



Economic rationality and the future of rural biomass: Evidence from Romania's energy transition

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Abstract: This study provides a novel, community-level analysis of rural biomass adoption in Eastern Europe, integrating technical efficiency data with socioeconomic perceptions from Ghelinița, Romania. Using mixed methods, it reveals a paradox: universal reliance on firewood (100%) coexists with minimal awareness of alternative biomass (23%). The research uniquely links boiler performance data to household-level attitudes, showing that economic and institutional barriers – rather than environmental motivations – govern adoption. By aligning quantitative emission reductions with qualitative insights, the study offers an innovative framework for designing targeted, evidence-based biomass policies in underrepresented rural contexts of the European energy transition.

Keywords: rural energy transition, community adoption, socioeconomic drivers, policy framework, emission reduction, renewable heating systems

1. Introduction

Energy is a central pillar of modern civilization: it powers industry, heating, mobility, and underpins economic growth and social welfare [1]. Historically, much of this energy has been supplied by non-renewable fossil fuels (coal, oil, natural gas), but there is widespread recognition that these sources are finite, contribute substantially to greenhouse gas (GHG) emissions, and are often associated with environmental pollution [2]. Reports by the International Energy Agency emphasize that the declining reserves of fossil energy carriers compel a shift towards renewable sources to meet growing global energy demand [3]. Similarly, the Intergovernmental Panel on Climate Change (IPCC, 2022) underscores that achieving a low-carbon future will necessitate expanded deployment of renewable energy, including biomass, to reduce climate change impacts and environmental degradation [4].

Renewable energy sources (RES) – such as solar, wind, hydropower, geothermal, and biomass – are naturally replenished, and when sustainably managed, offer lower environmental impacts compared to fossil fuels. Biomass in particular holds promise because it can be deployed in various forms: direct combustion, biogas, biofuels, waste residues, etc. [5]. The adoption of RES is now central to international and regional climate mitigation goals. For instance, the European Union (EU) has set targets for 2030 that specify that a substantial share (e.g. 32 %) of energy consumption must come from RES. The International Renewable Energy Agency (IRENA) reported that increased RES contributes to GHG reduction and sustainable development aims [6].

Despite this, global deployment of biomass has both opportunities and challenges. On the opportunity side, modern solid bioenergy use (industrial heat, building heating, etc.) is growing. According to IEA's report, modern solid bioenergy accounted for ~3.5 % (16 EJ) of total final energy consumption globally in 2023 [7], with an additional ~19 EJ used in more traditional (often inefficient) methods for cooking and heating, especially in developing regions.

Moreover, global analysis has highlighted those policies that are crucial in governing the sustainability of biomass use [8]. Variables such as distance between biomass source and point of use [9], moisture content [10], transportation and processing emissions [11], land use [12], and feedstock type all mediate whether biomass energy truly yields net environmental and economic benefits [13]. A recent systematic review on the governance of woody biomass found that although biomass is widely promoted, its classification as sustainable is contingent on such mediating factors; policy frameworks vary widely in how they regulate production, transportation, and end-use practices [8].

An additional trend: economic analyses are increasingly quantifying not only the environmental but also the socioeconomic implications: job creation [14], reduced import dependency [15], regional development [16]. Studies show that the biomass sector can contribute significantly to economic growth, particularly in rural areas [17], if feedstock supply chains, technical knowledge, and social acceptance are well addressed [18]. For example, Nosenzo estimates that agricultural residues globally could displace up to 4.5 % of global fossil fuel energy with sizable emission reductions and economic benefit though logistical and policy challenges remain [19].

Biomass is organic matter derived from plants and animals; it encompasses forest residues, agricultural by-products, energy crops, organic waste, and animal manure. Recent studies have explored advanced conversion technologies and improvements in catalysts, pre-treatment, etc. At national levels, many studies focus on biomass potential, economic growth, environmental impacts (GHG emissions), and drivers and barriers. The biomass energy production potential in agricultural holdings has been studied in relation to farm size, showing that smaller holdings still can make meaningful contributions if logistics and economies of scale are addressed

[20]. Another recent work quantifies how the biomass sector contributes to GDP growth, taking into account environmental sustainability [21]. It finds positive effects, particularly when biomass production is coupled with policy support and infrastructure improvements.

Regarding public attitudes, Ghelintă rural municipality was surveyed ($n \approx 189$) by the authors between 1 and 30 April 2025, who found that awareness, knowledge, and perceptions of local drivers and barriers strongly predict the intention to adopt agro-biomass heating solutions [22]. The study also shows that political or regulatory barriers and knowledge act as mediators/moderators in these relationships.

Globally and in the EU, policy frameworks such as the EU's Renewable Energy Directives (RED II/III) [23] and National Energy & Climate Plans (NECPs) and financing mechanisms like the Modernization Fund or Just Transition Fund play central roles in promoting biomass and renewables generally [24].

Environmental sustainability: ensuring that biomass harvesting does not lead to deforestation [25], loss of soil carbon, biodiversity risks, or emissions that offset the benefit [26]. The woody biomass governance review highlights these risks and how policies differ in handling them.

