DYNAMIC MODELING OF HOUSEHOLD ENERGY VULNERABILITY: EMPIRICAL EVIDENCE FROM MOLDOVA'S COMPENSATION SYSTEM

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Abstract
This study examines the dynamics of household energy vulnerability in the Republic of Moldova, a country characterized by near-total dependence on imported energy and high exposure to external price shocks. Building on the national framework for vulnerability classification (Law No. 241/2022 and Government Decision No. 816/2024), the analysis integrates administrative, household, and elasticity data to assess the effectiveness of monetary compensations introduced during the 2022-2025 heating seasons. Using a panel data-based simulation anchored in empirical energy-burden ratios (R), the model reconstructs household-level heterogeneity and evaluates how compensation policies affect energy poverty rates over time. Results confirm that while energy vulnerability remains widespread, particularly among high and very high categories, targeted compensations significantly alleviate gas-related burdens, whereas electricity poverty persists more rigidly.

Key words: *compensations; energy vulnerability; energy poverty; Republic of Moldova; simulations.*

JEL Classification: Q48, I32, O13

I. INTRODUCTION

In recent decades, global energy shifts, driven by renewables, volatile fossil fuel markets, and geopolitical tensions, have made energy access central to economic and social security. In Central and Eastern Europe, high import dependence, aging infrastructure, and low incomes amplify energy insecurity (Balan, 2024).

Moldova illustrates this vulnerability: almost entirely reliant on imported gas and electricity, it faces acute exposure to external shocks (IEA, 2022, 2024). After years of low prices through Gazprom agreements, gas and electricity costs rose over sixfold in 2021, severely straining households (UNDP, 2022, 2025), as shown in Figure 1. Unlike energy poverty, which reflects static income–expenditure relations, energy vulnerability captures dynamic risks, price volatility, efficiency, and supply security, offering a broader view of household resilience (Thomson et al, 2017). Moldova's recent policies, including Law No. 241/2022 and Government Decision No. 816/2024, approving the Regulation on the Allocation of Energy Compensation in the Form of Monetary Payments, translate these concepts into action, positioning the country as a key case of turning theoretical frameworks on energy vulnerability into concrete public policy.

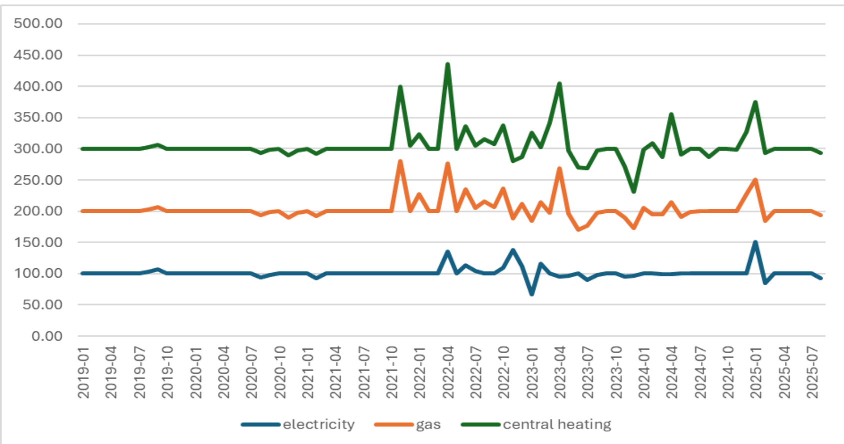


Figure 1 - Energy price index (last month=100) by energy type between 2019-2025.
Source: Statbank, NBS.

Each household's support depends on income, energy source, the income–expenditure ratio (VGL/MCF), and the energy burden coefficient (R) - the share of available income spent on energy (see Appendix A). Energy costs are based on last winter's average use at current tariffs, while available income excludes essential expenses and mortgage payments. A higher R signals greater vulnerability and determines the household's assigned vulnerability category (see Table 1).

