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The Importance of Place: Lessons From the Spatial Mapping of Hungarian Household Heating

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***Abstract*—The study described here examines the spatial patterns of household heating energy consumption in Hungary, mapped at a high-resolution 1 km² grid level. The research focuses on traditional fuels and modern renewable heating technologies. The study's objective is to reveal how spatial structure and socio-economic context influence households' positions on the energy ladder and to identify clusters representing different stages of the energy transition. Methodologically, the analysis uses global and local Moran's I to detect spatial autocorrelation, identify hot and cold spots, and cluster grid cells by their heating profiles. The results demonstrate that the geography of residential energy use is shaped not only by socio-economic variables but also by strong spatial dependencies. Neighborhood effects, local technological diffusion, and territorial path-dependencies all play a decisive role in how households progress along the energy ladder. This implies that energy transition processes unfold unevenly and are highly sensitive to the local context.**

***Index Terms*--energy ladder, heat pump, solar PV, firewood, spatial econometrics**

I. Introduction

The energy transition is a complex, multidimensional, multidirectional, and extremely variable spatial process that involves moving away from fossil fuels toward zero-carbon technologies. It is proceeding at different speeds across social groups and regions, highlighting regional, social and economic inequalities in the adoption of new technologies and social practices [1], [2], [3], [4].

In this study, we draw on three theories (energy ladder, fuel stacking, and technology diffusion) to explain residential heating energy use and the diffusion of related technologies across households and settlements. We show how neighborhood effects and spatial relationships among 1 km^2 territorial units influence the choice between energy sources and heating technologies in Hungary. The main objective is to analyze spatial dependence in the use of traditional fuels (coal and lignite, wood, and other heating materials, such as household waste) and modern renewable heating technologies (i.e., heat pumps, solar collectors, and solar panels) at below the settlement level. The analysis uses a regular grid of 1 km × 1 km cells, with each grid cell (1 km²) serving as the basic spatial unit. After measuring spatial autocorrelation, we identify spatial clusters among grid cells. We assume that in the household sector, the energy transition represents a positive shift towards higher-quality energy sources, or in other words, a step up the energy ladder. In our interpretation, each cluster can be mapped to a distinct step on the energy ladder, distinguishing lagging areas from those leading the energy transition. We propose two hypotheses to examine whether spatial relationships play a role in the energy mix and thus in the adoption and spread of modern renewable heating technologies:

H1: Both socio-economic characteristics *and* spatial location significantly influence household energy consumption, and households with similar energy mixes are spatially concentrated in Hungary.

H2: Based on the residential energy mix, Hungarian households can be classified into spatial clusters.

II. Theoretical Background

A. The energy ladder and energy-stacking theory

The quality of primary and secondary energy sources is determined by both physical and economic factors. Physical characteristics include energy content, efficiency, cleanliness of combustion, and the amount of pollutants emitted, while economic factors include energy prices, conversion costs, substitutability, and flexibility of use [5]. Based on these factors, electricity can be considered the highest quality energy source, as it is clean, efficient, and suitable for all basic household activities. In contrast, solid fuels, especially household waste and primary solid biomass, are of the lowest quality.

The energy ladder theory ranks energy sources according to quality and assumes that as income increases, households switch from lower-quality energy sources to cleaner, typically renewable energy sources [6], [7]. The theory also presumes that a given household activity (e.g., heating, cooking) is associated with a single energy source, thus ruling out parallel use.

An important limitation of the energy ladder approach is that the energy mix is not determined solely by income, but also by several other factors, such as energy prices, education, energy and environmental awareness, type of residence, cultural factors, and the condition of the building stock. In practice, the simultaneous use of multiple fuels and technologies (e.g., mixed-fuel boilers, gas boilers, and heat pumps) is common, contradicting the theory's assumption of linearity.

Fuel-stacking theory accepts these criticisms and provides a more nuanced description of household energy use. According to this theory, households often only partially switch to cleaner energy sources, while retaining older, more polluting fuels [8]. The main reasons for this are the high costs of modern technologies, experience with traditional fuels, and the need for security of supply. Due to such parallel use, the energy transition is a slower, non-linear process in which lower-quality energy sources remain in use for long periods.