Residents' perceptions play a crucial role in the adoption of biomass-based energy systems [22]. Factors such as smoke, odour, and ease of operation directly influence how local communities evaluate these technologies. Even when economic and environmental benefits are recognized, concerns about air quality, maintenance requirements, or fuel handling often discourage widespread use [27]. Others highlight that limited technical knowledge and administrative barriers remain major obstacles to uptake in rural areas [22]. Many residents lack accurate information about biomass efficiency, emissions, and long-term cost savings, while complex bureaucratic procedures further erode trust in such initiatives. Consequently, improving public awareness, education, and transparent communication between communities and local authorities is essential to enhance social acceptance and ensure the sustainable integration of biomass systems in rural energy transitions [28].

Many studies address national or regional potential or high-level economic models, but fewer focus on community-level investigations of biomass adoption, integrating technical, economic, environmental, and social dimensions alike. Within local studies, the focus is often on heating systems or biogas, less commonly on a comparative assessment of different types of biomass feedstocks (forest, agricultural, communal waste) in how accessible they are, how acceptable socially, what barriers are technical vs perceptual.

While economic growth or emission reduction potentials are modelled, fewer studies test specific hypotheses about what drives acceptance, e.g. cost savings vs sustainability values, technical understanding vs regulation with mediating variables in local populations. Also, there is a limited number of case studies based

on actually functioning biomass installations in villages to examine what practical challenges emerge (maintenance, feedstock procurement, local governance).

Given the background, this research aims to address some of these gaps by focusing on a rural community in Ghelînța, Romania, where biomass energy systems are already in place. These systems contain especially biomass boilers in public buildings using local wood chips. The study proposes to integrate community members' perceptions, knowledge, socio-economic drivers and barriers alongside an assessment of different biomass types and their energy/environmental potential.

Research Questions

RQ1: How well do members of the Ghelînța community understand the types and uses of biomass for energy (forest, agricultural waste, energy crops)?

RQ2: What economic, environmental, and social benefits of biomass do residents perceive as most important?

RQ3: What are the main barriers (technical, regulatory, cost, knowledge) that inhibit the adoption of biomass systems at the household or community level?

RQ4: To what extent do residents' knowledge, environmental values, and cost perceptions influence their intention to adopt biomass energy solutions?

RQ5: How do actual local installations (e.g. municipality biomass boilers) perform in respect to cost, feedstock supply, maintenance, emissions relative to the expectations/perceptions of residents?

Hypotheses

Based on prior literature and preliminary observations, the following hypotheses will be tested:

H1: Even though local residents recognize the potential of RES, many do not possess enough technical knowledge to move towards adoption.

H2: Sustainability values (i.e. concern for environment, climate change, resource depletion) positively correlate with acceptance of biomass systems but are not the primary decision factor for adoption.

H3: Economic concerns – particularly cost savings and energy expense reduction – serve as more influential motivators for biomass adoption than environmental or sustainability motives.

H4: Strong local institutional or community support (local administration, policy, social influence) significantly increases the acceptance and likelihood of the adoption of biomass energy solutions.

H5: Among biomass feedstock types, those that are most accessible will be preferred, and perceptions of ease of supply will moderate the effect of economic and environmental motivations on adoption intention.

To conclude the above-mentioned aspects, the global and EU literature underscores the urgency and promise of biomass as a RES. It also shows that policy, governance, feedstock logistics, technical knowledge, and social acceptance are decisive. In Romania, studies confirm potential but also show that acceptance and uptake are uneven and influenced by awareness, costs, and regulatory barriers. This paper focusing on the Ghelintă community fills a much-needed niche: a local-level case study that combines quantitative potential (various biomass types) with perceptions and attitudes, testing explicit hypotheses about what drives adoption. The findings are expected to be relevant both locally and more broadly, for rural communities in Romania and similar settings in Europe, contributing to evidence for policy design, community engagement, and technology deployment.

Based on these gaps, the study pursues five main objectives: (1) to analyse the types of biomass feedstock available in the study area and their energy potential, (2) to examine residents' knowledge, awareness, and perceptions, (3) to identify technical, regulatory, economic, and social barriers to adoption, (4) to evaluate the contribution of biomass systems to environmental, economic, and social goals, and (5) to derive policy recommendations for fostering uptake within the EU/Romanian energy transition context.

2. Materials and methods

The research applied a mixed-methods approach, combining both secondary and primary data collection to ensure a comprehensive understanding of the investigated topic. The research design was developed to integrate quantitative and qualitative methods, allowing for triangulation of data and the generation of robust, multi-layered insights.

2.1. Secondary research and contextual analysis

In the first phase, secondary research was conducted to establish the theoretical and contextual framework of the study. A systematic review of relevant scientific literature, policy documents, strategic energy plans, statistical databases, and technical reports was carried out. This phase aimed to identify the current state of knowledge regarding biomass-based energy production, RES integration at local and regional levels, and climate adaptation strategies. It also helped to delineate the socio-economic, environmental, and technological factors influencing the acceptance and implementation of biomass energy systems in rural communities. Objectives 1 and 4 are addressed through technical and economic analysis, Objectives 2 and 3 through survey and interviews, and Objective 5 through the triangulation of all findings. These results directly address RQ1 by showing that while residents are highly familiar with firewood, the knowledge of biomass sources is limited and underutilized.

