

Article

Urban–Rural Disparities in Greenhouse Gas Emissions: Fuel Consumption in Moldovan Households and Implications for Energy Policies

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Abstract: Climate change, driven by greenhouse gas (GHG) emissions, poses a critical global challenge, with household energy use as a significant contributor. In the Republic of Moldova, stark urban–rural disparities in fuel consumption and emissions necessitate targeted research to inform effective energy policies. This study analyzes GHG emissions from household fuel consumption, focusing on the differences between urban and rural areas, using a quantitative approach guided by the Intergovernmental Panel on Climate Change (IPCC) methodologies. The findings reveal that rural areas, heavily reliant on traditional fuels like firewood, contribute disproportionately to emissions compared to urban areas, where modern energy sources such as natural gas dominate. Nationally, the research provides critical data to shape energy transition strategies, promoting renewable energy adoption and energy efficiency in rural areas. Internationally, it offers a valuable case study on household emission dynamics in developing countries, contributing to the global understanding of energy use patterns and their environmental impacts. Recommendations include enhancing access to cleaner energy, modernizing infrastructure, and encouraging sustainable practices to align with Moldova’s commitment to GHG reduction goals and serve as a model for similar contexts worldwide.

Keywords: greenhouse gases; household energy consumption; urban–rural disparities; energy efficiency; renewable transition; environmental impact



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1. Introduction

Climate change is one of the greatest challenges contemporary society faces. Greenhouse gas (GHG) emissions have significantly contributed to this global phenomenon [1–3], causing a considerable increase (by 63%) between 1990 and 2020, with a 1.1 °C rise in the global average surface temperature [4]. Human activities have unequivocally contributed to global warming, leading to widespread adverse impacts on food and water security, human health, economies, and societies, as well as losses and damages affecting both nature and people (high confidence level) [5,6]. The household sector accounts for approximately 60% of total GHG emissions, with a major share attributed to the following three dominant sources of emissions (around 80%): fuel consumption in residential heating, transport, and food systems [7]. Typically, households with varying income levels exhibit distinct emission patterns, particularly in regions where alternative energy resources are limited and households rely on traditional fuels such as firewood and agricultural waste [7–10].

To address this critical issue, this study employs an internationally recognized methodology, specifically the Intergovernmental Panel on Climate Change (IPCC) guidelines, to analyze the greenhouse gas (GHG) emissions associated with household energy use. A quantitative approach is applied to examine disparities in the emissions between urban and rural areas, leveraging activity data and emission factors for accuracy. Additionally, the study includes a focused analysis on the emissions from food preparation, a common and substantial contributor to household GHG emissions. By combining regional data

with stratified calculations, the study fills a significant gap in the literature by focusing on lower-income countries such as Moldova, which are underrepresented in global studies on urban–rural disparities in emissions.

In the Republic of Moldova, the use of fuels for heating and cooking is an essential component of household energy consumption, especially in rural areas where access to natural gas and electricity is limited or nonexistent in certain regions. This is characteristic of most developing countries, which are heavily reliant on firewood and other types of traditional biomass (such as agricultural waste and manure) for cooking, lighting, and heating. These practices generate significant amounts of CO₂ and other greenhouse gas emissions [11,12]. In comparison, urban areas have a lower dependency on solid fuels, which are partially replaced by natural gas and electricity [2,13]. These disparities underscore the need for a detailed assessment of GHG emissions originating from households and the factors influencing these differences between urban and rural areas.

While existing research primarily focuses on high-income and upper-middle-income countries, there is a dearth of comprehensive studies examining the specific dynamics of GHG emissions in developing countries. This study not only bridges this gap but also introduces a methodological framework adaptable to similar contexts. It aims to identify the key drivers behind these disparities, providing actionable insights for targeted policy development.

The literature on consumption-based carbon emissions of urban and rural residents primarily focuses on high-income countries [14,15] and on upper-middle-income countries such as China [16]. There is a limited number of studies on carbon emissions in lower-income countries [17,18]. Moreover, there are no global comparative studies on the consumption patterns and associated carbon emissions of urban and rural residents in developing countries [2].

This study aligns with the Republic of Moldova's broader efforts to reduce greenhouse gas emissions, supported by recent governmental initiatives such as the National Energy and Climate Plan and investment programs promoting energy efficiency and renewable energy adoption. These efforts emphasize the importance of addressing emissions at both the household and public levels, particularly focusing on activities like cooking, which contribute significantly to domestic energy use and environmental impact.

This study aims to quantify the greenhouse gas (GHG) emissions associated with fuel consumption in households in the Republic of Moldova, using internationally recognized methods for emission calculation based on activity data and emission factors in accordance with IPCC guidelines [19]. Additionally, the paper analyzes the emissions specific to food preparation, a common and frequent activity that significantly contributes to household GHG emissions.

Through this approach, the study seeks to provide a clear picture of how domestic energy consumption influences GHG emissions and to identify the main household sources of emissions. The relevance of this study lies in supporting policy decisions by providing essential data for developing strategies tailored to reduce emissions in the Republic of Moldova.

In the context of international commitments to combat climate change, this research can guide the implementation of energy efficiency policies and the transition to renewable energy sources, with implications for other regions with similar energy consumption structures [20]. The study also highlights opportunities to reduce emissions in rural areas through expanded access to cleaner energy and by encouraging energy efficiency in households.

2. Methodology

This study employed a quantitative approach to evaluate the greenhouse gas (GHG) emissions associated with fuel consumption of households in the Republic of Moldova. The methodology is based on IPCC guidelines, combining activity data with emission factors specific to each type of fuel [8]. Data from the National Bureau of Statistics (NBS) for the years 2016 and 2022 were used, converted into kilotons of CO₂ equivalent (kt CO₂ eq)

(Table 1). Emissions were quantified for each fuel type and each area (urban and rural), providing a comprehensive view of the regional and temporal variations.

