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"Landscape" of energy burden: role of solid fuels in Central and Eastern European residential heating

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ABSTRACT

Energy convergence, the decoupling of economic growth and energy use, and sustainable energy transition are all desirable objectives in the European Union. However, there are many contradictions and conflicts in the energy and climate policy that slow down the energy transition. In this paper, we focus on some of these barriers. The main research objective is to measure the changes in the household energy mix in Central and Eastern Europe (CEE) and infer the degree of the energy transition in the household sector. For this purpose, Moore, MLI and the NAV index, as well as the delinking factor are applied. The results shed light on the slowness of the just energy transition in CEE between 2006 and 2020 and confirm the presence of the dual fuel trap. The households in CEE have been stuck in the traditional biomass trap and beyond it, the natural gas consumption also contributes to higher exposure and vulnerability of households. We conclude that territorial differences and spatial characteristics of household energy use need more attention to achieve the energy and climate policy agenda of the European Union. Based on our results, energy efficiency and deep renovations must be prioritized to achieve sustainable and just energy transition in the studied countries.

Keywords

Household energy use;
Dual fuel trap;
Traditional biomass trap;
Energy poverty;
Just energy transition

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1. Introduction

Due to the high share of energy expenditure, household energy consumption is a mutual challenge to energy security and human development in Europe [1]. The economic implications of the COVID-19 pandemic and the war in Ukraine highlighted that energy affordability is the major driver of social welfare and justice in Central and Eastern Europe (shortly CEE). Affordable energy services are interlinked by sustainable and just energy transition, mainly by households' energy efficiency performance and dependence on heating fuels [2].

One of the most critical issues in the social dimension of household energy consumption is energy poverty. It is a key pillar of energy justice that upholds social rights to access affordable energy services. The use of conventional biomass is closely linked to energy poverty, which is no longer a problem only for the lowest income deciles but also for the middle class, as a result of the energy crisis of 2021-2022. To reduce it, more attention should be paid to the residential energy mix. Traditional biomass is the fuel for the poor, and it must be distinguished from modern renewables in all cases. The sustainable energy transition must be based on the latter to avoid the firewood trap. However, fuel switching for the households is not a simple task. The theory of energy ladder and energy stacking highlights these challenges that may further slow down the energy transition.

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The article aims to measure the changes in the household energy mix (i.e. electricity, natural gas, solid fuels, district heating) with special regard to solid fuels and natural gas. The nexus of energy affordability and social security policies are significant in the CEE; therefore, six EU Member States (Austria, Czechia, Hungary, Poland, Slovakia and Slovenia) were selected for further assessment. These countries have similar cultural backgrounds and socio-economic structures (see more about energy cultures in [3]), and Austria can serve as a reference. Two research questions are developed to examine the energy transition trends in the residential sector of CEE:

Q1: Can the degree of the energy transition in the household sector be measured? If yes, do the changes confirm the energy ladder or the energy stacking theory?

Q2: Can a rapid reduction in energy poverty be expected?

The remainder of this paper is organized as follows. The theoretical background section reviews relevant literature building on the theory of energy ladder and energy stacking and highlights some spatial aspects of energy poverty in CEE. The data and methodology section introduces the applied data and methodology; (i) structural change indices (Moore, Nav and MLI index) are used for measuring the changes in the residential energy mix; (ii) the delinking factor is used to analyze whether the households in Austria, Czechia, Hungary, Poland, Slovakia and Slovenia still heavily rely on solid fuels and whether the natural gas dependency decline. The following section presents the results, including our main findings on the degree of energy transition in the household sector and on delinking, both connected to the dual fuel trap. Finally, the paper provides some policy recommendations and presents the conclusions.

2. Theoretical background

Energy use still plays a critical role in human well-being and determines the quality of life in the long term. Lack of energy, or using not appropriate heating and cooking devices and stoves can cause serious health issues, like respiratory illness, lung disease, stress, cardiovascular conditions, etc. [4,5]. It strongly affects, among other things, the regional GDP per capita, unemployment, or even life expectancy at birth.

There is still a long-lasting debate around the proper definition and measurement of energy poverty. Energy poverty is a cultural issue too, the interpretations are varied in different world regions and we can distinguish objective, subjective and composite approaches [6]. One of the most widely accepted definitions is that energy poverty is “households’ inability to secure a socially and materially necessitated level of energy services in the home” [7,8].

As Bouzarovski and Tirado Herrero (2017) argue, between the spatial formations and the energy transition a bidirectional relationship can be identified. However, it is quite novel because the spatial approach is still not widely used in energy economics. The energy poverty literature and research often neglect the spatial characteristics of the energy mix. In our interpretation, it means that usually one lead energy source determines the residential energy use of an area. As many scholars point out the geographical energy poverty divides the EU and it still does exist [8–10]. LaBelle (2020) presents it in more detail regarding Poland, Lithuania and Hungary [3]. For example, in the Podkarpackie region in Poland, or Northern Hungary and Southern Transdanubia regions in Hungary, it is clearly the case. It can be stated that solid fuels (mainly firewood, coal and coke) are typical energy sources for heating in CEE, and a high level of energy poverty is connected to them.

However, the use of solid fuels raises more questions. They still have a major role not only in household heating but in the achievement of climate change mitigation goals. In many EU regions, the traditional biomass is still used in its basic format (as fuelwood) for heating, water heating and cooking. Open roaring log fires in homes are not uncommon, nor are low-efficiency thin-walled iron stoves. Traditional biomass largely contributes to the EU Member States meeting the renewable energy targets. Although it is counted as a renewable energy source its household use raises serious sustainability issues [11,12]. We must not forget the initiatives to change the content of biomass (as a concept), questioning its carbon neutrality (namely that firewood should no longer be considered a renewable energy source) [13].