2.2. Primary research: Quantitative survey

The second phase focused on primary data collection through a structured questionnaire. The survey method was chosen because it enables the collection of a large number of responses in a relatively short time, providing statistically representative and comparable data. The target population comprised the residents of the selected rural municipality, with the aim of achieving a representative sample that reflects the demographic structure of the community. The questionnaire was available digitally while the respondents were approached in person, which allowed the researcher to gather additional contextual information beyond the predefined questions. In total, 189 valid responses were collected. For a population of approximately 5,000 inhabitants, the survey meets the criteria for a 95% confidence level with a margin of error of 7%, ensuring statistical reliability (*Table 1*).

Table 1. Summary of key parameters for the questionnaire survey

Category	Details
Survey type	Questionnaire-based survey
Target population	5,000 residents
Confidence level	95%
Representativeness	Representative survey
Margin of error	$\pm 7\%$
Number of valid completed questionnaires	189
Sampling method	Randomized
Survey period	1–30 April 2025

Source: authors' compilation

Descriptive statistics were first applied to summarize the characteristics of the sample, including frequencies, percentages, means, and standard deviations. Inferential statistical analyses were conducted to examine relationships and differences among variables. Depending on the measurement scale and research objectives, two-way factorial ANOVA, Chi-square tests, correlation analyses, and linear or logistic regression models were employed. Statistical significance was determined at the 95% confidence level ($p < 0.05$).

Given the survey's representative nature and a sample of 189 valid responses out of a 5,000-resident target population, weighting procedures were considered where demographic proportions differed from population benchmarks. Confidence intervals and a $\pm 7\%$ margin of error were applied to key estimates. All analyses were performed using IBM SPSS Statistics 29.0.

The main objective of the survey was to assess local knowledge and expectations regarding biomass to energy projects, and to explore how community perceptions influence their acceptance at the local level.

2.3. Qualitative research: Semi-structured interviews

To complement the quantitative findings, semi-structured interviews were conducted with key local stakeholders, including the mayor, vice-mayor, school director, and representatives of the four local forest associations, as well as the representative of Green Energy Cluster, a boiler operator, representatives from the cultural centre and local SMEs. These interviews aimed to obtain in-depth insights into the local decision-making processes, institutional perspectives, and practical challenges related to the implementation of biomass-based energy systems. The qualitative data provided valuable background information on technological preferences, policy constraints, and local development priorities, which enriched the interpretation of the survey results.

2.4. Technical and economic analysis

A significant part of the research focused on the technical and operational characteristics of biomass-based heating and energy systems. This involved examining system efficiency, maintenance requirements, types of boilers and associated technologies, as well as identifying potential technical barriers and optimization opportunities. The economic analysis investigated both investment and operational costs, comparing biomass-based systems with conventional heating such as firewood- or natural-gas-based. Special attention was given to cost reduction potential for municipal institutions and households, as well as to the financial mechanisms and funding schemes that could support the implementation of biomass systems. This analysis aimed to assess the long-term economic viability of biomass-based energy solutions.

2.5. Environmental impact assessment

The study also included an environmental impact analysis, focusing on the effects of biomass utilization on air quality, carbon emissions, and local ecological balance. This assessment aimed to determine whether biomass-based systems represent a sustainable solution and to identify the environmental safeguards and regulatory measures to maximize their positive impacts.

3. Results and discussions

3.1. The viability of biomass-based local energy systems

The empirical results of the study provide strong evidence that biomass-based energy systems represent a viable, cost-effective, and sustainable alternative for

rural energy autonomy in Romania. Based on both secondary and primary data, the analysis reveals the economic, technical, and social feasibility of biomass utilization, with Ghelința serving as a representative case for rural localities that seek energy independence while promoting sustainable development.

A central element of the analysis concerns the comparative cost structure of different energy sources available in Romania. Data for 2024–2025 show significant disparities in the cost of producing 1 MWh of energy from various fuels. This comparison underscores the substantial economic advantage of woodchip-based systems, whose unit energy cost is nearly three times lower than that of natural gas (*Table 2*).

Table 2. Current prices and costs of locally available fuels

Type of Fuel	Price (per unit)	Price per 1 MWh (RON)	Price per 1 MWh (EUR)
Natural gas	310 RON / MWh	310 RON / MWh	≈ 62.6 EUR / MWh
Firewood	~ 400 RON / m ³	~160 RON / MWh	≈ 32.3 EUR / MWh
Woodchips	250 RON / tonne	90 RON / MWh	≈ 18.2 EUR / MWh