Table 1 – Vulnerability Thresholds determined by R (2022-2023 Winter Season).

Category	Definition	Description
Very High	$R \geq 90\%$	Households spend nearly all available income on energy, showing severe vulnerability.
High	$35\% \leq R < 90\%$	Energy costs take up a large portion of available income, creating financial stress.
Medium	$20\% \leq R < 35\%$	Energy costs are moderately burdensome but generally manageable.
Low	$R < 20\%$	Energy costs are low relative to income, indicating minimal vulnerability.

Note: R(%) = CEPR / VDAE, where **CEPRA** – household's estimated monthly energy expenditure, calculated using last year's average consumption (in Gcal, m^3, or kWh) at current, non-compensated tariffs.
VDAE – income available to pay for energy, equal to total household income after deducting: **MCF** – minimum essential expenditure level, and **RLCI** – monthly mortgage payment.

Once households are classified into specific vulnerability categories, their energy tariffs are recalculated to incorporate the relevant subsidies and category-based adjustments. During online registration on the government platform, household information is automatically verified against official databases to ensure data accuracy, consistency, and to avoid duplication. By March 2023, over 763,000 households, around 75% of all households in Moldova, had enrolled in the system (UNDP, 2023). Figure 2 illustrates the distribution of approved beneficiaries by vulnerability category and the corresponding CEPRA values (energy costs during the heating season) for different energy sources. The pie chart reveals that most registered beneficiaries, 78.2% belong to the very high vulnerability category, followed by high (12.9%), medium (7.2%), and low (1.7%) groups, confirming that the program primarily supports the most economically exposed households. The bar chart compares CEPRA levels across vulnerability categories and energy sources, showing that while costs remain fairly consistent within each category, natural gas and total CEPRA values are substantially higher than for electricity or district heating.

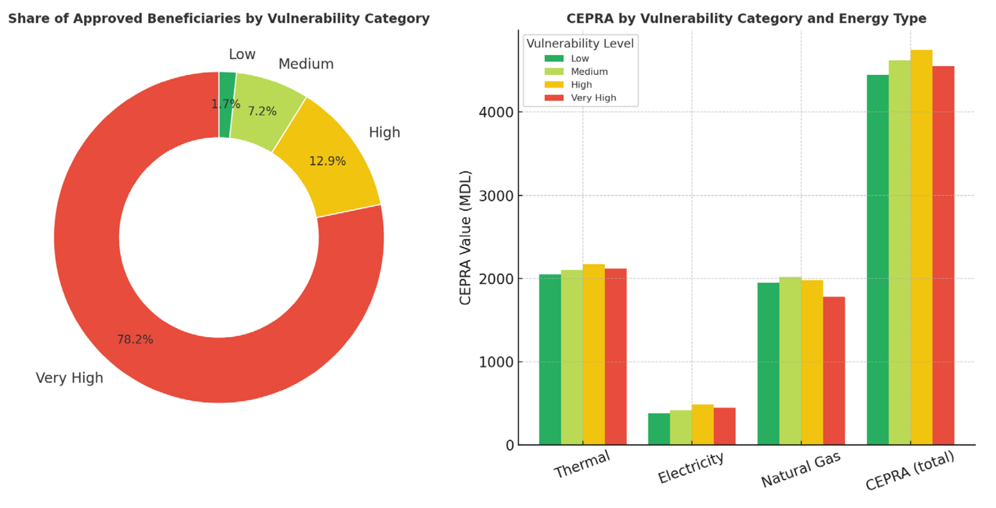


Figure 2 – The distribution of vulnerability categories and CEPRA in the 2022-2023 Winter season.
Source: UNDP (2023).