Beyond the environmental issues, solid fuel use is tightly connected to energy affordability that became a central part of social policies in numerous Member States. According to Eurostat (2021) 6.9% of the population (EU-27) was unable to keep their home adequately warm in 2019, which indicates that this year around 30 million people lived in energy poverty in the European Union (in 2020 this number increased further up to 35.8 million). Especially in the post-communist economies the bad combination of high energy costs, inadequate household income and obsolete housing stock results in a high level of energy poverty [1,9,16,17]. This social group is highly exposed to the changes in energy prices or even to the changes in the current legislation and in their case the home-heating energy poverty risk is high [6]. They do not have any choice but to use cheap dirty energy sources for heating or under-consuming energy [18]. Shielding policies for energy-poor households are critically important, however, the new Social Climate Fund maybe not provide enough support.

Already the 'Fit for 55' states that biomass consumption has to be kept within the limits of sustainability, but it neglects to reveal the connection between traditional biomass use and energy poverty. As Bajomi, Feldmár, and Tirado-Herrero (2021) conclude traditional biomass and other solid fuel users are more exposed to energy vulnerability and they are the most affected by energy poverty [19]. Solid fuels are typical fuel sources for poor households (i.e., lowest income groups).

Achieving the energy transition and meeting the target of making Europe the first carbon neutral continent go hand in hand with the higher share of renewable energy sources in final energy consumption. However, not only the importance of renewables should be highlighted but the renewable energy mix too. The use of modern and clean renewable energy sources should be emphasized instead of traditional biomass. Even if traditional biomass is used, higher added value is needed. This could mean several solutions including more efficient technologies. For example, the widely used thin-walled iron stoves have to be replaced by modern, more efficient brick stoves or ovens [19]. Burning fuelwood can be sustainable and efficient (both cost-effective and environmentally friendly) but only with proper heating equipment. As Cutz et al. (2017) conclude the use of traditional biomass for heating has to be replaced by modern energy sources, or at least more efficient stoves are preferred and the biomass has to be processed in dedicated biomass power plants to reduce the CO_2 emission.

However, it is important to consider the social side of this policy recommendation and highlight the difficulties around fuel switching. These households mainly live in rural areas with low disposable income. The dwellings are in bad condition, low efficiency, leaking roof and mould are widely present too. Many times even the windows, and proper doors are missing, insulation does not exist, 'eat or heat' dilemma is typical [20]. Residents are typically under-educated without stable income [8]. They need serious financial and professional support, otherwise, the fuel switch does not happen.

To highlight the risk of traditional biomass trap and the difficulty of fuel switching, we use the energy ladder and energy stacking theory. The energy ladder model presents the energy transition in the residential heating and cooking activities as a linear and unidirectional way in which the households switch from lower quality energy sources (e.g. traditional biomass or other solid fuels) to modern fuels as a result of their growing income and higher quality of life [21,22] (Figure 1). The elements of the classical 4A concept, namely availability, affordability, accessibility, and acceptability play also an important role in fuel choice. As you move up the energy ladder, your well-being increases too. This is closely related to the theory of consumption, which says that as our income increases, not only do we consume more, but also higher quality goods. The theory assumes that households use one type of fuel for one household activity.

Based on the energy stacking theory, it is not expected that households in need may entirely give up their lower-quality energy sources and switch to modern energy sources quickly. Multiple fuel use is more likely, and it may slow down the energy transition.

A research gap is identified regarding the nexus of energy poverty, traditional biomass trap and energy transition in the household sector. We confirm the presence of the traditional biomass trap in CEE and provide some explanation based on the energy stacking theory. We connect it to the progress of the energy transition in the household sector highlighting its obstacles and challenges. We raise the attention to the importance of the energy mix and to the fact that the traditional biomass is the fuel for the poor. Our hypotheses are the following:

H1: The progress of the sustainable energy transition is measurable but its' degree is stagnating or even declining.

H2: The households in CEE are stuck in a solid fuel trap and neither relative nor absolute delinking of household expenditure on solid fuel and natural gas heating energy sources can not be identified.

3. Data and methods

To measure the changes in the household energy mix in CEE and infer the degree of the energy transition in the

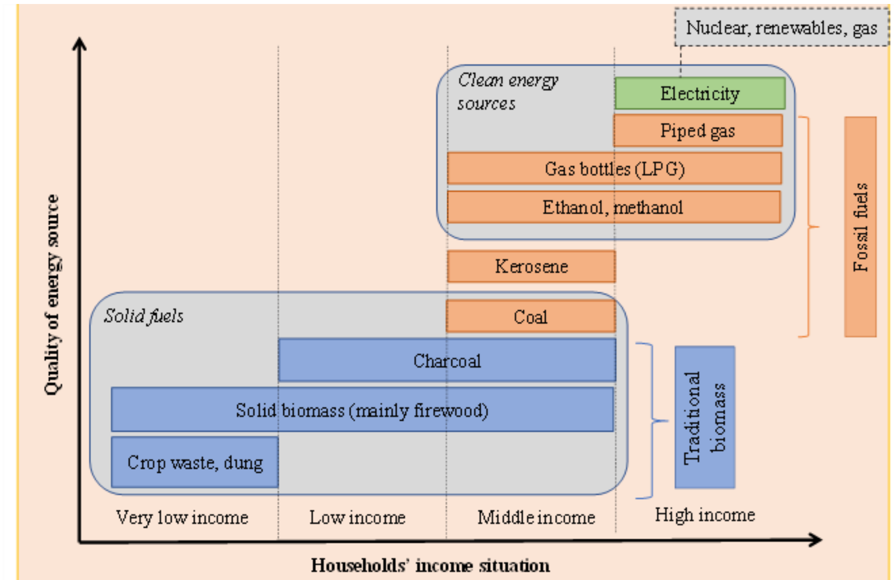


Figure 1: Energy ladder theory for households heating and cooking. Source: own compilation based on [23,24]

household sector structural change indices (Moore, NAV and MLI index) and delinking factor are applied. To achieve this, we introduce a fuel-specific indicator of energy burden, the Share of Household Energy Expenditure (SHEE). In addition, the methodology of these indicators and the sources of data used are detailed in this section.