Source: authors' compilation

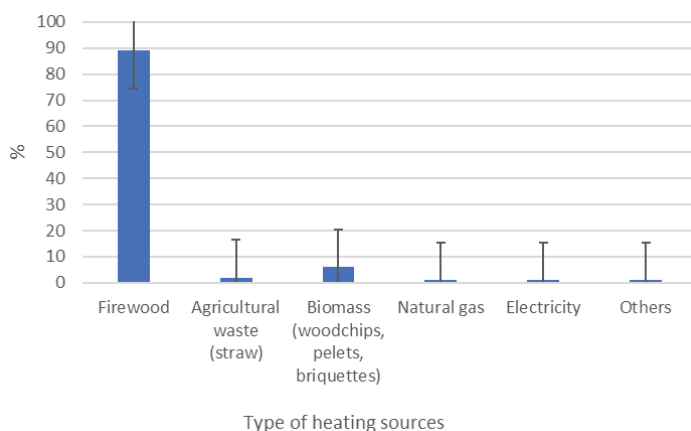
These figures confirm that biomass – especially in the form of woodchips – constitutes the most cost-efficient and locally adaptable energy source. While firewood remains a viable alternative, it presents logistical challenges such as higher storage requirements and labour-intensive preparation. In contrast, natural gas, though convenient, entails significantly higher costs and dependence on centralized infrastructure. The introduction of a temporary price cap on firewood and related materials in Romania (400 RON/m³) offered short-term relief to households during the energy crisis, but regional disparities in availability and enforcement diminished its long-term effectiveness.

The findings therefore reinforce the economic rationale for transitioning to biomass systems, particularly in localities where raw materials – such as forestry residues and wood-processing by-products – are readily available. Ghelința's experience confirms that local fuel sourcing, combined with efficient conversion technology, can reduce annual energy costs for public institutions by up to 60% compared to previous heating methods.

3.2. Social perceptions

Representative survey data (n = 189) provide insights into how residents and institutional stakeholders perceive biomass energy adoption. The most striking result is that 100% of the respondents use firewood as their primary heating source, indicating a complete dependence on traditional biomass. This finding

underscores a unique homogeneity in rural heating practices, which is rarely observed even in Central and Eastern European contexts. Despite the availability of alternative fuels, the absence of diversification highlights both the cultural persistence of wood use and limited access to novel energy infrastructure (*Figure 1*). This provides an empirical basis for exploring energy poverty, transition barriers, and decarbonization in rural communities [29].



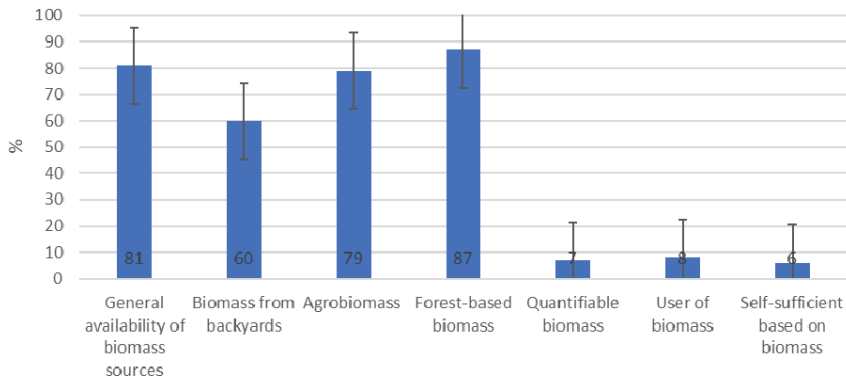
Source: authors' compilation

Figure 1. Share of heating sources in Ghelintă

Although 81% of respondents are aware of the existence of local biomass waste, only 8% currently utilize biomass for energy purposes. This contrast between knowledge and adoption demonstrates a significant implementation gap – a critical insight for policy and rural development strategies.

Furthermore, 87% recognize forest residues and 79% agricultural by-products as potential sources, revealing a latent RES base that remains underexploited. This supports a novel argument that awareness alone does not ensure behavioural change in RES adoption – a key theme in energy sociology and environmental psychology (*Figure 2*).

Nearly half of the respondents (48%) perceive biomass as cheaper or somewhat cheaper than other fuels, yet only 6% believe it could fully cover the community's energy demand. This reflects a mixed perception of cost-effectiveness and scepticism towards self-sufficiency, suggesting that economic optimism coexists with doubts about scalability. It demonstrates that perceived feasibility, not just affordability, shapes acceptance of community-based energy systems – a concept valuable for renewable energy policy design. This finding answers RQ2 by confirming that cost savings and energy independence are the dominant perceived benefits.



Source: authors' compilation

Figure 2. Availability and share of biomass users in Ghelintă

While 28% would financially support a communal biomass heating system and 60% would consider it depending on costs, this indicates a high potential for collective action – contingent on transparent and affordable financing.

Moreover, 86% of the respondents believe that community energy self-sufficiency is important or very important, reflecting a broad social mandate for sustainable local energy initiatives. This offers strong empirical evidence for community energy governance models and highlights economic trust as a determinant of collective investment behaviour.

Cross-tabulated data show that among those aware of local biomass resources, 61% would be willing to use biomass energy compared to a much lower proportion among the uninformed group. This statistically relevant association illustrates that informational awareness directly influences adoption willingness, identifying education and outreach as high-impact policy levers. It introduces a measurable link between informational capital and behavioural readiness in rural renewable energy transitions.

Although 37% of households earn over 7,000 RON/month, nearly 25% spend more than 500 RON/month on heating, suggesting a disproportionate financial burden for a subset of the population. This reinforces concerns about energy inequality and vulnerability to fuel price fluctuations, particularly in single-fuel systems reliant on firewood. It highlights energy justice dimensions in biomass-rich communities – a growing topic in sustainable development research.