Table 1. Energy consumption from fuels in households and conversion coefficients for fuel to energy and CO₂ emissions.

Fuel Consumed	U.M.	Fuel Consumption						(NCV)	EEF (CO ₂)
		2022			2016			(TJ/Gg)	(kg/TJ) ²
		Total	Urban	Rural	Total	Urban	Rural		
Coal	Gg	76.7	6.4	70.3	58.8	18.7	40.1	22.0	98,600
Natural gas	Gg	297.2	174.16	123.04	223.37	151.22	72.15	48.0	56,100
Liquefied Petroleum Gases (LPG)	Gg	49.2	0.7	48.4	34.8	4.8	29.003	47.3	63,100
Diesel fuel	Gg	305.9	-	305.9	0.47	-	0.43	43.0	74,100
Briquettes and pellets	Gg	13.9	-	13.5	18.97	-	13.30	11.6	100,000
Firewood (Fuelwood)	Gg	1859.40	260.12	1599.2	1683.99	238.9	1445.08	15.6	112,000
Wood waste (wood/wood waste)	Gg	242	12.2	229.8	532.18	-	495.18	15.6	112,000
Animal waste	Gg	47.6	-	41.1	15.96	-	14.9	11.6	100,000
Agricultural waste	Gg	93.7	-	93.2	139.52	-	134.14	11.6	100,000
Charcoal	Gg	0.9	0.0	0.9	-	-	-	29.5	112,000
Electricity	mio. kWh	1648	765.9	887.1	1668.7	825.6	843.1	-	684 (2016 y) 648 (2022 y)

1-OPSB-Other Primary Solid Biomass OPSB; NCV—Net Calorific Values; EEF—Effective emission factor. Source: authors' own elaboration.

2.1. Data Collection

Fuel consumption data for the households were obtained from reports by the National Bureau of Statistics of the Republic of Moldova (NBS) for 2016 and 2022 [21,22]. These data were converted into standardized mass units (Gg). For each type of fuel, the default calorific values (NCV) [19] and emission factors (EF) as per IPCC guidelines [23] were used to calculate the corresponding emissions. The carbon intensity of electricity generation values for Moldova in 2016 and 2022 were 648 and 684 g CO₂ equivalent per kWh, respectively [23].

2.2. Emission Estimates

To estimate the greenhouse gas (GHG) emissions from household fuel consumption, the following calculation formula based on stratified fuel weights was applied:

$$E_{i,y} = AD_{i,y} * EF$$

where $E_{i,y}$ represents the GHG emissions of fuel i in the Republic of Moldova for a selected inventory year (2016 and 2022), expressed in kilotons of CO₂ equivalent per year (kt CO₂ eq) [24]; and $AD_{i,y}$ represents the activity data for each fuel, expressed in terajoules (TJ), calculated based on the Net Calorific Values (NCV) as specified by the IPCC (2006) for the respective country (Republic of Moldova), for the given year [19].

The greenhouse gas emissions from household fuel consumption for food preparation were calculated using the following formula:

$$E_{food\ i,y} = AD_{i,y} * EF_{i,y} * f_{i,y}$$

where $E_{food\ i,y}$ represents the GHG emissions associated with food preparation for fuel i in the selected inventory year (y), expressed in kilotons of CO₂ equivalent (kt CO₂ eq); and $f_{i,y}$ denotes the fraction of the fuel consumption attributed to food preparation activities in households for fuel (i) in year (y).

Urban–Rural Disparity Analysis. The urban–rural comparative analysis highlights differences in energy consumption patterns and associated emissions. This analysis is essential for identifying the specific influences of infrastructure and the availability of energy resources in these areas.

Validation and Interpretation of Results. The results were validated by comparing them with the previously published data in the literature, ensuring consistency with the regional and international trends. This approach reinforces the reliability of the findings and their relevance to broader contexts.

2.3. Study Advantages and Limitations

The methodology offers the advantage of providing a standardized and internationally recognized framework for emission calculations, enabling a detailed urban–rural comparison while offering actionable insights for policy adaptation in developing countries with similar energy profiles. However, it relies on aggregated regional data, which may overlook local-specific nuances, and lacks household-level granularity, restricting micro-level behavioral analysis. Additionally, the use of default emission factors may not fully reflect Moldova’s regional conditions, introducing potential uncertainties.

To address these potential limitations, sensitivity analyses were conducted to evaluate the variability of emissions under different conditions, providing a range of possible outcomes. Future research could further enhance accuracy by incorporating locally measured emission factors that reflect regional variations in fuel quality and combustion efficiency.

Furthermore, uncertainties in the activity data, often sourced from national statistics, can arise from inconsistencies in data collection methods or reporting standards. Cross-referencing these datasets with independent sources, such as energy providers, or integrating real-time monitoring systems could help validate findings and ensure consistency over time.

Lastly, while the aggregated data approach provides a broad overview, it may limit the granularity required to capture household-level disparities. Future studies should include detailed household surveys and standardized questionnaires to collect primary data, offering more precise insights into individual consumption patterns and their impact on GHG emissions.

This approach ensures a comprehensive assessment of the household emissions, laying a foundation for targeted energy policy interventions while acknowledging the areas for improvement.

2.4. Urban–Rural Household Data

The data on the total number of households and their average size in urban and rural areas were obtained from the National Bureau of Statistics of Moldova (BNS) for the years 2016 and 2022. Using these official figures, the total number of households in the urban and rural areas was calculated based on the average household size reported by the BNS. These calculations served as a basis for contextualizing the analysis of GHG emissions in the study (Table 2).

Table 2. Urban and Rural Household Distribution in Moldova (2016 and 2022).