3.1. Data sources

Our main data source for the energy consumption expenditure of private households and income was Eurostat [25]. The "Consumption expenditure of private households" indicator is based on surveys carried out at a national level with the aim to determine the weights of the basket of goods and services used for the calculation of the Harmonized Index of Consumer Prices (HICP). Data were collected via the national household budget surveys (HBS) in the participating countries. The results of the survey were data sets of mean consumption expenditure of private households along with the structure of mean consumption expenditure and household characteristics. Household final consumption expenditure is measured in PPS (Purchasing Power Standard). Consumption Expenditure information is collected according to the Classification of Individual Consumption by Purpose (COICOP).

The income indicator in Eurostat is a part of the data collection about income distribution and monetary poverty. The total disposable income of a household is calculated by adding together the personal income received by all household members plus income received at a household level and includes all income from work, private income from investment and property, transfers between households and all social transfers received in cash, including old-age pensions.

The definition of household is based on the criteria of coresidence and sharing of expenditures for the purpose of the HBS. In the case of both indicators, private household is defined as "a person living alone or a group of people who live together in the same private dwelling and share expenditures, including the joint provision of the essentials of living", according to Eurostat.

Here we note, that similar to Cutz et al. (2017) in this paper we distinguish two main types of biomass, such as traditional and modern biomass based on the end-use and burning technology [12]. In our research, solid fuels include firewood, coal and briquettes. It should be noted that the Eurostat database does not contain differentiated expenditure indicators of solid fuels, therefore detailed information on household use of coal, fuelwood and illegal fuels (separately) is not available. However, for the structural change indices we apply the share of fuels in final energy consumption of the household sector (%) indicator provided by the Eurostat. It is based on the final energy consumption of the households by energy sources, such as solid fossil fuels, oil and petroleum products, natural gas, electricity, heat, renewables and biofuels and other fuels (PJ).

3.2. Introducing fuel-specific indicators of energy burden: Share of Household Energy Expenditure (SHEE)

In order to quantify the energy affordability of the investigated CEE countries, a households' energy-related welfare index is introduced, as a ratio of household energy expenditures and their incomes. Although the literature on energy poverty deals with the financial indicator of energy consumption) [26,27], we did not find an indicator that would identify the cost burden of individual energy carriers in proportion to their income. The novelty of our research is determining indicators that characterize the household's expenditures in fuel-specific dimensions.

Countries have a significantly different mix of household energy sources; therefore, the welfare aspects of family's energy use should adequately reflect the expenditure on electricity, gas, liquid and solid energy carriers. The welfare dimensions of household energy use also depend on household income. Considering this evidence, the Share of Household Energy Expenditure (SHEE) index is defined as:

$$SHEE_i^j\left(t\right) = \frac{C_i^j\left(t\right)}{I^j\left(t\right)} \tag{1}$$

where SHEE is the share of household energy expenditure, C is the annual fuel-specific energy costs per household (PPS/households), I is the annual household income (PPS/households), (i = electricity, natural gas, liquid fuels, solid fuels, district heating), j=Austria [AT], Czechia [CZ], Hungary [HU], Poland [PL], Slovakia [SK] and Slovenia [SI]). The SHEE index can be produced relatively accurately from Eurostat statistical data for each energy carrier and is suitable for spatial and temporal comparisons.

3.3. Structural change indices – Moore, NAV and MLI index

A number of indicators can be used to measure structural change, including Moore index (the degree of industrial structure upgrading), the NAV index (norm of absolute values, also known as Michaely or Stoikov index), the LILIEN and the modified LILIEN index (MLI index) [28]. The Moore index measures the degree of structural change. The index (Eq. 2) was developed by Moore (1978) and it is "based on the fact that the structure of output in any period can be described by a vector whose coordinates are the quantities of outputs which form the basis for calculating the index numbers" [28–31].

$$M_t^+ = \sum_{i=1}^{n} W_{i,t} * W_{i,t+1} / \left[(\sum_{i=1}^{n} W_{i,t}^2)^{1/2} * (\sum_{i=1}^{n} W_{i,t+1}^2)^{1/2} \right] \tag{2}$$

where Mt^+ is the Moore value of structural change; $W_{i,t}$ is the share of fuels in final energy consumption of the household sector (i = solid fossil fuels, oil and petroleum products, natural gas, electricity, heat, renewables and biofuels and other fuels) in t period; $W_{i,t+1}$ is the share of fuels in final energy consumption of the household sector in t+1 period.

The change in the energy mix is shown by the cosine of the angle between vectors $\cos\alpha = M_t^+$, $\alpha = \arccos M_t^+$. The higher the α, the higher the rate of the change in the energy mix. The unit of measure is degree.