When assessing barriers, the dominant constraint is financial: 75% of participants point out high investment costs as a major obstacle, 36% mention technological challenges, 25% note limited resource availability, and 28% point to a lack of technical expertise. This indicates that although biomass systems enjoy broad conceptual support, their practical implementation depends heavily on financial

and capacity-building measures. In this section, research objective 3 – to identify technical, regulatory, economic, and social barriers to adoption – was realized.

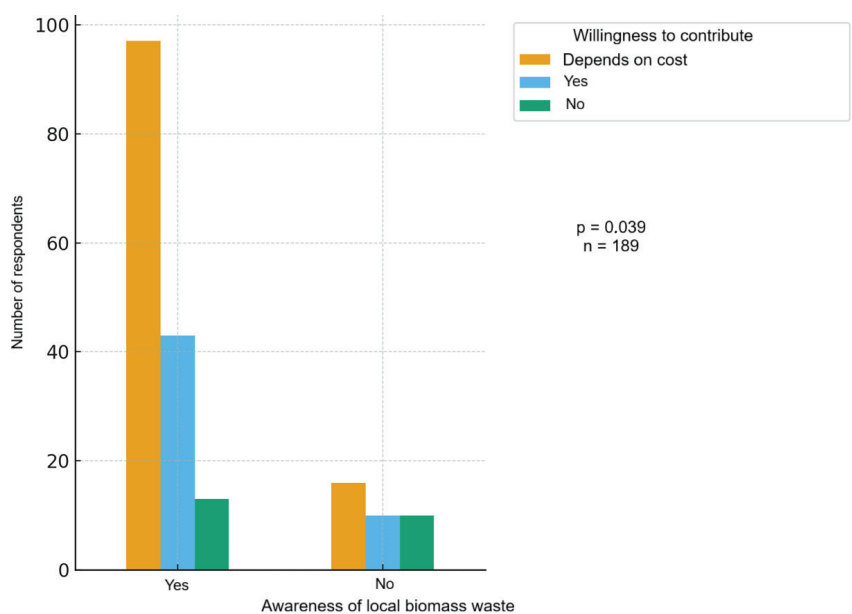
Policy preferences further reinforce this point: 82% of the respondents advocate for state subsidies as the most crucial support mechanism, followed by vocational training programmes (37%) and technology development grants (26%). Only 19% favour preferential loans, reflecting a cautious attitude towards debt financing. These findings suggest that effective biomass deployment in rural areas will require targeted public support to reduce upfront costs and fortify local technical skills.

The results of the Chi-square test indicate a statistically significant association between respondents' awareness of local biomass waste and their willingness to financially contribute to the establishment of a community biomass heating system ($\chi^2 = 6.474$, $df = 2$, $p = 0.039$). This finding suggests that a higher level of awareness regarding locally available biomass resources is linked to a greater propensity to support, or at least conditionally support, community-level renewable energy initiatives.

Respondents who demonstrated awareness of biomass potential were more likely to express willingness or conditional willingness ("depends on cost") to contribute financially, while those lacking such awareness exhibited a higher proportion of outright refusal. The clustered bar chart further visualizes this relationship, illustrating that biomass-aware individuals display a notably higher inclination towards supportive or conditionally supportive attitudes, whereas respondents without biomass awareness tend to be less supportive overall.

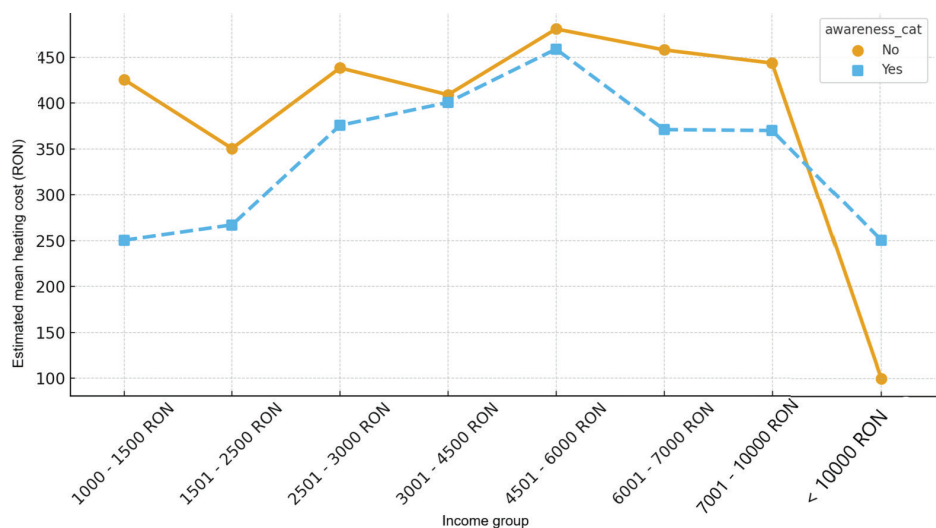
The results underscore the importance of informational and educational interventions aimed at enhancing public understanding of local RES, as awareness appears to play a pivotal role in shaping community acceptance and financial engagement in sustainable energy projects (*Figure 3*).