Year	Population			Average Household Size			Number of Households		
	Total	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural
2022	2,570,000	1,090,000	1,480,000	2.2	2.3	2.1	1,168,182	473,913	704,762
2016	2,830,000	1,120,000	1,700,000	2.4	2.3	2.5	1,179,167	486,957	680,000

3. Results

3.1. GHG Emissions from Total Average Fuel Consumption in Households

The analysis results indicate a significant contribution of traditional fuels to the GHG emissions in Moldovan households. For coal, total emissions increased from 127.5 kt CO₂ equivalent in 2016 to 166.4 kt CO₂ equivalent in 2022. This rise was more pronounced in rural areas, where emissions reached 152.5 kt CO₂ equivalent compared to 87.0 kt in 2016. In urban areas, emissions decreased significantly from 40.6 kt in 2016 to 13.9 kt in 2022.

Natural gas remains a significant source of emissions, with a total increase from 601.5 kt CO₂ equivalent in 2016 to 800.3 kt in 2022. The rise is primarily attributed to its growing adoption in both urban and rural areas. In urban regions, emissions rose from 407.2 kt to 469.0 kt, reflecting increased household energy demands and expanding infrastructure that supported natural gas access. Meanwhile, rural emissions nearly doubled, from 194.3 kt in 2016 to 331.3 kt in 2022, driven by the gradual improvements in infrastructure that enabled greater accessibility to this cleaner, but still carbon-intensive, energy source. The data suggest a positive trend in transitioning away from traditional fuels; however, the associated rise in emissions highlights the need for additional policies to promote renewable alternatives alongside natural gas, particularly in rural areas.

Firewood remains the most significant source of emissions, totaling 3248.7 kt CO₂ equivalent in 2022 compared to 2942.3 kt in 2016. This increase reflects the persistent reliance on traditional biomass in rural areas, where access to alternative energy sources remains limited. Rural areas generated 2794.1 kt CO₂ equivalent in 2022, a significant majority compared to urban areas, which produced 454.5 kt. The higher rural contribution can be attributed to socio-economic factors, such as affordability and availability of firewood, despite its high emissions footprint. In contrast, urban areas saw a moderate rise in emissions from 417.4 kt in 2016 to 454.5 kt in 2022, driven by population growth and increased energy demands.

Animal and agricultural waste showed reduced values, indicating a general decline in their use in households. Emissions from animal waste were 55.2 kt CO₂ equivalent in 2022, up from 18.5 kt in 2016, while emissions from agricultural waste decreased from 161.8 kt in 2016 to 108.7 kt in 2022. Electricity represents a significant emission source, contributing 1067.9 kt CO₂ equivalent in 2022 compared to 1143.9 kt in 2016. In urban areas, emissions decreased slightly from 564.2 kt in 2016 to 496.3 kt in 2022, while in rural areas, they remained almost constant at approximately 574.8 kt.

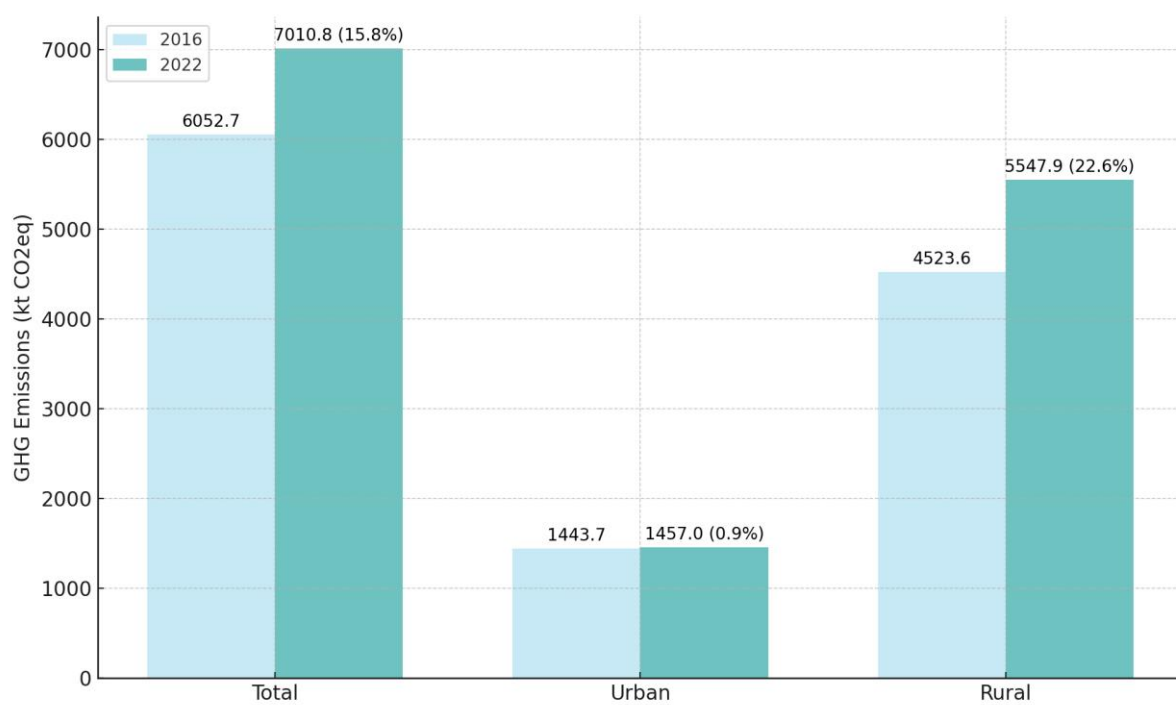
The data highlight both the challenges and opportunities in optimizing energy consumption and reducing emissions through the transition to cleaner and more efficient energy sources, particularly in rural areas (Table 3).