The formula of the NAV index based on Dietrich (2012) and Louhenapessy (2021) is the following:

$$NAV = \frac{1}{2} \sum_{i=1}^{n} \left| W_{i,t+1} - W_{i,t} \right| \tag{3}$$

The modified Lilien index (MLI) based on Dietrich (2012) is:

$$MLI = \sqrt{\sum_{i=1}^{n} W_{i,t} * W_{i,t+1} * \left[ln \frac{W_{i,t+1}}{W_{i,t}} \right]^2}, W_{i,t} > 0, W_{i,t+1} > 0 \tag{4}$$

All three indices can take values between 0 and 1. The closer the value is to 1, the more intense the restructuring. For example, if any index is 0.1, it means that 10% of energy resources have been affected by reallocation.

3.4. Delinking of household expenditure on solid and natural gas heating energy sources

Achieving the sustainable energy transition has to be reflected in the household energy expenditures too. The structure of energy expenditure changes and the importance of solid fuels declines, giving more space to higher quality energy sources. Here we note that according to the energy ladder theory the primary substitute for solid fuels is natural gas in heating and cooking (Figure 1). Delinking the household expenditure on solid fuels and household energy expenditure may provide appropriate information about it. However, based on our previous study [2] we highlight the slowness of the energy transition.

To measure the delinking we use the decoupling indicators created by the OECD (2002) and the UNEP (2011):

$$e = \frac{EXsolid_t - EXsolid_{t-1}}{EXsolid_{t-1}} = \frac{EXsolid_t}{EXsolid_{t-1}} - 1 \quad (5)$$

where e is the growth rate of the share of household expenditure on solid fuels, EXsolid is the share of household expenditure on solid fuels, and t is the current year.

$$g = \frac{EXgas_t - EXgas_{t-1}}{EXgas_{t-1}} = \frac{EXgas_t}{EXgas_{t-1}} - 1 \quad (6)$$

where g is the growth rate of the household energy expenditure on natural gas.

Measuring the delinking we introduce an intensity indicator:

$$i = \frac{\left(\frac{EXsolid_t}{EXgas_t}\right) - \left(\frac{EXsolid_{t-1}}{EXgas_{t-1}}\right)}{\frac{EXsolid_{t-1}}{EXgas_{t-1}}} = \frac{EXsolid_t}{EXgas_t} / \frac{EXsolid_{t-1}}{EXgas_{t-1}} - 1 \quad (7)$$

To measure the delinking, two indicators are introduced, the *delinking ratio* and *delinking factor*. Following the pioneering work of the OECD (2002), here the delinking factor is determined as follows [34]:

$$delinking\ ratio = \frac{EXsolid_t / EXgas_t}{EXsolid_{t-1} / EXgas_{t-1}} \quad (8)$$

The delinking factor is the following:

$$delinking\ factor = 1 - delinking\ ratio$$

$$= 1 - \frac{EXsolid_t}{EXgas_t} / \frac{EXsolid_{t-1}}{EXgas_{t-1}} \quad (9)$$

So:

$$delinking\ factor = -i \quad (10)$$

Hereinafter we denote the delinking factor as D:

$$D = -i \quad (9)$$

If $D > 0$, the trends of the examined indicators are separated (the intensity decreases, which means that the growth rate of the household expenditure on solid fuels is lower than the growth rate of household energy expenditure) so the delinking is fulfilled. The maximum value of D is 1. If $D \leq 0$, the delinking does not occur (the growth rate of household expenditure on solid fuels exceeds the growth rate of household energy expenditure), and this is a case of linking.

Table 1: Possible cases of delinking indicators

Case	e	g	i	D = –i	Specific cases of delinking
1	>0	>0	>0	<0 linking	expansive linking
2	>0	>0	<0	>0 delinking	weak delinking
3	<0	>0	<0	>0 delinking	strong delinking
4	<0	<0	>0	<0 linking	recessive linking
5	>0	<0	>0	<0 linking	expansive linking
6	<0	<0	<0	>0 delinking	weak delinking

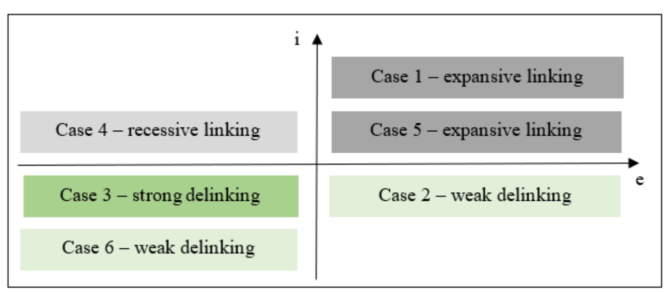
Note: white signifies cases of linking; grey signals cases of delinking
Source: own edition based on Conte Grand (2016, p. 653)

Table 1 allows for a deeper interpretation of the possible results (including six different cases). We avoid interpreting the cases where the value of *g* or *e* is equal to zero.

We distinguish two linking (expansive and recessive) and two delinking (strong and weak) cases (Figure 2). Cases 1, 4 and 5 show linking, and Cases 2, 3 and 6 are delinking.

In Case 1, the rate of household expenditure on solid fuels fluctuation and the household energy expenditure growth is positive, and moreover, the household expenditure on solid fuels increases more than the actual increase in household energy expenditure (it results in positive *i)*. The term expansive linking refers to the absence of delinking. In Case 5 despite the reduction in household energy expenditure the household expenditure on solid fuels increases (expansive linking). Recessive linking can be observed in Case 4. Regarding affordability, it is a more favorable situation, both the household expenditure on solid fuels and household energy expenditure decrease, but the latter to a greater extent.

