

Article

Engineering Architectures of Decentralized Energy Islands Based on Circular Bioenergy Models in Ukraine

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Abstract

Ukraine's energy strategy under martial law necessitates decentralized local energy systems to counter electricity shortages and systemic infrastructure failures. The study develops and validates an optimization model for designing the architecture of decentralized "energy islands" based on circular bioenergy models for agricultural waste use. Empirical verification was conducted using data from the Vinnytsia region in Ukraine. The model accounts for a multi-level structure that separates micro/small generation (0.1–2.0 MW) from medium generation (1–20 MW) based on the logistical radius for raw material collection. The model incorporated the Value of Lost Load (VLL), enabling the monetization of avoided socio-economic losses from energy shortages. In addition, the coefficient of energy island sustainability (I_{sred}) was introduced to quantitatively assess the effectiveness of investments in terms of replacing external resources. The modeling revealed the nonlinear nature of the total cost function, enabling us to determine an optimal energy-autonomy range of 40% to 50% for communities. At this threshold, the total construction and logistics costs are minimized. The potential socio-economic losses from blackouts are effectively mitigated, as confirmed by the calculated sustainability coefficient (I_{sred}), which ranges from 0.78 to 0.94 across the studied communities. The resource potential assessment confirms that the region's total potential is approaching 30 million tons of oil equivalent, driven by solid biofuels, agricultural residues, and energy crops (miscanthus, switchgrass). The classification of biomass supply chains shows that exceeding the transportation radius by more than 70 km at the meso level, or deviating from the optimal logistics lever by 20%, reduces the profitability of projects below the critical limit of 15%, which justifies strict localization within raw-material clusters. This enables local communities to eliminate natural gas consumption, reduce energy supply operating costs by 15%, and ensure the autonomous and stable operation of critical infrastructure facilities during prolonged disruptions to the national power grid.

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1. Introduction

Ukraine’s energy strategy under the conditions of martial law and post-war reconstruction tasks justifies the critical need to transition from vulnerable centralized hierarchical networks to decentralized local energy systems based on the resource potential of territorial communities. The leading role in this transformation belongs to bioenergy technologies, which are integrated into circular economic models through the highly efficient conversion of agricultural biomass and phytoenergy resources into renewable electrical and thermal energy. The concept of a decentralized “energy island” allows for ensuring the functional autonomy of critical infrastructure facilities, minimizing systemic socio-economic risks and creating fundamental prerequisites for decarbonization and sustainable endogenous development of rural areas.

A local energy cluster is an integrated network that unites producers, consumers and engineering energy storage systems. Thanks to the use of “smart grid” technologies, the system is able to balance supply and demand in real time and create a kind of “energy island” based on the territorial community. The systematic combination of the assessment of local bioenergy potential with the development of adaptive investment models and intelligent Smart Grid management systems creates the necessary basis for the transformation of the energy sector of territorial communities on the principles of a circular economy. As a result, the proposed architecture not only ensures a high level of autonomy of critical infrastructure in the face of external destabilizing factors, but also acts as a strategic tool for sustainable socio-economic development and environmental security of regions in the context of the post-war reconstruction of Ukraine.

The creation of bioenergy clusters for the production of energy carriers in territorial communities is a strategically necessary step to ensure energy independence and environmental security.

1.1. Conceptual Foundations of the Circular Energy Model

The traditional energy model is linear: the community purchases a resource from outside, consumes it, and disposes of by-products (waste and emissions) [1]. Instead, the circular model of the local cluster should be based on closing cycles. The main source of energy is local renewable resources: solar radiation, wind power, and, most importantly for the circular economy, organic waste from agriculture or woodworking. The conversion of waste into biogas or thermal energy allows the community to simultaneously address waste disposal and reduce the cost of heating municipal facilities (Table 1).

Table 1. System model of a local community energy cluster.

Analysis Area	Key Characteristics and Components	Role in the Circular Economy
Resource base	Local renewable energy sources (sun, wind), biomass, agricultural waste, wastewater, excess heat from enterprises	Closing the loop: converting waste into an energy resource, minimizing losses during transportation.
Technological block	Solar and wind parks, biogas plants, heat pumps, storage systems (ESS), Smart Grid.	Efficiency: optimal use of each unit of energy produced through “smart” distribution.
Economic model	Energy cooperatives, municipal-private partnership, prosumerism	Capital retention: money remains within the community, creating an internal investment resource.