The two-way factorial ANOVA ($\text{heating_cost_num} \sim C(\text{income}) \times C(\text{awareness_cat})$) revealed a significant main effect of income group on monthly heating cost ($F(7,173) = 3.88$, $p < 0.001$) and a significant main effect of biomass awareness ($F(1,173) = 6.24$, $p = 0.013$) but no significant interaction between the two factors ($F(7,173) = 0.61$, $p = 0.744$). Mean heating expenditures increased progressively with income, ranging from approximately 270 RON/month among respondents earning below 1,500 RON to over 460 RON/month in the 4,501–6,000 RON category. Across nearly all income strata, participants aware of local biomass waste sources reported heating costs that were 8–15% lower than their non-aware counterparts. The interaction plot confirmed a parallel pattern between awareness groups, indicating that biomass awareness consistently lowers heating costs across income levels without modifying the income/cost gradient. This pattern implies an additive main effect, whereby informational or behavioural awareness contributes independently to reduced heating expenditures, regardless of household income (*Figure 4*). With this subchapter, research objective (2) to examine residents' knowledge, awareness, and perceptions was realized.



Source: authors' compilation

Figure 3. Willingness to contribute to biomass valorization



Source: authors' compilation

Figure 4. Interaction of income group and biomass awareness concerning mean monthly heating costs

3.3. Qualitative results

Institutional innovation and the local adaptation of biomass energy systems

The interviews with municipal decision-makers revealed that the introduction of biomass-based heating in Ghelintă represents a locally adapted institutional innovation, emerging from a combination of resource constraints, transnational learning, and targeted financial support. As the mayor explained, the absence of natural gas infrastructure and the loss of approximately 3,000 hectares of communal forest after border reallocation created a structural dependence on external energy sources. Joining the Bioenergy Village Horizon 2020 Project in 2016 provided both technical exposure and legitimacy for experimenting with renewable heating alternatives. The municipality, in collaboration with experts from Green Energy Cluster and the local Incubator House, successfully mobilized 260,000 euros from the Norwegian Fund, enabling the installation of three modern biomass boilers. The transition led to an estimated 60% reduction in public heating expenditures while maintaining stable heat supply across all public institutions. This transformation demonstrates how rural municipalities can strategically leverage external funding and local waste resources to achieve both energy cost efficiency and environmental sustainability.

Socio-technical diffusion and behavioural acceptance of biomass heating

Stakeholder narratives indicated that the diffusion of biomass-based heating in Ghelintă was initially hindered by local scepticism and cultural attachment to traditional firewood. As several respondents noted, early perceptions framed biomass as “dirty fuel”, unsuitable for domestic use. However, over time, the visible economic and functional advantages – particularly automated operation, lower fuel prices, and reduced manual labour – catalysed a process of behavioural acceptance and technological trust. As a result, several local SMEs, bakeries, and guesthouses transitioned to biomass boilers, and even private households began to adopt the technology. The municipality’s strategy of demonstrating tangible cost savings in public institutions played a pivotal role in normalizing biomass as a viable energy source. This reflects a broader socio-technical dynamic in which economic rationality, rather than purely environmental motivations, acts as the dominant driver of renewable energy adoption in rural contexts.

Capacity building, educational spillovers, and regional policy implications

The interviews also uncovered substantial educational and capacity-building effects stemming from the biomass initiative. The school director highlighted

how the heating system not only reduced operational costs but also enhanced students' environmental literacy through experiential learning projects on RES and sustainability. The system's operation revealed secondary technical challenges – such as outdated radiators unable to fully utilize the boilers' high thermal output –, demonstrating that technological modernization requires systemic infrastructure compatibility. From a governance perspective, both the vice-mayor and the project initiator emphasized that local biomass utilization reduces dependency on external fuel markets and fosters regional energy autonomy. However, they also stressed the need for institutional and financial support mechanisms at national and EU levels to replicate this model elsewhere. Overall, the Ghelintă case exemplifies how a rural community, through coordinated institutional action and translocal knowledge transfer, can establish a scalable model of decentralized, low-carbon energy governance that integrates environmental, economic, and educational dimensions. Thus, RQ3 is addressed: high upfront costs, technical gaps, and regulatory hurdles emerge as the central barriers.

3.4. Technical and economic analysis

Ghelintă commune's biomass heating infrastructure demonstrates a high degree of technical maturity. The system is centred on automated heat plants equipped with modern woodchip boilers operating within the 50–250 kW range, tailored to institutional heat demand. The boilers utilize standardized G30 dry coniferous biomass with a combustion efficiency of 85–90%, which is comparable to advanced European biomass technologies (*Table 5*).

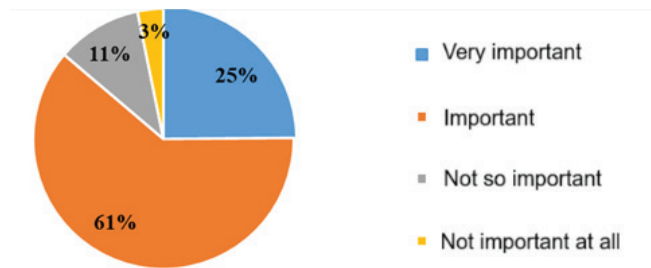
Automation represents a major technical advantage: fuel feeding, temperature regulation, and safety controls operate autonomously, requiring minimal human supervision. Each installation includes integrated fire prevention systems, flame and temperature sensors, and screw-type feeding mechanisms that ensure steady and controlled combustion. The thermal energy produced is transferred through heat exchangers connected to institutional heating networks, with thermostatic regulation optimizing energy use.