Cases 2 and 6 are delinking situations, but their extent is quite weak. In Case 2, both the household expenditure on solid fuels and the household energy expenditure



Note: dark grey marks expansive linking, light grey – recessive linking, light green – weak delinking, dark green – strong delinking

Figure 2: Delinking cases

increase; however, i is negative. Case 6 is like Case 4, both the growth rate of household energy expenditure and the household expenditure on solid fuels are negative, but the drop rate of the household expenditure on solid fuels is higher. Case 3 shows absolute or strong delinking when household energy expenditure increases with declining household expenditure on solid fuels.

4. Results and discussion

To assess the results of our research, we first describe the household energy mix and the energy burden in CEE. This section is followed by the assessment of the dynamics of energy transition in the region, where we discuss the results of structural change indices and the delinking analysis.

4.1. Description of household energy mix and energy burden in Central and Eastern Europe

In CEE household energy use accounts for approx. 25-30% of the final energy consumption, which highlights its primary importance both from the perspective of climate change mitigation, energy security and social justice. Figure 3 shows the residential energy mix (i.e. electricity, gas, oil and petroleum products, primary solid fuels, heat and other renewables) in CEE for 2020.

The household *per capita electricity consumption* reflects the welfare effects; therefore, the families in advanced economies (Austria and Slovenia) have higher per capita electricity consumption. In these countries, the ratio of the households' electrification (share of electricity in household energy consumption) exceeds 25%, while in Czechia, Hungary and Slovakia is around 18%. In the case of Poland, the households' electrification is 12%. It is possible that electricity also serves as a primary heating source in Austria and Slovenia or supplementary technology in household heating in Czechia and Hungary. There are significant differences in the *per capita use of natural gas* among the investigated countries. Hungarian and Slovakian households strongly depend on natural gas, which exceeds 40% of the household energy mix. In the case of Austria and Czechia, the weight of natural gas is moderated and reflects a well-balanced mix of household heating sources. In the case of Poland and Slovenia, natural gas represents a minor share of household heating, less than 17% of the total household energy consumption. The share of household use of natural gas highlights the importance of structural differences in the buildings' stock, their heating modes and energy performances.

It can be concluded that natural gas and solid fuels represent 65-70% of the households' total energy consumption; therefore, their role should jointly be analyzed in the context of energy poverty. The shares of household energy expenditure (SHEE) for natural gas and solid fuels are assessed between 2005 and 2020 in the selected countries (Figure 4). As outlined in the section Methodology, the ratio of energy expenditure and incomes reflects the social welfare related to heating fuel use. The main results are as follows.

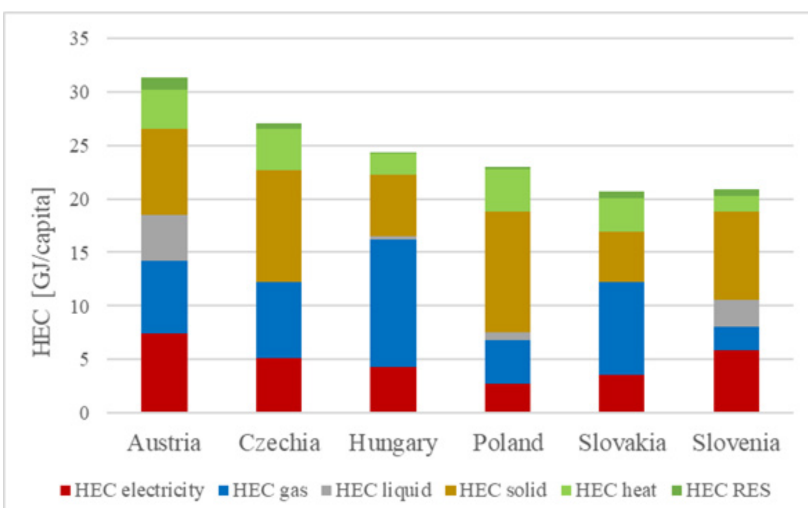


Figure 3: Household energy consumption (HEC) per capita in Central Eastern Europe (2020, GJ/capita). Data based on [25]

- In *Austria*, the share of energy expenditure is less than 1% for both natural gas and solid fuels resulting in a negligible impact on a household's budget. There is long-term stability and no significant differences in SHEE of natural gas and solid fuels, which means successful pricing and energy taxation policies to moderate social inequalities of different household heating resources.
- In *Czechia*, there is a significant difference in the SHEE of natural gas and solid fuels. The share of household energy expenditure on solid fuels (almost 75% fuel wood and 25% coal) is long-lasting low (less than 1%), similar to Austria. However, the share of energy expenditure related to the consumption of natural gas is between 3-5%, reflecting the market prices of natural gas.
- In *Hungary*, the shares of energy expenditure on natural gas and solid fuels are significantly higher than in Austria and Czechia, mainly due to the lower living standards. In the case of household consumption of natural gas, a positive, long-lasting social welfare impact has been presented since 2014, mainly due to state intervention (introduction of price cap). However, no similar welfare benefit is shown in the case of solid fuels, indicating growing energy-related inequalities in Hungarian society.
- In the case of *Poland,* the share of energy expenditure is declining in the longer term and has no significant differences in SHEE between natural gas and solid fuels. It should be noted that more than 50% of the solid fuels are coal and lignite from domestic sources.
- *Slovakia* has significant differences between the share of household energy expenditure for natural gas and solid fuel. While the SHEE for natural gas has been around 4.5-5% since 2010, the share of expenditure for solid energy sources

