Harsány, the DH coverage could be around 27% if the significant excess heat source from the local biogas plant would be utilised.

The even lower values, between –0.5 and –0.3 show that the possibilities are far from optimal, but they are not entirely excluded ('*recommended with strong limitations*'), even though individual heating solutions could provide better choice such as PV and heat pump combination [47]. In addition, there are 3 small villages (*Répáshuta*; *Kács* and *Borsodgeszt*) with very low HD and HDD, where a centralised heating solution would not be feasible ("*not recommended*").

3.6. Social acceptance

Based on the survey findings, 54% of the households would join a modern DH system and 9% would only



1 Biogas plant
2 Geothermal wells
3 Potential areas for solar collector fields
4 Mineral extraction and dumpsites (without potential areas for solar collector fields)
5 Pastures (without potential areas for solar collector fields)
6 Built-up area of settlements

Figure 6: Land availability of solar thermal, geothermal and biogas excess heat sources

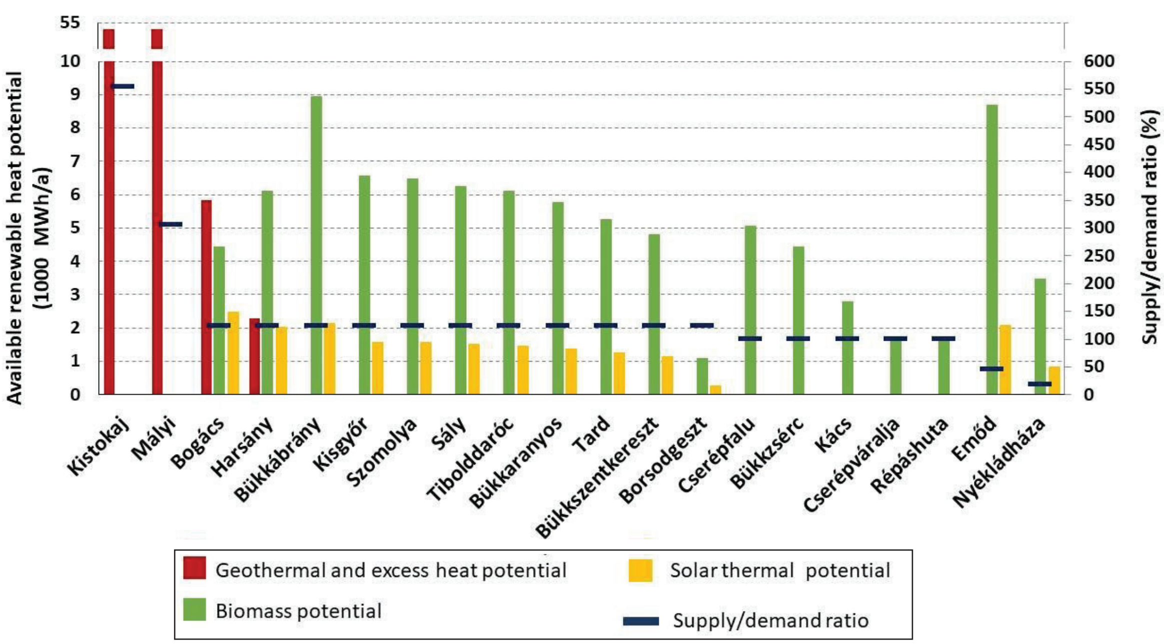


Figure 7: Sustainable renewable-based thermal potentials for prospective DH developments by settlements