B. Technological diffusion

In presenting diffusion, we apply a geographical approach, which focuses on acceptance, market, and infrastructure [9]. This takes into account the role of space, with "diffusion moving like a wave from the source to nearby locations and then to more distant ones" [9, p. 6]. "During diffusion, not only [does] a technology spread […], but also the knowledge necessary for its production and use" [10, p. 62].

From this perspective, the energy transition can be understood as the broad adoption of modern, clean, and efficient renewable energy technologies. Historically, the diffusion of new energy sources and related technologies has taken several decades, often around 50 years [2]. Most prior approaches, however, focus on large-scale systems spanning multiple economic sectors. As noted by [4], analyzing the energy transition at a more fine-grained territorial level can provide additional insights. Such focused analyses may reveal patterns and relationships that remain hidden in international-level studies.

C. The two ends of the energy ladder in Hungary – traditional fuels and modern renewable heating technologies

1. Traditional fuels

The use of traditional fuels (biomass, coal, lignite, household waste) causes significant social problems. According to the data presented in [11], in 2022, 9.3% of the European Union's population was unable to heat their homes, meaning 41.5 million people were living in energy poverty. The latter is a particularly serious problem in Hungary, where the typically low energy efficiency of residential buildings and low average household income exacerbate the situation [1], [12]. In Hungary, 9.1% of the total population and 23.7% of persons at risk of poverty or social exclusion live in underheated dwellings, placing the country in the middle of the EU ranking (the EU averages are 17.9% and 31.2%, respectively) [11].

According to [13], users of traditional fuels are more exposed to the risk of energy poverty and much more vulnerable. They typically live in rural areas and have low disposable incomes. Their properties (buildings) are generally in very poor condition and have low energy efficiency. Roofs often leak, and structures are often infested with mold and mildew. In many cases, there is no insulation, and the "eat or heat" dilemma is common [14]. People living in such conditions are generally poorly educated, with high levels of functional illiteracy and no steady income [15]. Without serious financial and technical assistance, switching fuels is simply not feasible.

Among traditional fuels, solid biomass is the most significant and perhaps one of the most controversial and contradictory renewable energy sources. While solid biomass (typically firewood or its processed forms, such as pellets) accounts for 38.2% of renewable energy consumption in the European Union, in Hungary, the figure was 61.4% in 2022, with households the most significant consumers. In the European Union, the share of primary solid biomass in household energy consumption was 17.6% (22.8% in Hungary) in 2022, while in heating, the figures were 25.6% in the European Union and 30.2% in Hungary [11].

2. Modern renewable heating technologies

At the top of the energy ladder, we find heat pumps, solar panels, and solar collectors, which enable the production of electrical or thermal energy on a household scale. The total cost of installing these systems is decreasing year by year. Today, solar panel systems are considered the most typical modern renewable energy technology in Hungary, where in 2024, total solar PV capacity was 7,551 MW, of which household-scale solar PV installed capacity was 2,690 MW [16]. Their use reduces dependence on energy imports, contributes to climate mitigation efforts, and protects consumers from energy price fluctuations. Their benefits accord with the priorities set out in the energy trilemma, i.e., improving energy security, environmental sustainability, and equity [17].

III. Data and Methodology

A. Data

Municipal-level analyses are always hampered by severe data limitations. At the time of writing, the 2022 Hungarian census data were available; thus, the analysis is based on this. We aimed to use indicators that met the following criteria: (1) availability of data for all municipalities, (2) replicability of the analysis in other time periods, and (3) comparability across the selected territorial units. Table 1 lists all the data. The data source in all cases is the Hungarian Central Statistical Office [18].