The (UNDP, 2023) report provides estimates of demand and income elasticities by vulnerability level, showing how households adjust energy use to price and income changes. Price elasticities (Table 2) reveal that demand for electricity, gas, and other fuels is inelastic, all own-price values are negative (–0.06 to –0.36), meaning consumption falls slightly when prices rise. Gas is somewhat more price-sensitive than other fuels, especially among low- and medium-vulnerability groups. Cross-price elasticities are also small and mostly negative, indicating that energy types act as weak complements, not substitutes. As vulnerability increases, both own- and cross-price elasticities decline in magnitude, showing that highly vulnerable households, already consuming minimal energy, are least able to adjust to price shifts.

Table 2 - Price elasticities for different energy sources by vulnerability category.

		Electricity	**Gas**	**Other**
Low Vulnerability	Electricity	-0.283	-0.053	-0.597
	Gas	-0.071	-0.36	-0.635
	Other	-0.039	-0.028	-0.934
Medium Vulnerability	Electricity	-0.165	-0.077	-0.698
	Gas	-0.095	-0.246	-0.82
	Other	-0.045	-0.038	-0.911
High Vulnerability	Electricity	-0.103	-0.081	-0.737
	Gas	-0.1	-0.144	-0.914
	Other	-0.048	-0.042	-0.905
Very High Vulnerability	Electricity	-0.065	-0.086	-0.853
	Gas	-0.099	-0.153	-0.859
	Other	**-0.051**	**-0.042**	**-0.9**

Source: UNDP (2023)

Income elasticities (Table 3) confirm that all energy sources are normal goods, with demand rising as income increases. Values hover around or slightly above one, suggesting nearly proportional responses. Gas shows the highest income elasticity (1.065-1.16), implying stronger sensitivity to income growth, while electricity and other fuels remain closer to unity. Notably, electricity elasticity exceeds one (1.004) for very vulnerable households, possibly reflecting a shift toward cleaner energy as incomes rise.

Table 3 - Income elasticities per vulnerability category and energy type.

	Electricity	**Gas**	**Other**
Low Vulnerability	0.932	1.065	1.001
Medium Vulnerability	0.941	1.16	0.995
High Vulnerability	0.92	1.158	0.996
Very High Vulnerability	1.004	1.11	0.994

Source: UNDP (2023)

The estimated income and price elasticities form the analytical basis for projecting **CEPRA** (energy costs during the cold season) beyond 2022–2023. By capturing how energy demand responds to changes in income and prices, they enable modeling of household consumption under different economic or policy conditions.

II. EMPIRICAL ANALYSIS

The first step of the analysis involves projecting future CEPRA values using a constant-elasticity expenditure model. The same elasticity parameters are applied across all periods, reflecting the assumption that these values capture structural determinants of energy demand, such as dwelling efficiency, income composition, and heating technologies, that evolve gradually over time. Keeping elasticities constant ensures temporal comparability and prevents artificial differences unrelated to actual behavioral change.

The CEPRA (Consumul Energetic Proiectat în Regim de Ajustare) indicator was estimated for each energy type e and month t during the winter period (November–March) according to the following model:

$$E_{et} = B_e\left(\frac{P_{et}}{\bar{P}_e^{\text{winter 2023}}}\right)^{1+\varepsilon_e}$$

where B_e is the baseline expenditure for energy type e, P_{et} is the observed price in month t, $\bar{P}_e^{\text{winter 2023}}$ is the average winter-2023 price used as a normalization reference, and ε_e represents the price elasticity of demand. Monthly CEPRA values were then obtained by summing expenditures across energy types, isolating the effect of price dynamics on household energy burdens while maintaining consistent behavioral parameters.

We employ an empirical, bottom-up simulation, the panel data approach, to reconstruct household energy-burden heterogeneity without relying on parametric assumptions. The approach directly approximates the observed population structure: a large pool of energy-burden ratios (R) is generated to match the empirical shares of vulnerability groups (low, medium, high, very high). Sampling from this pool, rather than from theoretical distributions, preserves the heavy upper tails and within-group dispersion typical of administrative microdata.