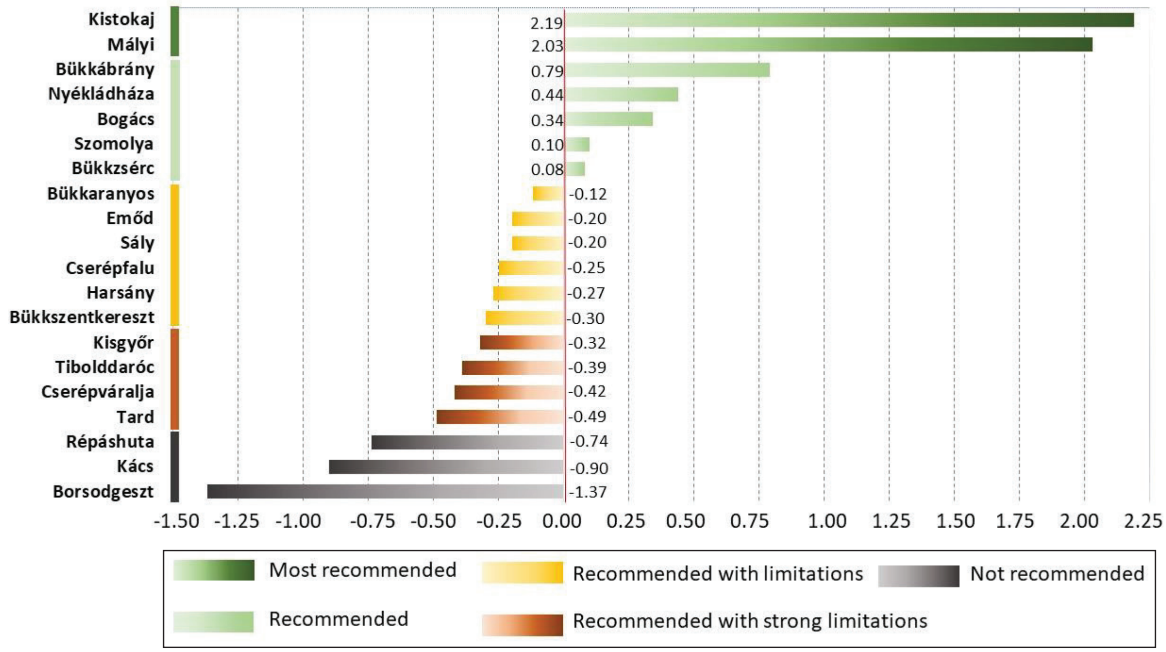


Figure 8: Result of the standardization process and recommendation level for DH development

connect if they could keep their former heating system as a backup. Approximately 33% of the interviewees rejected the idea of joining a new DH system and another 4% refused to answer. Regarding the two settlements with the most favourable conditions for DH development, 67.8% of their population would "accept" or "accept with preconditions" to have their household connected to a modern DH system.

4. Discussion

The discussion contains the following topics: energy mix, sustainability limits, BÜKK-PETA comparison, prospective DH developments.

4.1. Current energy mix and sustainability limits

The fuel import dependence of residential heat production is connected to the high level of imported natural gas consumption, which should be minimised as soon as practicable. Another challenge is the locally mined lignite. Its 7% utilisation ratio needs to be decreased to zero to mitigate its devastating effects on the local environment, including air quality and ecology, moreover, on the global climate. According to the present research findings on firewood heating, it can be stated that its recent utilisation far exceeds (by 52%) the production of the ecologically sustainable local forestry.

Based on the above-mentioned facts it can be concluded that the supply-side of residential heating should be substantially restructured. Therefore, the utilisation of available geothermal, excess heat and solar potential could be even more crucial in the future.

One of the main research outcomes is that most of the settlements have a sufficient amount of local renewable energy sources to fulfil their RHD considering the strong sustainability concept. Combining complementary technologies enables HDH systems to be implemented, though their optimal composition is site-specific and depends on many factors. A proposal for this HDH energy mix can be envisaged in a subsequent study. In the case of 18 settlements, the supply-demand ratio reaches or exceeds 100%. Although, energy demand for heating is very high compared to the possibilities which could be reached by the existing technologies. The most important step ahead would be an urgent increase in building energy efficiency (supported by national or EU funds) in order to significantly reduce RHD. This step combined with the switch to DH technology has the potential to reduce energy bills for the consumer and consequently promote access to sustainable heating [67] and mitigate energy poverty [68].