A defining advantage of Ghelintă's biomass system lies in its integration with local resource cycles. The successful implementation of biomass-based energy systems in Ghelintă has been strongly linked to the degree of community support for local energy self-sufficiency. Survey results indicate that 25% of the respondents consider community-level energy independence very important, while 61% rate it as important. Only 11% regarded it as not particularly important, and 3% deemed it not important at all. These findings demonstrate that the overwhelming majority (86%) of the residents attach great importance to local energy autonomy and decentralized energy production (*Figure 5*).

Table 3. Technical parameters of the analysed biomass heating infrastructure

Parameters	Cultural centre	Mayor's office	Primary school	Elementary school	Kindergarten	Medical centre	Bowling alley	Residential block	Sports hall	Total
Specific heat demand (m ³)	4.05	1.71	6.58	1.75	1.512	1.536	2.646	2.688	7.08	27.512
Nominal boiler capacity (kW)	142	77	329	61	53	54	106	108	227	1,080
Installed boiler capacity (kW)	150	100	250	60	60	50	100	100	150	1,020
Share of heat from biomass (%)	100	100	100	100	100	100	100	100	100	100
Flue gas outlet temperature (°C)	162	169	155	172	175	171	169	169	167	–
Flue gas loss (%)	12	12	10	13	13	13	12	12	10	–
CO ₂ emission (%)	1	20	9.89	12.6	12.6	12.8	30	10.35	9	–
NO emission (ppm)	61	62	58	65	64	66	62	63	61	–
Boiler energy efficiency (%)	89.52	85	87	85	85	85	86	86	89.92	–
Biomass storage capacity (days)	10	20	8	7	25	2	5	14	21	–
Fuel storage capacity (m ³)	50	78	70	32	70	8	26	68	115	–
Average annual operating hours (h/year)	1,450	2,180	2,150	2,165	2,143	1,990	1,660	2,080	1,535	–
Heating energy (MWh/year)	217.5	218	537.5	129.9	128.58	99.5	166	208	230.25	1,935
Electricity consumption (MWh/year)	1.45	6.54	6.45	1.99	3.32	1	1.66	2.3	4.61	35.72

Source: authors' compilation



Source: authors' compilation

Figure 5. Respondents' perception of the importance of community energy self-sufficiency (%)

Interviews made with municipal representatives and institutional stakeholders further revealed that active community participation played a decisive role in the acceptance and long-term functioning of the biomass heating system. Responses suggest a clear attitudinal link between sustainability orientation and support for local energy autonomy: those who consider environmental sustainability “very important” (25%) also overwhelmingly view community-level energy self-reliance as “very important”. This alignment between environmental values and local energy goals has created a strong social foundation for the successful operation of biomass-based district heating systems. Hence, research objective 4 – to evaluate the contribution of biomass systems to environmental, economic, and social goals – was realized.

Sustainable utilization of local biomass resources

An essential component of Ghelintă's energy independence is the sustainable and efficient use of locally available biomass resources. Based on field data and technical assessments, the average harvestable biomass yield is 18–20 m³/ha/year. The municipality currently utilizes approximately 278 ha of local forested, former pasture land for energy wood extraction annually, which results in an annual biomass output of about 144 m³ (8 ha × 18 m³/ha) (Table 6).

Considering that the total available biomass stock within the municipality is estimated at 5,400 m³, the current harvesting rate ensures a renewable supply capacity of approximately 38 years without depleting the resource base. This sustained yield scenario guarantees a long-term, stable, and environmentally sound heat supply for public institutions such as schools, kindergartens, the mayor's office, and healthcare facilities. Moreover, it minimizes dependence on external energy markets while fostering local economic resilience and rural development.

With this aspect, research objective 1 – to analyse the types of biomass feedstock available in the study area and their energy potential – was realized.

Table 4. Local energy self-sufficiency indicators

Parameter	Value	Explanation
Harvestable biomass per hectare	18 m ³	Average annual yield per hectare
Harvested area per year	8 hectares	Area utilized annually for energy wood
Annual biomass extraction	144 m ³	8 ha × 18 m ³ /ha
Total available biomass	5,400 m ³	Total local potential
Duration of self-sufficiency	≈ 38 years	5,400 m ³ ÷ 144 m ³ /year

Source: authors' compilation

3.5. Environmental impact assessment

The present study provides novel quantitative and qualitative evidence that community-scale biomass-based heating systems, when implemented with modern combustion technology and local feedstock sourcing, can substantially reduce carbon emissions and improve local environmental performance. Empirical data from Ghelinta municipality show that biomass-fuelled heating networks achieve average boiler efficiencies between 80 and 89% while maintaining low CO₂ concentrations (≈ 1%) and moderate NO₂ emissions (58–66 ppm). When compared to fossil-based systems, results demonstrate an 85–90% reduction in annual CO₂ emissions, highlighting the environmental effectiveness of biomass conversion technologies in rural communities. These findings advance theoretical assumptions by providing site-specific evidence on emission reduction potential and operational performance under real conditions, supported by direct measurements from nine public buildings (*Table 5*).