The process begins with constructing an empirical R-pool. For each vulnerability group g, its population weight defines the proportion of draws allocated to the interval [$R_{(min,g)}$, $R_{(max,g)}$]. Within each range, heterogeneity is introduced by concentrating 70% of draws toward the upper end (where most households cluster), spreading 20% uniformly across the full range, and placing 10% near the lower boundary (representing relatively better-off households). The concatenated and randomized draws form a smooth, continuous empirical distribution of R that embeds both population weights and within-group variability (see Figure 3).

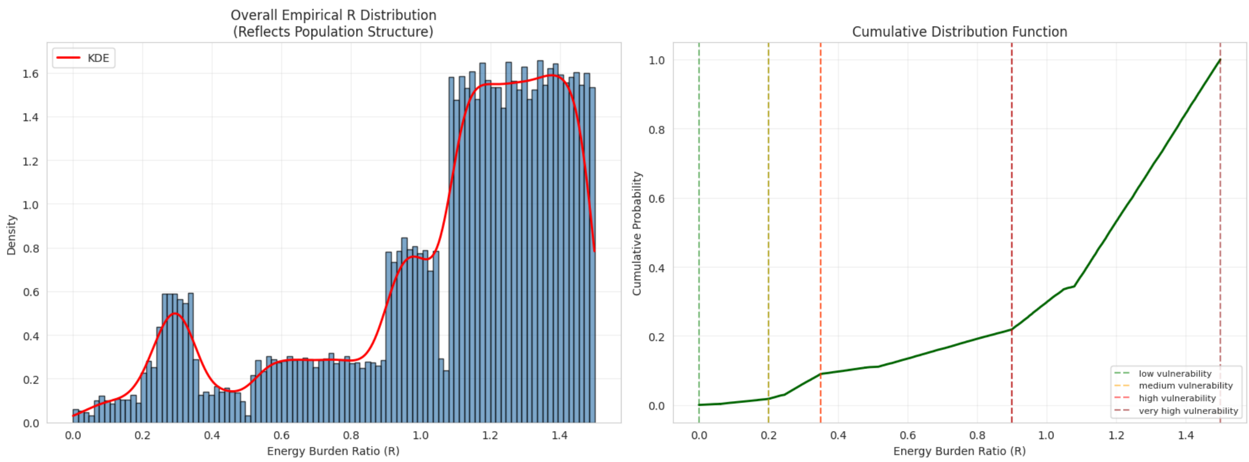


Figure 3 - Empirical R distribution and its CDF.
Source: Elaborated by the author.

Next, a synthetic household panel is generated by resampling from this pool. For each group g, base burdens (R^{base}) are repeatedly drawn until the target number of households is reached, keeping only values within the group's range. Each household is assigned a stochastic size (with group-specific mean and variance) and a Bernoulli probability of using electricity as the main heating source, calibrated by group characteristics.

Methodologically, this design isolates policy effects from distributional assumptions. Anchoring the micro-distribution of R in an empirical pool aligned with observed group weights limits bias from unrealistic parametric tails. The inclusion of electricity-use gates, "debranșat" uplifts, and month-specific bounds ensures consistency with regulatory definitions, while safeguards and soft floors on R^{real} prevent extreme or artificial zero-benefit cases.

A key advantage of this empirical framework is its dynamic, time-varying structure. By extending the household panel across multiple winter months and policy years, the model captures realistic temporal variation in energy burdens (R), consumption (VGL), and projected costs (CEPRA). These fluctuations, driven by controlled stochasticity, reflect genuine changes in prices, climate, and household behavior. Because aggregation respects survey weights, the resulting group-level and fiscal estimates remain consistent with the underlying population structure. Similar types of analyses were undertaken by Bohr (2019), Forrester et al. (2024), Aguilar and Fuentes-Albero (2025), and Bourguignon and Spadaro (2006).