4.2. BÜKK results comparison with PETA database

This step was used as a validation of the research outcomes. At first sight, there is an apparent difference between the two value sets, as PETA shows 25% higher HDs consecutively for the settlements. This is reasonable since this research work targeted only the residential sector, which means that public services and the industrial sector were excluded from the investigation. However, there are some other important differences and anomalies between the results. In detail:

a) In the cases of the three smallest settlements (*Borsodgeszt, Cserépváralja, Répáshuta*) with RHD values below 2,000 MWh/year, PETA does not contain any information;

b) Two neighbouring settlements (*Mályi* and *Nyékládháza*) are grouped into one single 'prospective supply district' polygon in the PETA map, as they are too close to each other to handle separately. Their heat demand has become indivisible; thus, these settlements were also merged together in the comparison phase;

c) There are two settlements (*Bükkszentkereszt*, *Kács*), where BÜKK results present higher values (Figure 9). This could be partially caused by the error rate (25%) of heat demand calculation from the BÜKK region. These differences are significant; therefore, the real total heat demand of these villages should be slightly higher than the values of PETA according to estimation of the present research work;

d) Another remarkable negative deviation was detected in the cases of four settlements (*Bükkábrány, Szomolya, Cserépfalu, Tard*). This anomaly should be considered since all these villages have been marked as prospective DH supply areas, where the recommended DH rate was quite high, between 30–60%. However, results regarding BÜKK show that the values of *Bükkábrány* and *Szomolya* are 15–25 percentage points (pp) lower. Furthermore, in the events of *Cserépfalu* and *Tard*, the differences are more than 25 pp (Figure 9). According to this result, it seems that PETA significantly overestimates the heat demands of these settlements. To confirm this statement, a corroborative calculation was made based on the available non-residential natural gas consumption statistical dataset. The result of the validation confirmed the presumption that the non-residential sector has only a moderate natural gas consumption in this area.

e) From the 20 investigated settlements only *Mályi* has significant non-residential natural gas consumption caused by the local brick factory. However, this consumption seems not to be represented in PETA [4]. Therefore, it is assumed that in the case of the prospective DH supply of *Mályi* and *Nyékládháza*, the annual HD was slightly underestimated. Thus, the recommended 10% DH coverage by PETA could be much higher according to the results of BÜKK.