Impact of educational institutions	Scientific support, energy audit, training, creation of “living laboratories”	Intellectual cycle: continuous technology renewal and personnel support for the sustainability of the model.
Environmental impact	Reduction in greenhouse gas emissions, reclamation of landfills, reduction in thermal pollution.	Regeneration of the natural environment through reduction in man-made load.
Social aspect	Creation of new jobs and ensuring energy security, development of a culture of thrift towards energy carriers	Stimulation for improving the quality of life and social cohesion of the community around common interests.

Source: based on [1].

The key element of the model is the transformation of waste into an energy resource, which allows for closing the cycles of production and consumption within the community. This approach provides a double effect: on the one hand, the ecological pressure on the environment is minimized and the problem of waste disposal is solved, and on the other hand, the financial autonomy of the community is formed through the development of the energy cooperative movement and prosumerism. Thus, the circular model becomes the foundation of energy security and a catalyst for sustainable socio-economic development of territories.

1.2. Literature Review and State of Scientific Development of the Problem

1.2.1. Investment and Economic Aspects of Community Energy Autonomy

An important aspect of implementing the “energy island” strategy is the transformation of approaches to attracting capital to rural areas, which are the main suppliers of bioresources. The investment attractiveness of rural areas under martial law directly depends on the ability of local communities to form a safe environment for capital [2]. This confirms the view that investments in biofuel generation should be considered as a tool for capitalizing territorial communities.

At the same time, the success of the “green” reconstruction of Ukraine’s energy sector is impossible without adhering to clear environmental guidelines. Study [3] emphasizes that “the post-war recovery of Ukraine should be based on the principles of a “green” economy, where investments should work not only to restore capacity, but also to introduce innovative technologies that meet European energy efficiency standards”.

The institutional readiness of territorial communities for such transformations is closely related to the effective management of secondary resources. In accordance with previous studies [4], it has been determined that building institutional capacity in the field of waste management as a secondary resource is the foundation for Ukraine’s European integration and the transformation of environmental challenges into energy assets.

At the same time, studies [5] emphasize that the decentralization reform under martial law is faced with the need to quickly adapt management decisions to the realities of energy shortages, where the community is transformed from a management object into an active subject of the energy market.

When considering financial barriers and price fluctuations in the energy market, it is advisable to take into account the position of [6] which justifies that effective regulation of prices for fuel and energy resources is a key tool for strengthening energy security in times of crisis transformations.

1.2.2. Technological and Resource Aspects of Bioenergy Clusters

The introduction of biofuel generation within local clusters based on territorial communities corresponds to global trends described in study [7], which emphasize that the development of bioeconomy opens up new opportunities for the formation of sustainable

development, since the transition to bioresources allows for replacing traditional fuels and creating closed cycles of electricity production, which is critically important for global ecological balance.

When assessing the environmental impact of a community's economic growth through energy autonomy, it is worth turning to the methodology of using the decoupling effect [8], which, according to the authors, allows for objectively determining the degree of decoupling between the pace of economic development and the level of technogenic load on the environment, which is a necessary indicator when assessing the effectiveness of "green" investment projects.

At the same time, for the practical implementation of the bioenergy potential of territorial communities in the regions of Ukraine, the choice of a stable raw material base is of critical importance. As noted in previous work [9], the study of the adaptive properties of energy crops under different growing conditions allows for predicting stable biomass yields, which is a necessary foundation for the smooth functioning of local "energy" islands and minimizing the risks of fuel dependence.

However, it is worth noting that the formation of the architecture of the "energy island" should be based on the best global practices adapted to Ukrainian realities. In this context, the study [10] states that international experience confirms the effectiveness of decentralized models of energy supply to rural areas, where the combination of municipal initiatives and private capital creates an effective mechanism for achieving complete energy independence of communities.

Economic recovery of the agricultural sector under conditions of martial law is impossible without a systemic approach to investment. According to research [11], the investment attraction strategy should be integrated into the general plan for the development of rural areas, where the creation of alternative generation facilities acts not only as a technical task, but as a key factor in restoring the capitalization of the agro-industrial complex.