In 2016, the total GHG emissions generated by households in the Republic of Moldova amounted to 6052.7 kt CO₂ equivalent, of which 1443.7 kt came from urban areas and 4523.6 kt from rural areas. By 2022, total emissions increased to 7010.8 kt CO₂ equivalent, reflecting a 15.8% rise compared to 2016. In urban areas, emissions rose slightly from 1443.7 kt to 1457.0 kt (+0.9%), while in rural areas, the increase was significantly more pronounced, from 4523.6 kt to 5547.9 kt (+22.6%). These figures indicate an intensification in the consumption of traditional fuels in rural areas, underscoring the need for more sustainable energy policies (Figure 1).

Table 3. GHG emissions from total consumption, by fuel type used in households.

Fuel Consumed	GHG Emissions, kt CO ₂ eq					
	2022			2016		
	Total	Urban	Rural	Total	Urban	Rural
Coal	166.4	13.9	152.5	127.5	40.6	87.0
Natural gas	800.3	469.0	331.3	601.5	407.2	194.3
LPG	146.8	2.1	144.5	103.8	14.3	86.6
Diesel fuel	974.7	0.0	974.7	1.5	0.0	1.4
Briquettes and pellets	16.2	0.0	15.7	22.0	0.0	15.4
Firewood (Fuelwood)	3248.7	454.5	2794.1	2942.3	417.4	2524.8
Wood waste (wood/wood waste)	422.8	21.3	401.5	929.8	-	865.2
Animal waste	55.2	0.0	47.7	18.5	-	17.3
Agricultural waste	108.7	0.0	108.1	161.8	-	155.6
Charcoal	3.0	0.0	3.0	-	-	-
Electricity	1067.9	496.3	574.8	1143.9	564.2	576.0

LPG—Liquefied Petroleum Gases.

**Figure 1.** Total GHG emissions from fuel consumption in households.

These changes are likely influenced by shifts in fuel consumption patterns and by economic and social factors that have encouraged the greater use of polluting energy sources, particularly in rural areas.

3.2. GHG Emissions from Fuel Consumption per Household

In 2022, firewood remained the primary source of emissions, reaching 4.770 t CO₂ equivalent in both urban and rural areas. This reflects its continued dominance in rural households, driven by affordability and accessibility, despite its high emission footprint. Compared to 2016, total emissions increased from 4.281 t CO₂ equivalent to 4.770 t CO₂ eq, highlighting the

persistent reliance on traditional fuels. In rural areas, emissions from firewood remained stable, while urban emissions showed a modest rise, from 4.036 t CO₂ equivalent to 4.770 t CO₂ eq, likely linked to population growth and increased energy needs.

Natural gas showed a slight decrease in urban areas, from 1.151 t CO₂ equivalent in 2016 to 1.090 t CO₂ equivalent in 2022, while in rural areas, emissions remained relatively stable, indicating the sustained preference for this fuel. This may reflect the adoption of more efficient appliances or energy-saving measures in urban households. In rural areas, emissions remained relatively stable, suggesting a steady, albeit limited, transition to this energy source. These trends underline the need for targeted policies that prioritize cleaner energy options in both urban and rural settings, particularly to reduce firewood dependency in rural areas.

Emissions from electricity usage showed a slight increase in urban areas, from 1.215 t CO₂ equivalent in 2016 to 1.234 t CO₂ equivalent in 2022, while in rural areas, emissions decreased from 0.971 t CO₂ equivalent in 2016 to 0.876 t CO₂ equivalent in 2022 (Table 2). This urban–rural difference can be attributed to increased electricity consumption in urban areas, associated with household modernization.

For fuels like coal, emissions remained relatively constant, with a slight increase in the total level from 0.562 t CO₂ equivalent in 2016 to 0.634 t CO₂ equivalent in 2022, with minimal differences between the urban and rural areas. In contrast, LPG emissions increased significantly from 0.199 t CO₂ equivalent in 2016 to 0.458 t CO₂ equivalent in 2022, suggesting a growing trend in the use of this fuel.

Another notable aspect is the near-total decline in the use of agricultural and animal waste, with emissions dropping from 0.534 t CO₂ equivalent and 0.580 t CO₂ equivalent in 2016 to almost zero in 2022 in both urban and rural areas (Table 4). This reflects a possible replacement of these traditional resources with more modern and energy-efficient alternatives.

Table 4. GHG emissions by fuel type from average household consumption.

Fuel Consumed	GHG Emissions, t CO ₂ eq					
	2022			2016		
	Total	Urban	Rural	Total	Urban	Rural
Coal	0.634	0.502	0.650	0.562	0.690	0.517
Natural gas	0.800	1.165	1.090	1.221	1.151	1.184
LPG	0.458	0.371	0.460	0.199	0.235	0.194
Diesel fuel	0.016	0.000	0.016	0.015	0.000	0.015
Briquettes and pellets	0.568	0.000	0.607	0.000	0.000	0.000
Firewood (Fuelwood)	4.770	4.770	4.770	4.281	4.036	4.403
Wood waste (wood/wood waste)	0.001	0.001	0.001	3.180	0.000	3.180
Animal waste	0.003	0.000	0.002	0.580	0.000	0.580
Agricultural waste	0.001	0.000	0.001	0.534	0.000	0.534
Charcoal	0.099	0.081	0.099	0.000	0.000	0.000
Electricity	1.070	1.215	0.971	1.022	1.234	0.876

In 2022, the total emissions per household decreased by 27.6% compared to 2016, from 11.6 to 8.4 t CO₂ eq, indicating a possible shift to more efficient energy sources or a general reduction in consumption. In urban areas, emissions increased by 11%, from 7.3 t CO₂ equivalent in 2016 to 8.1 t CO₂ equivalent in 2022, suggesting intensified activities and higher energy consumption. In rural areas, emissions decreased by 24.3%, from 11.5 to 8.7 t CO₂ eq, reflecting a possible transition to more sustainable energy sources (Figure 2).