TABLE I. Data Used in Analysis

Indicators (unit: dwelling numbers)
households using firewood as heating fuel
households using coal and lignite as heating fuel
households using other fuels for heating
dwellings with a heat pump heater (availability of equipment)

dwellings with solar panels (availability of equipment)
dwellings with solar collectors (availability of equipment)
occupied dwellings

Coal, lignite, firewood, and household waste are the most widespread low-quality fuels; solar panels, solar collectors, and heat pumps represent modern heating technologies. For ease of understanding, we refer to the former as traditional fuels and the latter as modern renewable heating technologies. All occupied dwellings in Hungary are included in this study. In previous work [19], we have implemented a similar analysis at the settlement level. In this study, however, we sought to explore deeper correlations than those at the settlement level, so we worked with 1 km^2 grids, of which the territory of Hungary contains 91,892. Of these, 30,237 grids contain residential properties, which we considered the number of territorial units in our study.

B. Methodology

The analysis aimed to examine the spatial distribution of the share of dwellings using traditional fuels and modern renewable heating technologies, and to explore whether there is any regularity or spatial pattern in this distribution. Spatial autocorrelation indices are widely applied [20], [21], [22], [23]. We deployed Moran's I (similarly to [19], [24]) to test spatial dependence and identify hot and cold spots in the use of traditional fuels and modern renewable heating technologies. The null hypothesis is that there is no spatial dependence. Moran's I formula is as follows [25], [26], [27], [28] (Eq. 1):

$$I = \frac{n}{2A} * \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\delta_{ij}(y_i - \bar{y})((y_j - \bar{y})}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad 1)$$

where n is the number of municipalities, y_i is the value of the variable in each of the municipalities, $\bar{y}$ is the unweighted arithmetic average of the variable, the number of neighborhood links is denoted by A, and the δ_{ij} coefficient is '1' if municipalities i and j are adjacent, and '0' if they are not [24], [29].

E (I) shows the expected value of Moran's I:

- E (I) > –1/N–1, positive spatial autocorrelation,
- E (I) = –1/N–1, no spatial autocorrelation,
- E (I) < –1/N–1, negative spatial autocorrelation.

There may be no spatial autocorrelation globally (i.e., over a large territorial unit), although one may be present locally. Local Moran's I can be defined as (Eq. 2 and Eq. 3) [30], [31]:

$$I_i = \frac{(Z_i - \bar{Z})}{S_Z^2} * \sum_{j=1}^{N}\left[W_{ij} * (Z_i - \bar{Z})\right] \quad 2)$$

$$S_Z^2 = \frac{\sum_{j=1, j\neq i}^{n}(z_j - \bar{Z})^2}{n-1} \quad 3)$$

where: z_i denotes the value of the attribute for feature i, $\bar{Z}$ is the mean of the corresponding attribute, and w_{ij} is the spatial weight between feature i and j, with n equating to the number of features.

In the current study, queen contiguity is applied. Two spatial units are considered neighbors if they share at least one boundary point. Contiguity means that two spatial units share a common border of non-zero length.

For the obtained Local Moran's I value, negative values indicate negative autocorrelation, and positive values indicate positive autocorrelation [19]. However, the set of values of the function is wider than the interval -1 to +1. Local Moran's statistics can be used to identify areas that are similar to or different from their neighbors. The higher the Local Moran's I value, the more similar values are located closer together. A negative value indicates the variable is spatially random, with no discernible spatial pattern in its distribution. Spatial autocorrelation can thus be defined as the "absence of spatial randomness" [32].

Using Local Moran's I, we calculated the share of dwellings with traditional and modern renewable heating technologies at the 1 km^2 grid level in 2022. The results were then compared with the baseline data to investigate whether a high level of similarity is caused by a concentration of high or low values of the variable (Moran scatter plots). First, the standardized values of the observation units were plotted on the horizontal axis of a graph. In contrast, the corresponding standardized Local Moran's I values (average neighbor values) were plotted on the vertical axis. The scatter diagram helped classify the municipalities into four groups according to their location in the quadrants of the plot:

- Cluster 1. High-high: high values surrounded by nearby high values (positive autocorrelation)
- Cluster 2. High-low: high values surrounded by nearby low values (negative autocorrelation).
- Cluster 3. Low-low: low values surrounded by nearby low values (positive autocorrelation).
- Cluster 4. Low-high: low values surrounded by nearby high values (negative autocorrelation).