Figure 4 illustrates the average per household monthly compensation aggregated across all years (2022-2025) and categorized per vulnerability group and per energy type, created by the panel data based simulation. As we can infer, the averages are fairly similar to the compensations indicated by the Ministry of Labour and Social Protection of the Republic of Moldova (2024).

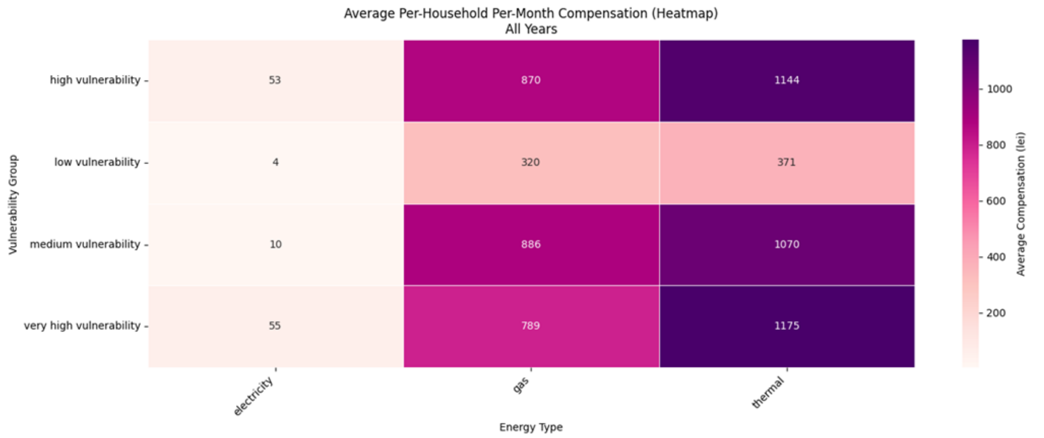
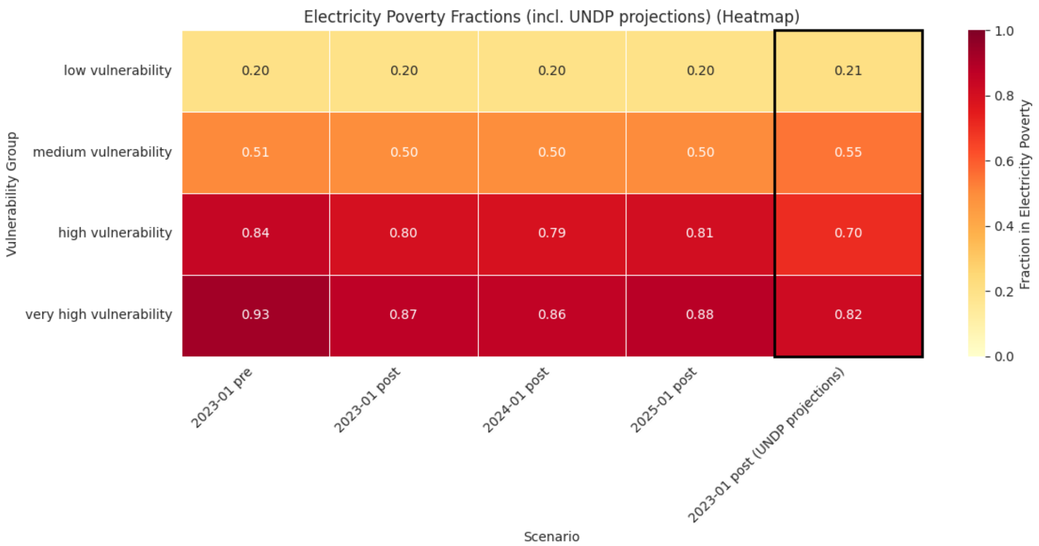


Figure 4 - Average Per-Household Per-Month Compensations categorised by energy type and vulnerability group.
Source: Elaborated by the author using panel data based simulations.