Figure 2. Total GHG emissions from average fuel consumption per household.

Overall, the data show a general reduction in emissions per household, with notable decreases in rural areas and a slight increase in urban areas, reflecting differences in energy consumption and adaptation to energy resources between the two settings.

3.3. GHG Emissions from Fuels Used for Cooking on Stoves and in Ovens

GHG emissions from fuels used for cooking on stoves varied significantly between urban and rural areas during 2016–2022. In 2022, natural gas emissions increased to 269.7 t CO₂ equivalent, compared to 161.2 t in 2016, marking a rise of approximately 67.3%. In urban areas, where access to natural gas is higher, emissions increased from 217.4 t CO₂ equivalent in 2016 to 255.1 t in 2022, reflecting both population growth and expanded infrastructure. In rural areas, the increase was even more pronounced, from 16.3 t CO₂ equivalent in 2016 to 66.9 t in 2022, representing a growth of over 300%.

This dramatic increase indicates a gradual shift from traditional fuels to cleaner energy sources, driven by improved infrastructure and government programs promoting natural gas access. However, the continued high reliance on firewood in rural areas suggests that further interventions are required to accelerate this transition.

Firewood and agricultural waste saw a decrease in emissions, from 270.1 t CO₂ equivalent in 2016 to 145.4 t in 2022, a reduction of approximately 46%. The use of electricity for cooking generated a modest increase in emissions, from 550.2 t CO₂ equivalent in 2016 to 595.9 t in 2022, reflecting an 8.3% rise, indicating the greater adoption of electricity for cooking in both urban and rural settings (Table 5).

Table 5. GHG emissions from fuels used for cooking food on stoves in households, t CO₂ eq.

Energy Sources Used to Cook Food	2022			2016		
	Total	Urban	Rural	Total	Urban	Rural
Natural gas	528.2	452.1	153.1	270.7	320.1	42.2
LPG	43.8	0.0	69.6	45.5	1.9	56.1
Firewood, agricultural waste	27.3	0.0	43.9	235.9	3.3	332.4
Electricity	15.0	9.9	6.3	40.0	40.1	5.2

GHG emissions from fuel use for cooking with an oven showed a general upward trend between 2016 and 2022. Emissions generated by natural gas increased from 270.7 t CO₂ equivalent in 2016 to 528.2 t in 2022, marking a 95% rise. In urban areas, this increase was from 320.1 t to 452.1 t CO₂ equivalent, while in rural areas, emissions grew from 42.2 t to 153.1 t, which was more than triple.

In contrast, emissions from firewood and agricultural waste decreased drastically, from 235.9 t CO₂ equivalent in 2016 to just 27.3 t in 2022, a reduction of approximately 88%. The use of electricity for ovens also declined, from 40 t CO₂ equivalent in 2016 to 15 t in 2022, a 62.5% reduction. This suggests a possible shift to other energy sources or improved efficiency in electricity use (Table 6).

Table 6. GHG emissions from fuels used for cooking food with ovens in households, t CO₂ eq.

Energy Sources Used to Cook Food	2022			2016		
	Total	Urban	Rural	Total	Urban	Rural
Natural gas	269.7	255.1	66.9	161.2	217.4	16.3
LPG	8.8	0.0	13.7	2.9	3.0	2.8
Firewood, agricultural waste	145.4	0.9	204.6	270.1	6.3	367.2
Electricity	595.9	222.3	362.1	550.2	205.4	327.8

For stoves, the total CO₂ equivalent emissions slightly increased from 592.1 t in 2016 to 614.2 t in 2022, representing a 3.7% rise (Figure 3). In urban areas, emissions rose significantly, from 365.4 t in 2016 to 462.1 t in 2022, marking a 26.5% increase. However, in rural areas, emissions dropped considerably, from 435.8 t in 2016 to 272.9 t in 2022, a reduction of approximately 37.4%, suggesting a potential shift in energy sources or improved consumption efficiency.