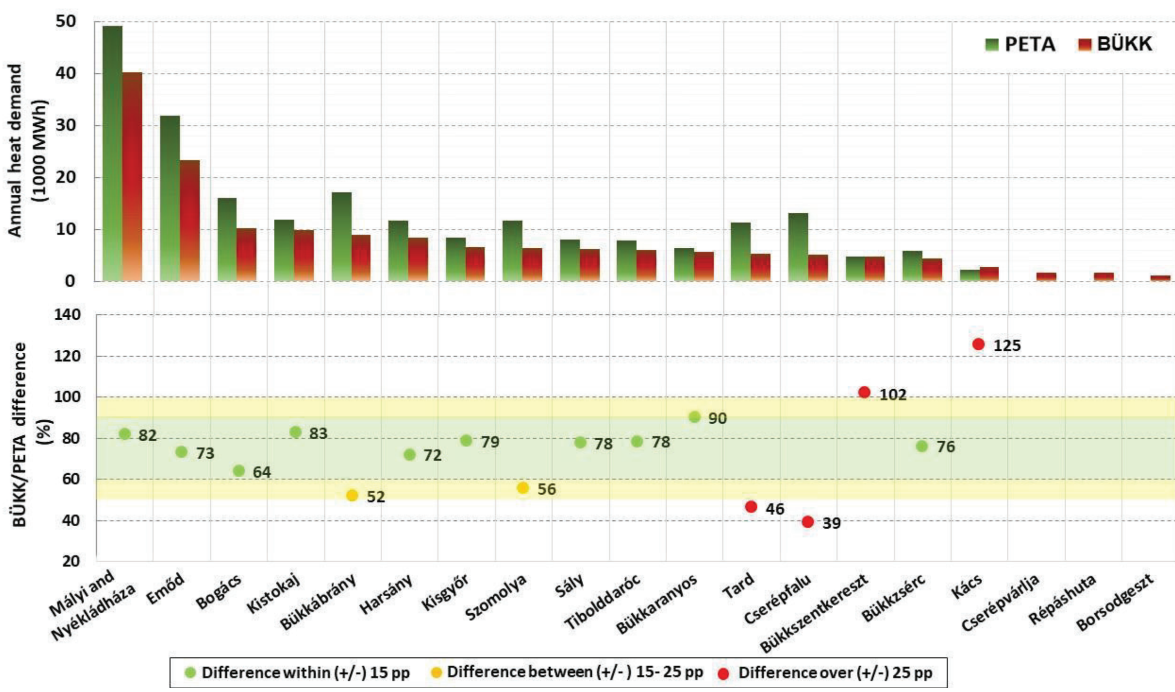


Figure 9: HD results-comparison of the examined settlements based on values of PETA and BÜKK.

Considering the PETA recommendations [5], minimum HDD is ~33,300 MWh/km^2 for conventional DHs in areas with existing buildings. This is four times higher than the average value in *Bükkalja* (8,000 MWh/km^2). However, in the *Güssing* region, even lower values are found. For instance, *Strem* and *Eberau* are not indicated in the PETA as prospective settlements for DH, due to their low HDD (5,000–6,000 MWh/km^2). In practice, however, well-functioning and expansive networks have been operating in these settlements [32]. Thus, DH developments are site-specific, and evaluations shall not be simplified to certain technical or economic indicators. PETA suggests DH developments for 8 settlements in the region with a recommended DH coverage between 10–60% [5]. The BÜKK research recommends such projects for 7 settlements. In the case of five settlements (*Mályi, Nyékládháza, Szomolya, Bükkábrány, Bogács*) the results are analogous in the two studies. However, in the case of *Tard* and *Cserépfalu*, the BÜKK project does not confirm the necessity of DH development. The possibility of a prospective DH project in *Harsány* is obvious because of the currently unused excess heat resource of the local biogas plant. However, a more detailed investigation is needed to determine the most sustainable way to exploit such energy sources.

4.3. Possibilities and limits of the prospective DH developments

Representing another key result of the research, three neighbouring municipalities (*Mályi*, *Kistokaj*, *Nyékládháza*) were identified as the most suitable ones for DH developments. In the case of *Mályi* and *Kistokaj*, the resource potential is enormous, while *Nyékládháza* has the second highest RHD, which is an important precondition of a DH development, but its renewable energy capabilities are modest. Therefore, cooperation between these municipalities could enhance the realisation of a joint DH project.

Another enhancing factor could be social acceptance, which is deliberately high in the study area. According to nation-wide research focusing on the social acceptance of DH [69], less than 15% of non-DH consumers would change to a modern DH system. Compared to the result of this research, 54% would join without conditions, and another 9% would join if they could keep their existing heating system as a backup. It seems that the social climate is definitely positive in the Bükkalja region. However, a significant share of the respondents mentioned that their final decision would depend on the details, particularly on financial implications.

Nevertheless, the feasibility of DH developments is generally hindered by the decreasing population and consequently descending RHD. Further essential hindering factors could be:

a) the high level of (energy) poverty, which makes external funding inevitable for such investment-intensive projects;
b) the missing supporting regulation in the field of community involvement in Hungary.

As for the sparsely populated settlements with very low RHD of the study area, efficient and low-polluting individual heating solutions, such as heat pumps combined with PV systems, can be a suitable alternative for the near future.

5. Conclusions

This research is based on a complex methodology comprising household-level surveys and resource availability analysis with strict sustainability criteria. Therefore, it can be used for preliminary studies of small-scale rural DH projects. Referring to the research questions, the following answers can be given:

a) the residential heating energy mix is mainly based on unsustainable technologies and fuels, moreover, the level of consumption is also untenable. Thus, rapid energy transition is inevitable;
b) in most cases the RHD and HDD have typical values for rural areas, however, the *specific heat demand* is much higher than the optimal, which can be explained by the bad condition of the building stock;
c) in general, the renewable resource abundance is discovered, however, in the case of biomass, significant residential overexploitation is revealed – one of the unexpected key findings of this research work;
d) there is a clear relevance of rural DH developments in the study area, as the majority of the communities have proper attributes to fully or partially cover the residential heat supply;
e) the correlation with the PETA database [5] is clear and strong, although there are some exceptions. These anomalies draw attention to the importance of more detailed sub-regional studies to promote local energy transition.