Similarly, we need to understand the impact of these compensations on energy poverty rates and compare these results with UNDP projections (2023). These are shown in Figures 5, broken down again by electricity and gas poverty fractions.



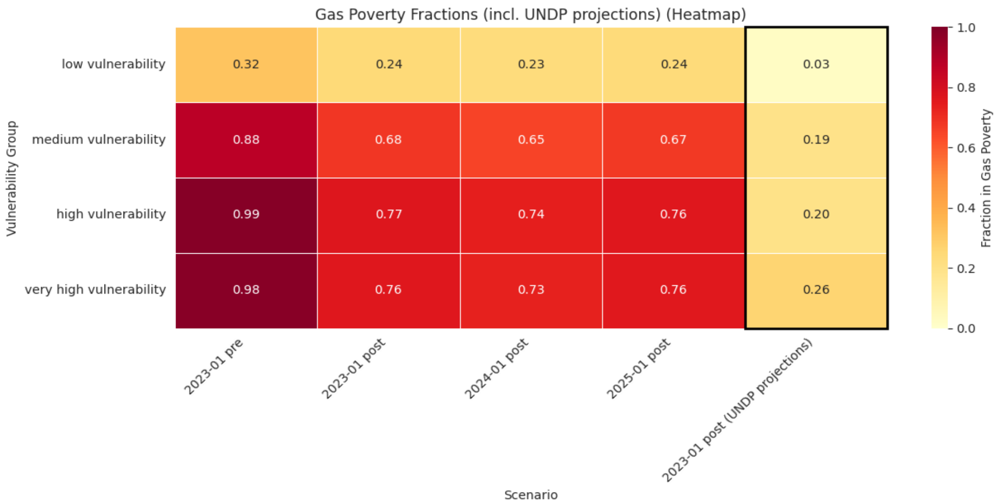


Figure 5 - Percentage of households in energy poverty. Average for each winter season for electricity and gas.

Source: Elaborated by the author, (UNDP 2023).

Note: Energy poverty is classified as spending over 10% of disposable income on energy consumption.

For both tables, results reveal that electricity poverty remains structurally persistent, particularly among households categorized as high or very high vulnerability. Their poverty fractions, ranging from approximately 0.80 to 0.93, display only modest reductions across the 2023–2025 horizon, indicating that even under post-policy and projected scenarios, these groups continue to experience entrenched hardship. By contrast, lower-vulnerability segments exhibit remarkable temporal stability, with fractions hovering around 0.20 for the low and 0.50 for the medium categories, implying relative resilience to energy cost fluctuations and compensatory scheme adjustments. The 2023 UNDP-projected scenario, similarly, introduces a mild downward correction in electricity poverty, most notably among high-vulnerability households, yet these changes are incremental rather than transformative, emphasizing the limited elasticity of electricity-related deprivation to short-term interventions.

In contrast, the gas poverty results reveal a far more dynamic and responsive pattern. Initial levels of deprivation are significantly higher across all groups in early 2023, but notable reductions are observed in the post-intervention periods. Medium and high vulnerability groups, for instance, decline from near-universal exposure (0.88–0.99) to substantially lower levels by 2024–2025, suggesting that targeted compensation mechanisms or relative price moderation have effectively mitigated gas-related burdens. The UNDP projections further accentuate this trajectory, forecasting a pronounced contraction of gas poverty, especially among low and medium vulnerability households, where fractions fall to 0.03 and 0.19, respectively. Overall, while electricity poverty appears structurally inelastic to short-term policy shifts, gas poverty demonstrates higher sensitivity and a stronger temporal adjustment path. This divergence highlights sectoral asymmetries in energy vulnerability, again depending on the primary energy type used by the respective household.