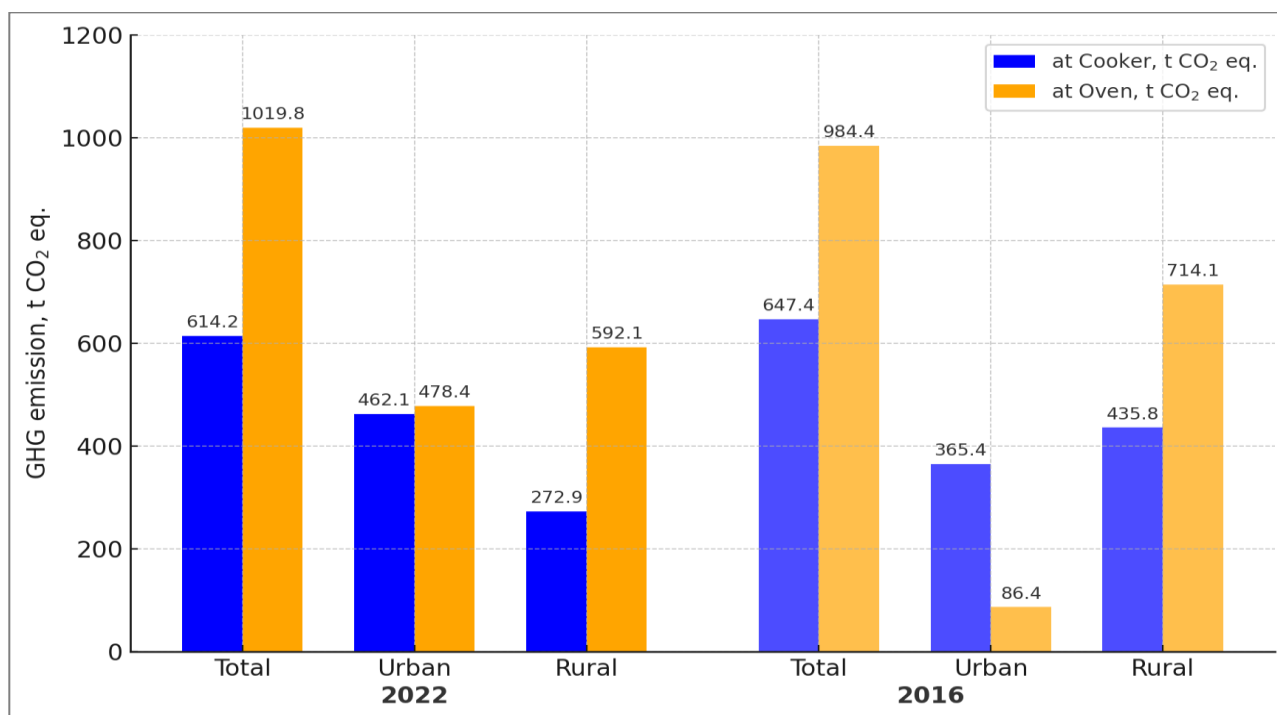


Figure 3. GHG emissions from fuels used in households for cooking on stoves and in ovens.

For ovens, the total CO₂ equivalent emissions increased from 984.4 t in 2016 to 1019.8 t in 2022, with a rise of 3.6%. In urban areas, emissions increased dramatically, from only 86.4 t in 2016 to 478.4 t in 2022, over five times higher, indicating more intensive use of

fuel-based ovens in urban zones. In rural areas, emissions slightly decreased, from 714.1 t in 2016 to 647.4 t in 2022, representing a reduction of approximately 9.3%.

The data suggest an increasing trend in the emissions from urban areas, particularly for ovens, while in rural areas, a general reduction in emissions is observed, possibly due to a transition to alternative energy sources or improved efficiency in fuel usage.

4. Discussions

Cooking-related emissions originate from the following two primary sources: emissions from the stove used and those generated during the food preparation process. These sources are influenced by both the characteristics of the stove (type of fuel used) and the cooking methods and ingredients. For instance, electric and gas stoves emit ultrafine particles and chemical compounds such as CO, NO₂, and formaldehyde, with the level of emissions varying significantly [25]. Studies indicate that in developed countries, gas stoves dominate and are used in 60–70% of European households and 58% of households in the United States. These observations are relevant for the Republic of Moldova, where cooking-related emissions are predominantly associated with natural gas and, to a lesser extent, electricity. Our study results align with these findings, providing a detailed perspective on regional cooking practices and their impact on greenhouse gas emissions.

The results of this study highlight the significant contribution of households in the Republic of Moldova to GHG emissions, revealing substantial differences between the urban and rural areas. In the rural households in Moldova, firewood remains the primary energy source, generating the highest greenhouse gas emissions during the analyzed period. This reliance on traditional fuels mirrors the patterns observed in other developing regions, where access to modern energy infrastructure is limited.

This pattern is similar to other countries [11,26], where households rely heavily on traditional biomass (e.g., in Nepal, contributing to annual emissions of 14.26 kg CO₂ per household [3,11]). In comparison, Romania's policies promoting the transition to renewable energy sources have significantly reduced the use of traditional fuels [27]. This example underscores the need for a similar approach in Moldova to reduce rural emissions.

In urban areas, natural gas and electricity dominate due to better access to modern energy infrastructure, resulting in higher per capita emissions compared to rural areas. However, Moldova's per capita emissions from electricity consumption are lower than those reported in neighboring countries, such as Belarus (10.1 t CO₂ eq/capita in 2022) and Romania (4.9 t CO₂ eq/capita), highlighting the potential opportunities for improvement through the modernization of urban energy systems [28]. This phenomenon is also observed in other countries, such as China, where rapid urbanization has led to increased household emissions associated with electricity consumption [13].

Another important dimension addressed in the study is the impact of cooking on GHG emissions. CO₂ emissions from households, generated by cooking activities, represent a major source of environmental degradation in low- and middle-income countries, accounting for approximately 6.7% of global greenhouse gas emissions [29–31]. The data from our research indicate an increase in the use of natural gas alongside a reduction in firewood and agricultural waste. This transition suggests improved access to modern resources in households while also highlighting the persistence of urban–rural disparities.

Understanding the specific contributions of cooking to household emissions provides valuable insights for designing targeted policies that address both environmental sustainability and public health, encouraging less processed food consumption and reducing indoor air pollution.

The calculated emissions were validated through cross-referencing with similar studies in comparable contexts. The emission factors for firewood aligned closely with those reported in Nepal [11], while the natural gas consumption patterns reflected trends observed in Romania [28]. This validation confirms the robustness of our findings and their relevance to the broader international discourse on energy-related emissions.

These findings align with the international studies on cooking emissions. For instance, research conducted in Binjai during the COVID-19 pandemic demonstrated that household activities such as cooking, electricity consumption, and waste management significantly contribute to greenhouse gas emissions [32]. Similarly, studies in Germany during Christmas markets showed that variables such as cooking temperature and the use of oil influence the dynamics of particle and aerosol emissions [33]. These studies emphasize the importance of local and regional factors in quantifying emissions, making the analysis conducted in the Republic of Moldova unique and critical for understanding the urban–rural disparities in lower-income countries.