Here, we note that, regarding the local spatial autocorrelation indicators, the choice of Local Moran's I is most appropriate when spatial outliers are sought. It shows where high-low values are clustered in space (HH-LL) and where spatial units that are significantly different from their neighbors are located (HL-LH).

IV. Results

The global autocorrelation of the proportion of dwellings with traditional fuels (i.e., across all grids with occupied dwellings in Hungary) was Moran's I = 0.352. For dwellings with modern renewable heating technologies, Moran's I = 0.053. Based on this, we conclude that both phenomena exhibit positive spatial autocorrelation, separately and together (E(I) = -1/30237-1 = -0.0000331), i.e., the spatial concentration of similar values is higher than expected under natural conditions (for example, grids associated with a high share of traditional fuel are commonly located next to other grids with a high share). Our null hypothesis (no spatial dependence) can therefore be rejected.

This also means that neighboring areas typically consume similar amounts of energy, confirming the finding [1] that a single energy source typically dominates residential energy consumption in a given area. In other words, each region or landscape has its own characteristic fuel that dominates the energy mix. In the vicinity of grids where one type of energy source is prevalent, neighboring grids tend to use the same energy source. If an energy source is not common in a given grid, it is unlikely to be used in the neighboring grid either.

In the next step, we examined the spatial patterns in more detail (Figures 1 and 2). The proportion of homes heated with traditional fuels is approximately 33.9% nationwide. In Nógrád, Szabolcs-Szatmár-Bereg, Somogy, and Tolna counties, the proportion exceeds 50%. In contrast, the proportion in the capital (Budapest) is only around 3%. Figure 1 shows that the more urbanized an area is, the smaller the proportion of traditional fuel use.

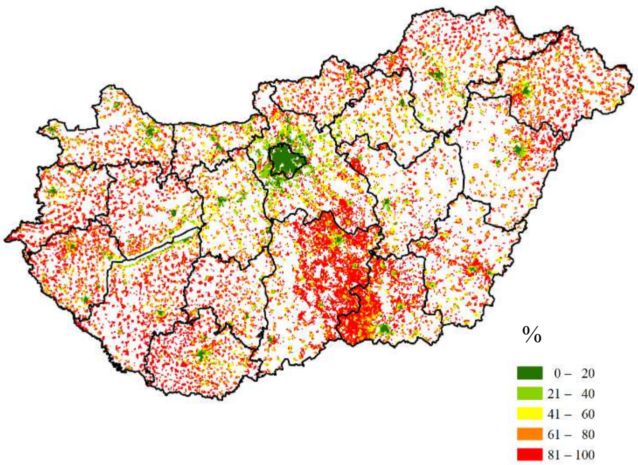

Figure 1. Share of traditional fuels used in the heating of occupied dwellings (2022) (%)

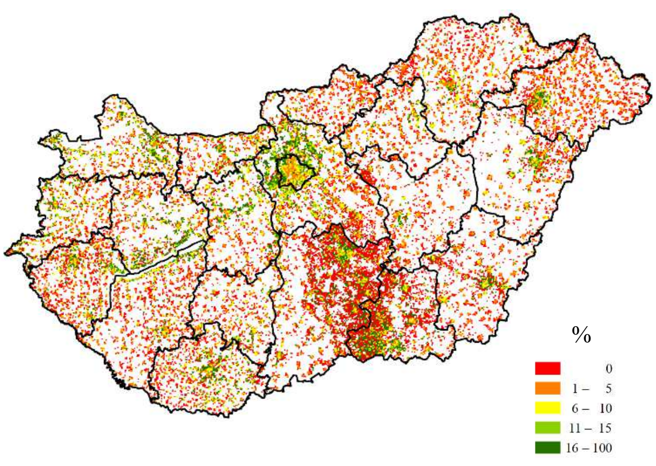

Figure 2. Share of modern renewable energy technologies used in the heating of occupied dwellings (2022) (%)

The proportion of dwellings with modern renewable heating technologies is 6.5%. A higher-than-average proportion is observed in Pest, Győr-Moson-Sopron, Fejér, Veszprém, Csongrád-Csanád, Baranya, Vas, and Hajdú-Bihar counties. In contrast, Nógrád county is in the most unfavorable situation in this regard.