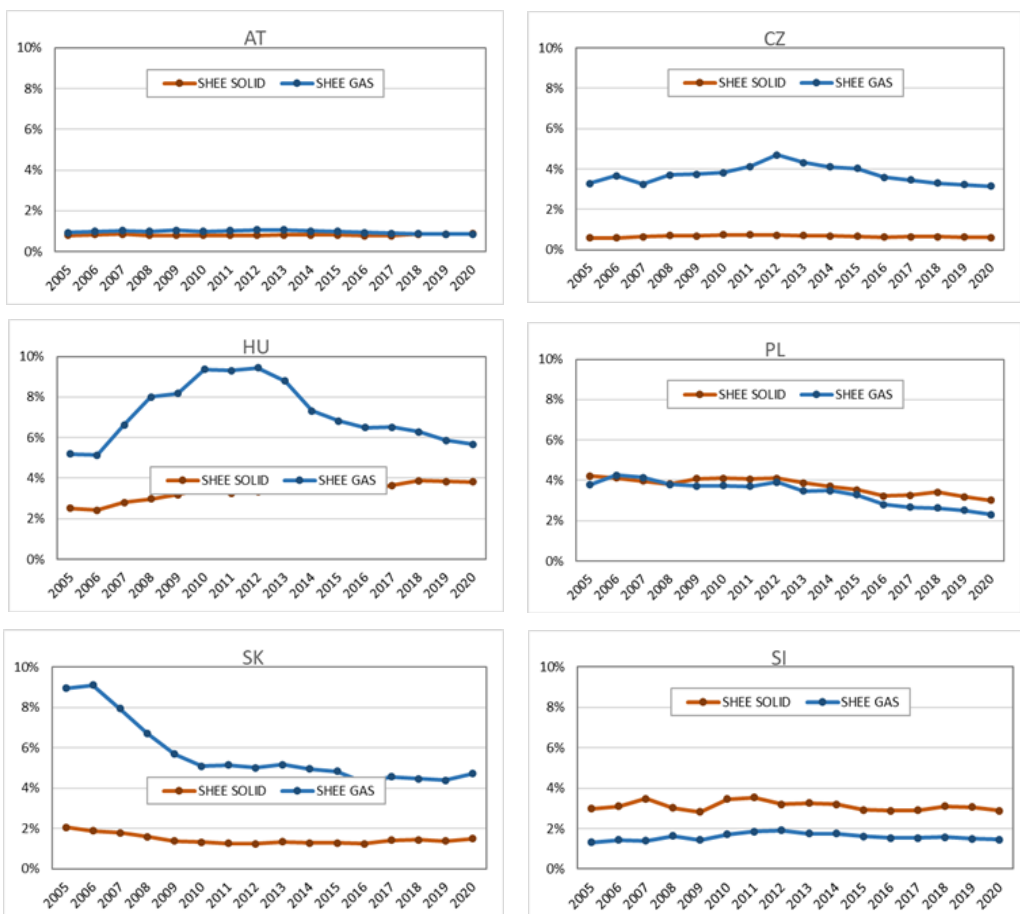


Figure 4: Share of household energy expenditure (SHEE index) in CEE (2005-2020)

is about 1.5%. Similar to Hungary, it highlights inequity between the gas and solid-consuming social groups.

- In *Slovenia*, the share of natural gas expenditure is similar to Austria. The value is declining in the long-term and less than 2%, which means a welfare advantage for gas-consuming households. Nevertheless, the SHEE values for solid fuels are almost double that of the gas ones, which present certain energy-related inequalities in Slovenian society.

4.2. Assessment of the dynamics of energy transition in Central and Eastern Europe – results of structural change indices and delinking analysis

From the point of view of the sustainable energy transition, the current way of using natural gas and traditional biomass results in a dual trap situation. Switching from natural gas to firewood may alleviate energy security challenges and be affordable, but it causes serious environmental and health risks. At the same time, replacing the use of biomass with natural gas increases exposure to the energy crisis and does not contribute overcome energy poverty. It is impossible to escape this dual trap in the current technological and policy circumstances. Breaking out of the dual fuel trap requires the acceleration of the energy transition. The electrification of the households, more intensive use of renewable energy sources (other than solid biomass) and energy efficiency improvements are the key pillars [37].

Table 2 shows the Moore, NAV and MLI values of structural change providing information about the speed of the change in the energy mix for the examined CEE countries. We break the results down into 5-year periods, always comparing each period with the previous one (chain base index numbers). In the European Union, the period of 2006-2010 shows a rather accelerating trend compared to the previous 5 years. However, in CEE, the results are much more controversial pointing out a slowdown in energy transition. This indirectly highlights the inadequacy of support and incentive schemes. The transition from fossil to renewable energy sources takes a long time, the energy mix is very rigid and changes only slowly.

In the case of household expenditure on solid fuels and household energy expenditure, the assessed countries mostly show mixed results in the time period of 2006-2020 (Table 3). From the 90 examined cases, 56 showed a case of linking, which means 62.2% of all cases. 27 was expansive linking and on the other side, there are 34 cases of delinking, of which 9 is strong delinking, which is 10% of all cases. There is no connection between these cases in time or from a geographical point of view (Austria: 2011, Czechia: 2009, 2012, Poland: 2006, Slovakia: 2011, Slovenia: 2008, 2012). Delinking didn't become permanent in any of the assessed countries.