Limitations and future directions. The methodology used, based on aggregated regional data, introduces certain uncertainties, especially for households with varied consumption patterns. To improve accuracy, future research should include detailed household-level data and account for socio-economic factors such as income and access to infrastructure. A broader comparison with similar countries in Eastern Europe could provide valuable insights for policy adaptation. To address these limitations, collecting primary data through detailed surveys and standardized questionnaires is essential. This approach would provide granular insights into the types and quantities of fuels used by households. Deploying real-time monitoring devices directly in households would further enhance data accuracy, enabling more precise analyses of the consumption patterns. Integrating socio-economic variables, such as household income, size, and consumption habits, into the analysis is critical for understanding the determinants of energy use. For instance, households with lower incomes may rely more heavily on traditional fuels, while higher-income households might have better access to modern energy infrastructure. Accounting for such factors would enable policymakers to design tailored interventions that effectively address disparities. Leveraging digital technologies to establish a national platform for collecting and managing household energy data could revolutionize the research landscape in Moldova. This platform would facilitate real-time data collection and allow researchers and policymakers to access updated and detailed information. By correlating primary data with external sources, such as satellite imagery and meteorological data, it would be possible to assess the influence of environmental factors, such as temperature variations and seasonal changes, on fuel consumption patterns.

Implications for Policy and Practice. The findings of this study emphasize the urgent need for Moldova to adopt comprehensive energy policies that address urban–rural disparities. Specific recommendations include the following:

- Expanding access to renewable energy sources, such as solar and wind, particularly in rural areas where dependency on traditional fuels is highest;
- Upgrading urban energy systems to reduce losses and improve efficiency, ensuring that electricity and natural gas are utilized more sustainably;
- Implementing educational programs to raise awareness among households about the benefits of energy efficiency and sustainable practices;
- Introducing subsidies and tax incentives for adopting modern energy technologies, especially for low-income households in rural areas;
- Developing an integrated data platform to monitor and evaluate the impact of energy policies, ensuring that interventions are evidence-based and adaptive to changing needs.

5. Conclusions

The conclusions of this study emphasize the need to adopt energy transition strategies in Moldovan households, aiming to reduce GHG emissions by promoting renewable energy sources and energy efficiency. The study demonstrates that firewood and natural gas are the main sources of emissions in rural areas, where reliance on traditional fuels remains significant. This trend, common to other Eastern European regions, underscores the necessity of a public policy framework that supports access to cleaner and more efficient energy resources.

The importance and value of this study at the national level lie in its provision of specific data for the Republic of Moldova, essential for shaping environmental and energy policies tailored to local needs. At the international level, the study contributes to a better understanding of household emissions in developing countries and can serve as a model for regions with similar energy structures, making it relevant to global strategies for GHG reduction.

The study's recommendations include promoting and supporting renewable energy sources in rural households, fostering energy efficiency, and encouraging the adoption of low-energy consumption technologies in both urban and rural settings.

To enhance the relevance and applicability of the findings, addressing certain identified limitations is crucial. A priority future direction involves collecting and utilizing localized emission factors for the Republic of Moldova. These factors would more accurately reflect the specific characteristics of fuels used nationally, such as firewood and biomass, reducing uncertainties associated with using standard IPCC factors. This approach would ensure a more faithful evaluation of emissions and increase the utility of results for national policy development.

Furthermore, integrating primary data collection through detailed household surveys is essential. These surveys would enable the analysis of consumption patterns and access to energy resources, providing a more granular understanding of the socio-economic factors influencing urban–rural disparities. Such insights are vital for tailoring energy transition strategies to specific household needs.

Additionally, incorporating seasonal analysis by correlating emission data with local climatic factors could offer further perspectives on energy consumption variations. This approach would improve the ability to design measures adapted to Moldova's seasonal energy context, supporting the shift toward cleaner energy sources.

These future directions represent important steps toward extending this study and supporting well-founded policy interventions aimed at significantly reducing greenhouse gas emissions and contributing to Moldova's energy sustainability.

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References

1. Mikhaylov, A.; Moiseev, N.; Aleshin, K.; Burkhardt, T. Global Climate Change and Greenhouse Effect. *JESI* **2020**, *7*, 2897–2913. [[CrossRef](#)] [[PubMed](#)]
2. Connolly, M.; Shan, Y.; Bruckner, B.; Li, R.; Hubacek, K. Urban and Rural Carbon Footprints in Developing Countries. *Environ. Res. Lett.* **2022**, *17*, 084005. [[CrossRef](#)]