A key novel result lies in the integrated environmental balance assessment that connects technological parameters (flue gas losses, efficiency, NO₂ levels) with life-cycle implications such as transportation emissions, local resource circularity, and community perception. The study identifies that flue gas losses of 10–13%, observed across the monitored heating facilities, still offer measurable room for optimization via heat exchanger integration, which could further enhance overall system efficiency and reduce energy waste. Moreover, the exclusive use of locally sourced biomass residues – including forestry and agricultural by-products – significantly reduces transportation-related greenhouse gas emissions and supports the circular economy. These empirical findings substantiate that biomass systems not only minimize direct air pollution but also foster regional carbon neutrality, resource efficiency, and socio-environmental resilience.

Table 5. Annual CO₂ eq. t/year emissions and energy capacity of public buildings

Facility/ building	Cultural centre	Mayor's office	Primary school	Elementary school	Kindergarten	Medical centre	Bowling alley	Block of flats	Sports hall	Total
Installed capacity (kW)	150	100	250	60	60	50	100	100	150	1,020
Thermal energy (MWh/year)	300	200	500	120	120	100	200	200	300	2,040
Natural gas heating (0.202 kg CO ₂ /MWh)	60.6	40.4	101	24.24	24.24	20.2	40.4	40.4	60.6	412.08
Firewood (MWh/CO ₂)	12.75	8.5	21.25	5.1	5.1	4.25	8.5	8.5	12.75	86.7
Wood chips (MWh/CO ₂)	7.5	5	12.5	3	3	2.5	5	5	7.5	51

Source: authors' compilation

The research also contributes new insights into the social and ecological sustainability dimensions of biomass utilization. Survey results reveal a high degree of public environmental awareness (79%), indicating strong local support for biomass-based solutions as tools for emission reduction and sustainable energy transition. However, the study also emphasizes the potential ecological risks – such as biodiversity loss and soil erosion – associated with intensive biomass extraction, underscoring the necessity of regulated forest management and responsible harvesting limits. The demonstrated correlation between community sustainability values and energy self-sufficiency introduces a novel socio-environmental linkage rarely quantified in previous regional energy studies. Overall, the findings position the Ghelinta biomass initiative as a scientifically validated example of low-carbon rural energy transformation, offering both practical data and conceptual frameworks for future sustainable energy policies. In this subsection, research objective 5 – to derive policy recommendations for fostering uptake within the EU/Romanian energy transition context – was fulfilled.

Together, these results address RQ4 and RQ5, confirming that cost perceptions strongly influence adoption and that local installations deliver measurable economic and environmental benefits in line with community expectations.

3.6. Reflection on the hypotheses

Empirical results confirm most hypotheses. H1 is validated: residents acknowledge biomass potential but lack technical expertise, limiting adoption. H2 is partially supported: sustainability values influence acceptance but remain secondary to financial concerns. H3 is strongly confirmed, as cost savings dominate motivation. H4 is supported, showing that municipal leadership and institutional savings foster acceptance. H5 is also validated: the availability of local woodchips enhances feasibility and positively moderates residents' willingness to adopt biomass solutions.

4. Conclusions

This study systematically addressed its five research questions and objectives through a mixed-methods investigation of biomass adoption in Ghelintă, Romania. Results demonstrate that while residents show a strong familiarity with traditional firewood, the technical knowledge of alternative feedstocks such as agricultural residues, communal waste, and energy crops remains limited. Economic considerations – particularly cost reduction and independence from external suppliers – emerge as the dominant perceived benefits, with environmental gains recognized but less influential.

The analysis identified high investment costs, limited expertise, and regulatory complexity as the principal barriers to adoption. Nevertheless, technical assessments of local biomass boilers confirm high efficiency, substantial CO₂ reduction, and strong alignment with community perceptions of cost savings even though scepticism about full energy self-sufficiency persists. Together, these findings support the proposed hypotheses: economic and institutional factors exert the greatest influence on adoption, while sustainability values and feedstock accessibility function as secondary but relevant moderators.

Policy preferences highlight a clear demand for targeted public intervention. State subsidies, vocational training, and technology development support were strongly favoured, whereas debt-financing mechanisms such as preferential loans were less attractive. These findings suggest that effective biomass deployment in rural Romania will require lowering financial barriers and strengthening local technical capacity through dedicated public support.

The study highlights that the respondents value economic security and convenience, while ecological concerns remain secondary but growing. If

financial and technical barriers are reduced, support for biomass shifts towards sustainability-driven motivations.

Beyond immediate household benefits, biomass systems generate long-term community value. Local fuel production supports stable employment, stimulates auxiliary economic sectors, and enables municipalities to reinvest savings into public services, thereby enhancing fiscal resilience and social cohesion. The Ghelintă case demonstrates that decentralized renewable energy systems can deliver both technical and social benefits when rooted in local resource management and strong community engagement.

Evidence from Ghelintă shows that rural energy independence is as much social and institutional as it is technical. Leveraging renewable biomass resources, community trust, and institutional innovation, the municipality has built a replicable model of decentralized, low-carbon energy governance. These findings offer practical guidance for policymakers aiming to scale similar rural initiatives across Europe, where local resource potential and social acceptance are key to advancing the energy transition.

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