According to the energy ladder theory, it is a natural process and basically, there is no obstacle to the sustainable energy transition. As a result of growing income and higher human well-being, the households carry out deep renovations, improve their heating systems and switch to modern and high-quality energy sources. *However, the energy stacking theory shows a very different picture, and it cannot guarantee the disappearance of solid fuels (including traditional biomass, charcoal, and coke) in household heating*. There is a serious risk that especially the energy-poor households are stuck in the traditional biomass trap. The delinking results show that the role of solid fuels in

Table 2: Changes of the household energy mix (Moore, NAV and MLI index) between 2000 and 2020, 5-years periods – results of structural change indices

	2001-2005			2006-2010			2011-2015			2016-2020		
	Moore	NAV	MLI	Moore	NAV	MLI	Moore	NAV	MLI	Moore	NAV	MLI
EU-27	3.795	0.033	0.031	7.734	0.054	0.063	4.415	0.039	0.036	1.965	0.019	0.017
AT	9.534	0.072	0.076	8.902	0.066	0.072	6.495	0.057	0.053	2.474	0.021	0.02
SI	4.274	0.036	0.040	7.365	0.06	0.067	12.028	0.103	0.118	8.368	0.069	0.083
SK	9.690	0.103	0.119	3.515	0.034	0.039	6.718	0.071	0.076	24.4	0.224	0.212
CZ	6.500	0.058	0.078	5.859	0.053	0.05	10.761	0.077	0.088	6.647	0.052	0.057
HU	5.215	0.061	0.031	11.802	0.108	0.125	8.124	0.072	0.081	10.471	0.087	0.107
PL	10.537	0.071	0.039	6.281	0.047	0.055	4.783	0.041	0.042	16.927	0.119	0.134

Note: red - slowing change, green - accelerating change compared to the previous 5-year period

Table 3: Delinking the household expenditure on solid fuels and total household energy expenditure (2006–2020)

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
AT	1	2	6	4	2	3	2	1	4	5	4	4	1	5	1
CZ	2	5	1	3	1	2	3	4	4	6	4	5	4	3	3
HU	4	2	2	1	1	6	1	5	4	4	4	1	5	4	4
PL	3	4	4	1	2	4	2	4	6	6	4	5	1	4	6
SK	6	4	4	6	4	3	4	1	4	5	4	1	5	6	2
SI	1	1	3	6	1	2	3	2	6	6	4	2	1	4	4

Note: dark grey marks expansive linking, light grey – recessive linking, light green – weak delinking, dark green – strong delinking

household energy expenditure is still significant, and the households could not break out of this fuel trap.

In the case of household expenditure on solid fuels and household expenditure on natural gas, the examined CEE countries show an overall transition from delinking in 2006 to mostly recessive or expansive linking in 2020 (Table 4). Out of the 90 cases, 54 show the linking of household expenditure on solid fuels and natural gas (60%). Out of the linking cases, 25 show expansive linking, which is 27,8% of the total cases. On the other hand, the number of delinking cases is 36 (40%), of which 11 show strong delinking, which is 12,2% of all examined cases. Strong or weak delinking was mostly a characteristic of the time period between 2006 and 2012, with an outlier case of strong delinking in Poland, in 2014. However, delinking of solid fuels and natural gases household expenditure didn't become permanent in any of the assessed countries, and the years after 2012 show mostly linking cases in the examined countries. The results show that both solid fuels and natural gas still play a significant role in the household energy mix confirming the presence of a dual fuel trap.

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5. Policy implications and recommendations

Profound changes in the amount and composition of household heating energy carriers would be necessary to achieve a sustainable and fair energy transition and carbon neutrality in CEE. The priority of getting out of the dual fuel trap is to reduce household heating energy

Table 4: Delinking the household expenditure on solid fuels and household expenditure on natural gas (2006-2020)

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
AT	2	2	6	3	5	3	2	5	4	5	4	4	5	5	5
CZ	2	5	2	3	1	3	3	4	4	6	4	5	4	6	4
HU	6	2	2	1	2	6	2	5	4	4	4	1	5	4	4
PL	3	6	4	5	2	4	2	4	3	4	4	5	5	6	4
SK	3	4	4	4	4	3	4	1	4	5	4	1	5	6	2
SI	2	5	3	4	1	2	3	5	6	6	4	1	1	4	6

Note: dark grey marks expansive linking, light grey – recessive linking, light green – weak delinking, dark green – strong delinking demands, i.e., deep renovation of residential buildings. Technologies for improving a building's energy performance are commercially available, but targeted grant schemes and innovative financing tools are needed. It is advisable to initiate special measures to support the renovation of family houses built in the 1970s and 1980s in rural, less developed regions.

Local heat supply systems (e.g., heat pumps, small-scale, central, local or mini district heating plants based on biomass or geothermal energy), which produce heat with higher efficiency and less environmental impact than individual heating, may also contribute to sustainable energy transition in rural regions. However, these investments' capital requirements are relatively high and mitigating their business risks is only possible with substantial state involvement (e.g., guarantee fund).

The spread of modern, low-emission biomass burning (e.g., wood gasification boilers and stoves), which should be linked to social measures to deal with energy poverty, can also help solve the dual trap situation. The switch from traditional to modern biomass is a desirable objective. It may reduce energy poverty and local environmental pollution and move toward a more sustainable energy mix. It can also positively affect regional economic development, resulting in higher human well-being. Keeping the biomass in the energy mix but using and burning it more efficiently would help the countries achieve the energy and climate targets and at least keeping the share of renewable energy sources in the final energy consumption.

Another adequate policy response could be the establishment of multifunctional heating energy communities, which do not merely supply energy but provide complex building energy services to community members. The range of non-profit services may include fuel switching, building renovation, financing and investment consulting, resource transfer and energy awareness rising, as well. Social innovations by institutional approaches should be emphasized. NGOs, local actors, and policymakers should come together to develop local multifunctional heating energy communities.