3. Filonchyk, M.; Peterson, M.P.; Zhang, L.; Hurynovich, V.; He, Y. Greenhouse Gases Emissions and Global Climate Change: Examining the Influence of CO₂, CH₄, and N₂O. *Sci. Total Environ.* **2024**, *935*, 173359. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Axelsson, K.; Gong, J.; Dugast, C.; Lambe, F.; Maquet, P.; Suljada, T. *Consumption-Based Emissions: A New Frontier for EU Climate Policy*; Stockholm Environment Institute: Stockholm, Sweden, 2024.
5. Calvin, K.; Dasgupta, D.; Krinner, G.; Mukherji, A.; Thorne, P.W.; Trisos, C.; Romero, J.; Aldunce, P.; Barrett, K.; Blanco, G.; et al. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change (IPCC); Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023.
6. Siminiuc, R. Analiza Exploratorie a Securității Nutriționale în Republica Moldova (Exploratory Analysis of Nutritional Security in the Republic of Moldova). In *Ph.D. Thesis*; Technical University of Moldova: Chișinău, Moldova, 2024.
7. Xie, J.; Zhou, S.; Teng, F.; Gu, A. The Characteristics and Driving Factors of Household CO₂ and Non-CO₂ Emissions in China. *Ecol. Econ.* **2023**, *213*, 107952. [\[CrossRef\]](#)
8. Flammini, A.; Adzmir, H.; Karl, K.; Tubiello, F.N. Quantifying Greenhouse Gas Emissions from Wood Fuel Use by Households. *Earth Syst. Sci. Data* **2023**, *15*, 2179–2187. [\[CrossRef\]](#)
9. Sun, X.; Mi, Z.; Zhang, J.; Li, J. Driving Factors of Carbon Emissions from Household Energy Combustion in China. *Energy Policy* **2024**, *186*, 114013. [\[CrossRef\]](#)
10. Liang, A.; Tian, Z.; Xiang, C. Research and Analysis of Urban-Rural Residential Carbon Emissions in China. *Sustain. Futures* **2024**, *8*, 100287. [\[CrossRef\]](#)
11. Tika Ram, P.; Hom Bahadur, R. Hourly Firewood Consumption Patterns and CO₂ Emission Patterns in Rural Households of Nepal. *Designs* **2020**, *4*, 46. [\[CrossRef\]](#)
12. Eshetu Abebaw, S. Household Fuelwood Consumption and Its Implication for Carbon Dioxide Emission. *New Energy Exploit. Appl.* **2024**, *3*, 215–227. [\[CrossRef\]](#)
13. Guan, X.; Guo, S.; Xiong, J.; Jia, G.; Fan, J.-L. Energy-Related CO₂ Emissions of Urban and Rural Residential Buildings in China: A Provincial Analysis Based on End-Use Activities. *J. Build. Eng.* **2023**, *64*, 105686. [\[CrossRef\]](#)
14. Heinonen, J.; Junnila, S. A Carbon Consumption Comparison of Rural and Urban Lifestyles. *Sustainability* **2011**, *3*, 1234–1249. [\[CrossRef\]](#)
15. Gill, B.; Moeller, S. GHG Emissions and the Rural-Urban Divide. A Carbon Footprint Analysis Based on the German Official Income and Expenditure Survey. *Ecol. Econ.* **2018**, *145*, 160–169. [\[CrossRef\]](#)
16. Wiedenhofer, D.; Guan, D.; Liu, Z.; Meng, J.; Zhang, N.; Wei, Y.-M. Unequal Household Carbon Footprints in China. *Nat. Clim. Chang.* **2017**, *7*, 75–80. [\[CrossRef\]](#)
17. Hubacek, K.; Baiocchi, G.; Feng, K.; Patwardhan, A. Poverty Eradication in a Carbon Constrained World. *Nat. Commun.* **2017**, *8*, 912. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Wang, Q.; Wang, S. Why Does China's Carbon Intensity Decline and India's Carbon Intensity Rise? A Decomposition Analysis on the Sectors. *J. Clean. Prod.* **2020**, *265*, 121569. [\[CrossRef\]](#)
19. Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies: Hayama, Japan, 2006; ISBN 4-88788-032-4.
20. European Environment Agency. *Trends and Projections in Europe 2024*; Publications Office: Luxembourg, 2024.
21. National Bureau of Statistic of the Republic of Moldova. *Energy Consumption in Households*; National Bureau of Statistic of the Republic of Moldova: Chisinau, Republic of Moldova, 2016; p. 71.
22. National Bureau of Statistic of the Republic of Moldova. *Energy Consumption in Households*; National Bureau of Statistic of the Republic of Moldova: Chisinau, Republic of Moldova, 2022; ISBN 978-9975-3554-8-3.
23. Ember and Energy Institute, Our World In Data. Carbon Intensity of Electricity Generation. Available online: <https://ourworldindata.org/grapher/carbon-intensity-electricity> (accessed on 30 September 2024).
24. FAO. *Methods for Estimating Greenhouse Gas Emissions from Food Systems*; FAO: Rome, Italy, 2023; ISBN 978-92-5-137492-4.
25. Gokhale, M. *Parichehr Salimifard Cooking Emissions*; School of Public Health, Harvard University: Boston, MA, USA, 2019; Volume 1, pp. 1–5. [\[CrossRef\]](#)
26. Bazgir, A.; Maleknia, R.; Rahimian, M. Unveiling Rural Energy Pattern Determinants: Insights from Forest-Dwelling Rural Households in the Zagros Mountains, Iran. *Front. For. Glob. Chang.* **2024**, *7*, 1348461. [\[CrossRef\]](#)
27. Hebda, W. Paliwa Kopalne w Transformacji Energetycznej—Przypadek Rumunii. Fossil fuels in the energy transition—The case of Romania. *Gospod. Surowcami Miner.—Miner. Resour. Manag.* **2023**, *39*, 85–106. [\[CrossRef\]](#)
28. Ritchie, H.; Roser, M. CO₂ Country Profile. Available online: <https://ourworldindata.org/co2/country/japan> (accessed on 16 November 2024).
29. Stoner, O.; Lewis, J.; Martínez, I.L.; Gumy, S.; Economou, T.; Adair-Rohani, H. Household Cooking Fuel Estimates at Global and Country Level for 1990 to 2030. *Nat. Commun.* **2021**, *12*, 5793. [\[CrossRef\]](#)
30. Jia, J.-J.; Zhu, M.; Wei, C. Household Cooking in the Context of Carbon Neutrality: A Machine-Learning-Based Review. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112856. [\[CrossRef\]](#)
31. Aamaas, B.; Grimsby, L.K. The Impact on Climate and Emissions of Clean Household Cooking Energy Policies in Tanzania. *Energy Policy* **2024**, *192*, 114211. [\[CrossRef\]](#)

32. Suryati, I.; Hijriani, A.; Indrawan, I. Estimation of Greenhouse Gas Emission from Household Activities during the COVID-19 Pandemic in Binjai City, North Sumatera. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *896*, 012054. [[CrossRef](#)]
33. Pikmann, J.; Drewnick, F.; Fachinger, F.; Borrmann, S. Particulate Emissions from Cooking Activities: Emission Factors, Emission Dynamics, and Mass Spectrometric Analysis for Different Preparation Methods. *EGUsphere* **2023**. *preprint*.

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