We then examined the share of occupied dwellings using traditional fuels and those equipped with modern renewable heating technologies together. To do this, we applied a bivariate test for spatial autocorrelation (bivariate Local Moran I). The null hypothesis was rejected (I = -0.062). In Figure 3, non-significant grids are not shown for the sake of clarity.

We use labels to distinguish between clusters (high-high, low-low, low-high, high-low) as follows: 1) Dual Grids, 2) Transition Grids, 3) Vulnerables, and 4) Winners.

1. High Modern and High Traditional Cluster – "Dual Grids."

"Dual Grids" number 2,130, accounting for 1.6% of occupied dwellings nationwide. In terms of population, this is the smallest cluster, with 156,896 people. They are mainly located in Transdanubia, Bács-Kiskun, and Csongrád counties. These areas are usually populated by small villages or farmsteads, as evidenced by the lack of prefabricated buildings (only 1.75%). The proportion of the population with lower educational attainment and lower income living in older houses (typically adobe houses) (26.15%) is higher than the national average (13.02%), which indicates more vulnerable households ("vulnerable" defined as the only way to avoid energy poverty is to compromise between meeting energy needs and other basic needs [Stojilovska et al. 2023], also known as the "eat or heat dilemma"). The presence of both traditional fuels (69.16%) and modern technologies (13.14%) exceeds the national average (33.88% and 6.53%, respectively). The cluster is characterized by duality, with very different-quality energy sources used in parallel.

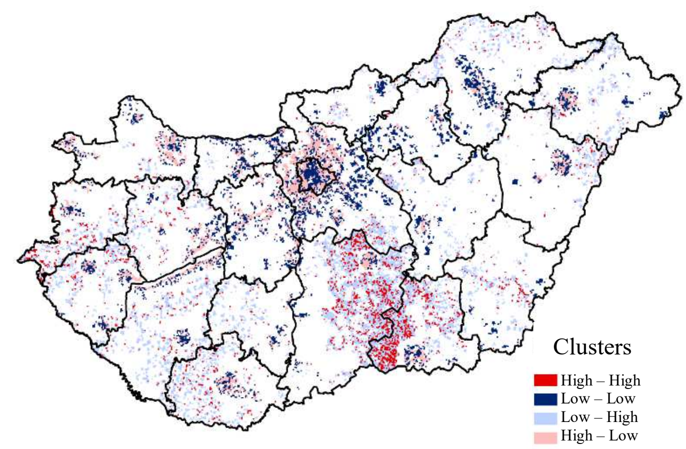

Figure 3. Spatial autocorrelation (bivariate Local Moran's I) of occupied dwellings heated with modern renewable energy technologies and traditional fuels in 2022

2. Low Modern and Low Traditional Cluster – "Transition Grids."

"Transition Grids" number 4,303, accounting for four-tenths of dwellings and one-third of the population nationwide. Transition Grids are predominantly located in urban areas, in most cases, larger cities, and on the southern shore of Lake

Balaton. The respective population is slightly more educated than the national average: the number of people with a high school diploma (31.15%) or a university or college degree (23.23%) is higher than the national average (28.29% and 19.1%, respectively). Neither modern renewable heating technologies nor the use of traditional fuels are typical (only 3.95% of homes have solar panels, collectors, or heat pumps, and only 14.38% are heated with traditional fuels). This suggests that transitional fuels are more prevalent, and is related to the very large share of panel buildings (25%) and thus to piped gas and district heating. The building stock is older than the national average, with far fewer houses built after 2000.