In the field of household heating, the sustainable energy transition can be achieved by integrating the following national or municipal level policies:

- social policies: in particular, grant schemes for housing, energy and poverty eradication;
- housing policies: measures to support the development of deprived areas, rural development, investment support for housing quality and home renovation;
- energy and climate policies: grant schemes for energy efficiency improvements in residential buildings, fuel switch to higher quality energy sources (with special regard to renewables), decarbonization in spatial and urban planning.

Sustainable energy transition may strengthen the regional and local governance mechanisms through decentralization. Typical measures of good governance practice are, among others, targeted education, training, awareness-raising, and housing-related information exchange based on broad public involvement. We note that sub-national public administrations can play an essential role in addressing the necessary policy integration toward sustainable rural energy transition.

The strategic integration of these policies should ideally include the harmonization of goals and tools as well as the coordinated allocation of financial resources. Energy poverty and regional social and economic inequalities are tightly connected, and a not adequately planned energy transition may make it deeper. Energy transitions are heterogeneous, which means that different policies, local solutions, and actions are needed. New vulnerabilities have to be avoided. Shielding policies for energy-poor households and the energy alleviation potential of the energy transition should be used (Bajomi, Feldmár, and Tirado-Herrero 2021). The energy transition without a serious and well-thought support system may exacerbate existing vulnerabilities or create new vulnerabilities. These vulnerabilities are present not only in the case of the lowest income deciles, but the bottom middle-income class may also be concerned. In their case switching to less polluting and higher quality energy sources may also cause problems.

6. Conclusion

The first research question established if the degree of the energy transition in the residential sector was measurable. The results show that based on the household energy mix conclusions can be drawn about changes in the energy transition. Examining the household energy mix in the selected Central and Eastern European countries, we found that there has been no significant structural change in energy carriers over the past two decades. The only significant change is that the use of coal was partially replaced by biomass and natural gas.

This indicates that neither the market processes nor the policy instruments have significantly influenced the structure of household energy consumption. The structural change indices shed light on the slowness of the energy transition in the household sector. The degree of change is decreasing. The delinking factor also confirms the significant presence of solid fuels in household energy expenditure. Answering the second part of Q1, our results confirm the energy stacking theory. It means that households do not give up entirely their lower quality energy sources, even if they switch to higher quality energy sources. It slows down the energy transition and it requires much more focused actions (e.g. energy efficiency investment programs, support of vulnerable households, etc.). Related to Q1 we may accept the first hypothesis (H1).

While there are no significant, long-lasting trends in the structure of household energy consumption, characteristic tendencies and spatial differences can be observed in the shares of household energy expenditure (SHEE index) for natural gas and solid fuels. In Austria, Czechia and Slovenia, there is no trend-like change in natural gas and solid fuel costs relative to family incomes. In Slovakia and especially in Hungary, the SHEE index of natural gas has decreased significantly, while that of solid fuel (mainly firewood) has increased, which indicates the strengthening of energy poverty in rural areas. In Poland, similar to Austria, the ratio of energy expenditure on natural gas and solid fuel (mostly coal) to incomes is permanently the same, indicating the state's harmonizing role in regulating energy prices.

The results confirm the dual trap of domestic heating as a significant barrier to a sustainable energy transition and social justice in the Central and Eastern European countries. In the trap, the natural gas-heated households remain permanently dependent on fossil fuels, and they are exposed to price volatility. H2 is accepted too. In parallel, households using solid fuels face with serious health and environmental risks.

Traditional biomass accounts for a high share of solid fuels. It is considered as a renewable energy source, but significant material and energy demands are associated with the production and transport of biomass. Firewood can come from forestry logging or energy plantations. The extraction of forest biomass raises various sustainability issues concerning biodiversity and ecosystem services. We also need to consider the scarcity of spatial opportunities for cultivation and the importance of carbon sequestration. If firewood comes from energy forests, it must be considered that energy tree plantations are an intensively cultivated monoculture, which also raises several nature conservation and ecological issues by eradicating biodiversity in large areas.

Referring to Q2, it would be optimistic approach to expect the rapid decline of energy poverty. Households, especially those living in obsolete family houses in rural areas are locked in heating fuels (natural gas and/ or solid fuels). They have no financial resources to save energy and no flexibility to change their energy mix. Based on energy consumption data, the phenomenon affects 25-30% of the population of Central and Eastern European countries, especially those living in rural and suburban regions, as well as social groups affected by energy poverty. There is a serious risk that not only the energy-poor households but even the middle-income class sticks in the dual trap. Member States with high energy intensity, a higher share of fossil fuels and traditional biomass in the household energy mix and lower well-being (lower disposable income) need special attention and strategies. The dual trap situation is closely related to rural energy poverty and local energy policies that do not sufficiently consider social aspects.

Policies supporting a sustainable energy transition should respond to this dual trap situation. Revision of national energy policies is also urgent because, during the European energy crisis unfolding in 2022, the uncertainties in natural gas supply may force the fuel switch to locally available energy carriers. Without effective and quickly implemented policy responses, the use of solid fuels (e.g., biomass, coals, illegal heating materials) will likely propagate in rural areas. If the national energy policies do not offer a feasible alternative to reduce and replace the domestic use of natural gas, then the solid fuel side of the dual trap situation will continue to deepen.

Further research is needed to harmonize energy supply security and rural development for all EU member states. It is necessary to introduce new energy indicators to monitor rural areas' just and sustainable energy transition. In this context, it is suggested to investigate the dual trap of natural gas-solid fuel use in various income groups in the case of all EU Member States.

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