III. CONCLUSION

The results of this analysis demonstrate that Moldova's energy compensation framework has played a stabilizing role during a period of unprecedented energy price volatility. The empirical, panel data–based simulation developed in this study provides a realistic representation of household energy burdens and the heterogeneity of policy effects across vulnerability categories. By anchoring the analysis in observed distributions rather than theoretical assumptions, it captures the uneven responsiveness of different energy types and population segments to price and income shifts. This methodological approach offers a transparent, data-driven basis for assessing the effectiveness of current interventions and identifying where further refinements are required.

Looking ahead, further work will extend these simulations into a forward-looking analytical tool for policy testing. This will involve constructing “what-if” scenarios that evaluate how alternative compensation schemes, tariff structures, or efficiency subsidies would affect both fiscal sustainability and household welfare. By modeling interactions between household behavior, energy demand, and government expenditure, such scenarios can help policymakers design interventions that optimize public spending while maximizing poverty reduction impact.

IV. APPENDIX A

Overview of Rules for Determining Household Energy Compensation Amounts.

Clause no.	Condition (translated)	Energy Source	Compensation Formula / Value	Explanation of Terms
2.1	Household consumers whose main heating source is natural gas, thermal energy, or electricity, and the ratio (VGL/MCF) ≤ 50%.	Gas, thermal energy, or electricity	**800 lei (fixed)***	VGL = Total monthly household income; MCF = Minimum household expenditure level.
2.2	Main heating source is solid fuel, and VGL ≤ MCF.	Solid fuel	**800 lei (fixed)**	Same condition, for solid fuel users.
2.3	Main heating source is natural gas; 50% < (VGL/MCF) ≤ 100%.	Natural gas	**C = CEPRA × 10% × (1 + (1 − VGL/MCF))**	CEPRA = Cost of energy during the cold period; C = Monetary compensation.
2.4	Main heating source is natural gas; VGL > MCF and R ≥ 100%.	Natural gas	**C = CEPRA × 10%**	R = Ratio between energy expenses and disposable income for energy.
2.5	Main heating source is natural gas; VGL > MCF and 20% ≤ R < 100%.	Natural gas	**C = CEPRA × 10% × R**	R = Energy expenses / disposable income (in %).
2.6	Main heating source is thermal energy or electricity; VGL ≤ MCF.	Thermal energy or electricity	**C = CEPRA × 20% × (1 + (1 − VGL/MCF))**	Higher compensation factor (20%) compared to gas users.
2.7	Main heating source is solid fuel, thermal energy, or electricity; VGL > MCF and R ≥ 100%.	Solid fuel, thermal, or electricity	**C = CEPRA × 20%**	Fixed rate compensation for full energy cost burden.
2.8	Main heating source is solid fuel, thermal energy, or electricity; VGL > MCF and 20% ≤ R < 100%.	Solid fuel, thermal, or electricity	**C = CEPRA × 20% × R**	Partial compensation based on ratio R.
2.9	Main heating source is solid fuel, gas, thermal, or electricity; VGL > MCF and R < 20%.	All types	**No compensation**	Households with low energy burden receive none.
2.10	Households using gas or electricity as main source and disconnected from thermal energy supply.	Gas or electricity	**CEPRA increased by +40% of CEPRA for thermal energy**	Adjustment for debranched (disconnected) households.
3	Minimum compensation threshold.	All	**Minimum 300 lei**	If calculated compensation < 300 lei but > 0, apply 300 lei.
4	Maximum compensation threshold.	All	**Maximum 800 lei***	No household can receive more than 800 lei.

Clause no.	Condition (translated)	Energy Source	Compensation Formula / Value	Explanation of Terms
6	Eligibility for electric heating households.	Electricity	Must meet **all**: (a) main heating source electric, (b) ≥250 kWh/month avg. in last cold season, (c) not connected to central heating or use < 0.3 Gcal/month, (d) use < 50 m³ gas/month.	If ineligible, use CEPRA for solid fuels.

Source: Ministry of Labour and Social Protection of the Republic of Moldova (2024).
*Since December 2024, the maximum threshold has been changed to 1000 lei for households whose main heating source was natural gas.

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