3. Low Modern and High Traditional Cluster – "Vulnerables."

The "Vulnerables" group comprises 8,628 grids, accounting for approximately 9% of occupied dwellings nationwide, home to 916,841 people. This cluster includes most of the peripheral settlements, which are the least developed in Hungary based on socio-economic indicators. These grids are home to people with lower levels of education: the proportion of the population (aged 15 and over) with at most a primary school education (18.65%) is well above the national average (15.97%). The share of dwellings heated with wood is highest in this cluster (66.89%), significantly greater than the national average (31.84%). The proportion of modern renewable heating technologies is low, at only 3.14% (the proportion of dwellings equipped with solar panels is 2.11%). Particularly worrying is the high share of coal, which exceeds the national average (2.8% compared to 1.3%). According to research, there is a close correlation between the type, age, and energy efficiency of buildings and household vulnerability [13, p. 9], suggesting that the external walls of occupied dwellings are a cause for concern. In this cluster, 31.77% of occupied dwellings are built of adobe and mud, and 4.69% are built of other materials. Panel buildings are almost completely absent (2.07%), with the remaining 57.27% and 4.21% made of brick, stone, manual walling elements, or cast-concrete, middle- or large-sized blocks, respectively. Only 5.11% were built after 2000. Households in this cluster are stuck at the bottom of the energy ladder, which makes them vulnerable. Energy poverty is likely to be widespread.

4. High Modern and Low Traditional Cluster – "Winners."

Finally, there are 3,443 grids among the "Winners". This includes 22% of occupied dwellings and 24% of the population nationwide. The Winners include Budapest and its agglomeration, as well as some rural agglomerations (Győr, Sopron, Pécs, Szeged, etc.). In eastern Hungary, however, some large cities and their catchment areas (e.g., Békéscsaba, Salgótarján) are less prominent than those in the western part of the country. More than 56.19% of the population (aged 15 and over) in these areas has at least a high school diploma. On average, the building stock is new(er) and energy efficient. Nearly 80% of inhabited dwellings are built of brick, stone, or hand-laid masonry, while adobe houses account for only 4.61%. More than a quarter (28.44%) of buildings were constructed after 2000.

V. Summary

In this article, we describe how we examined households' participation in the energy transition through their use of energy sources and related heating technologies. For this, we used the energy ladder and fuel-stacking theory, focusing specifically on the bottom of the ladder (low-quality, traditional fuels) and the top (modern energy sources and heating technologies), without addressing transitional energy sources. We paid particular attention to traditional fuels (household waste, coal, lignite, and firewood) and modern renewable heating technologies (solar panel systems, solar collectors, and heat pumps).

The cluster analysis shows that from the grid perspective (1km^2), residential energy consumption, and thus the composition of the energy mix, is significantly influenced by geographical location and neighborhood effects, and households with similar energy structures are concentrated in space. We were able to identify at a more fine-grained level than settlement that such grids may be classified at different levels of the energy ladder. Accordingly, our two research hypotheses are accepted

In Hungary, the grids we examined can be classified into four clearly distinguishable clusters based on the residential energy mix. Households located in "Dual Grids" are characterized by duality, with a significant mix of traditional fuels and modern renewable heating technologies. These are usually rural areas with more vulnerable households. The lack of energy infrastructure (less developed, more difficult to access, and expensive to connect) is likely to motivate people living here to use decentralized energy production. Households located in "Transition Grids" may be "complacent," meaning they are stuck in the middle of the energy ladder, with no clear upward or downward movement. Their energy source is often predetermined (e.g., gas, district heating panels), making it difficult to change. Members of the "Vulnerables" group are in the weakest position. The respective grids likely have the highest proportion of people living in energy poverty, as confirmed by the reviewed social indicators and building characteristics. Those belonging to the "Winners" cluster are the champions of the energy transition who have reached the top of the ladder. These are mainly residents of Budapest and a few rural agglomerations, who are well-educated, wealthier, and probably more environmentally conscious. The properties are, on average, newer, in good condition, and meet modern energy efficiency standards.

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