According to the results, locally available renewable energy-based DH systems could play a relevant role in the rural energy transition. However, in practice, there are several other aspects that have to be taken into account. Therefore, this work can be considered as a preliminary analysis, which can help the orientation of local and regional decision-makers. Finally, it can be stated that the outcomes of this research confirmed the hypothesis by identifying the villages of the study area that offer good possibilities for DH developments.

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Appendix 1.

Values of the three complex-parameters and their averages in the standardization process

Settlements	Complex parameter 1. HDD	Complex parameter 2. Linear HDD	Complex parameter 3. Supply/demand ratio	The average of the complex parameters
Bogács	–0.41	1.57	–0.14	0.34
Borsodgeszt	–2.16	–1.82	–0.14	–1.37
Bükkábrány	0.91	1.61	–0.14	0.79
Bükkaranyos	0.07	–0.28	–0.14	–0.12
Bükkszentkereszt	–0.19	–0.58	–0.14	–0.30
Bükkzsérc	0.42	0.19	–0.37	0.08
Cserépfalu	–0.32	–0.07	–0.37	–0.25
Cserépváralja	0.01	–0.90	–0.37	–0.42
Emőd	0.03	0.23	–0.87	–0.20
Harsány	–0.31	–0.35	–0.14	–0.27
Kács	–1.15	–1.18	–0.37	–0.90
Kisgyőr	–0.14	–0.69	–0.14	–0.32
Kistokaj	1.60	1.15	3.84	2.19
Mályi	2.45	2.09	1.54	2.03
Nyékládháza	1.36	1.08	–1.12	0.44
Répáshuta	–0.86	–1.00	–0.37	–0.74
Sály	–0.13	–0.32	–0.14	–0.20
Szomolya	0.35	0.09	–0.14	0.10
Tard	–1.01	–0.32	–0.14	–0.49
Tibolddaróc	–0.51	–0.51	–0.14	–0.39

Appendix 2.

Demand-side indexes of the settlements in the study area

Settlements	Gross RHD (MWh/a)	Net RHD (MWh/a)	In-built area of settlements (km^2)	HDD (MWh/km^2)	Road network length (km)	Linear HDD (MWh/km)
Bogács	15,470	10,279	1.51	6,807	11.65	882
Borsodgeszt	1,840	1,087	0.31	3,483	3.84	283
Bükkábrány	14,686	8,933	0.96	9,334	10.06	888
Bükkaranyos	8,532	5,753	0.75	7,723	10.38	554
Bükkszentkereszt	8,106	4,804	0.66	7,236	9.57	502
Bükkzsérc	6,940	4,434	0.53	8,397	6.95	638
Cserépfalu	7,780	5,063	0.73	6,983	8.54	593
Cserépváralja	2,552	1,707	0.22	7,619	3.83	446
Emőd	34,926	23,385	3.06	7,642	36.28	645
Harsány	12,594	8,394	1.20	6,995	15.48	542
Kács	4,350	2,788	0.52	5,393	7.03	397
Kisgyőr	10,253	6,559	0.90	7,321	13.58	483
Kistokaj	14,106	9,899	0.93	10,633	12.26	808
Mályi	25,901	17,910	1.46	12,267	18.39	974
Nyékládháza	31,656	22,385	2.20	10,175	28.13	796
Répáshuta	2,767	1,630	0.27	5,950	3.81	428
Sály	10,359	6,259	0.85	7,346	11.43	548
Szomolya	9,819	6,485	0.79	8,251	10.47	619
Tard	8,003	5,246	0.93	5,665	9.58	548
Tibolddaróc	9,284	6,092	0.92	6,629	11.83	515