To conclude the analysis of the institutional and theoretical basis of the "green" transition of communities of territories in general, it is important to take into account the results of research [12], which consider the transition to a "green" economy not just as an environmental initiative, but as a mandatory prerequisite for the sustainable development of territories.

In the context of achieving climate neutrality and building a "green" economy, the technological closure of waste disposal cycles is of particular importance. Research [13] substantiates that the production of biogas and biomethane from organic waste is not only a tool for decarbonization, but also a critically important element of sustainable development, which allows communities to transform environmental challenges into energy assets, while ensuring a high level of autonomy.

Analysis of the dynamics of the industry directly under the conditions of armed aggression allows us to identify new vectors of development. As noted in [14], the development of biofuel production in Ukraine during martial law acquired a strategic status, since local generation becomes an alternative to traditional energy carriers, allowing for diversifying sources of supply and increasing the energy sustainability of rural areas and industrial enterprises in critical periods.

1.2.3. Innovative Technologies and Management Systems in Energy Clusters

Complementing the analysis of the resource provision of "energy islands", it is worth paying attention to the results of the study [15], which state the need to solve the problem of energy shortage in territorial communities.

The technological aspect of the stability of such systems is detailed in work [16] where, using the example of corn silage, it is proven that the kinetics of anaerobic diges-

tion directly depends on the biochemical composition of the raw material. This emphasizes the need for accurate engineering calculations when designing biogas plants for “energy islands”. At the same time, the systematic assessment of biofuel production within crop rotations and the use of organic residues, presented in previous studies [17], confirms that rational management of agricultural technologies allows for maximizing energy output without compromising food security.

The effectiveness of the functioning of decentralized architectures critically depends on the implementation of innovations. As the authors note in [18], stimulating the implementation of new technologies and improving environmental management through the prism of the circular economy is a mediator of sustainable development of territories. Moreover, the search for new energy sources for local networks is not limited to biomass. At the same time, research [19] demonstrates the potential of using piezoelectric energy harvesting systems, which can become an additional element of “smart” buildings as part of an energy cluster.

The assessment of the potential of agricultural biomass as a sustainable source of biofuel, carried out in [20], allows us to classify communities according to their level of energy security. In turn, methodological approaches to predicting the yield of biofuel crops in Ukrainian conditions, outlined in study [21], create the basis for long-term planning of the energy balance of territories.

The practical implementation of circular models in rural areas is supported by research on the use of individual biogas plants for processing household waste [22]. This proves that the “energy island” can have a multi-level structure—from a separate farmstead to a large municipal cluster. Strategic management and assessment of security risks of such systems, as noted in the study [23], is a basic condition for the sustainability of urban and rural energy hubs.

The role of dynamic environments and the adaptability of circular economy business models are emphasized in work [24], which proves that ecological dynamism requires communities to be flexible in asset management. Finally, the safety of energy equipment operation and its technical conditions, analyzed in study [25], are the key to sustainable energy security, based on an integrated assessment of industrial and local generating capacities.

1.3. Purpose and Objectives of the Study

The purpose of this study is to develop and verify economic and mathematical tools for optimizing the level of bioenergy autonomy of territorial communities by forming local “energy islands” based on agricultural waste.

To achieve this goal, the following specific tasks have been defined:

- To assess the regional potential for biofuel production, taking into account the specifics of the agricultural sector of the studied region.
- To formulate an economic and mathematical objective function for minimizing total costs and losses to determine the optimal limits of energy self-sufficiency of communities.
- To substantiate the architecture of logistical and engineering solutions for the functioning of local bioenergy systems.
- To carry out empirical verification of the developed model on the example of a real agro-industrial cluster

2. Materials and Methods

Modern challenges caused by martial law and chronic energy shortages force us to fundamentally reconsider outdated approaches to energy supply of territorial communities. The traditional logic, which was focused exclusively on finding the cheapest kilowatt-

hour, no longer meets the realities of security. Today, we propose to shift the focus to creating an “energy island” model. In this system, the main criterion for success is not just financial savings, but strategic resilience—the ability of people and businesses in the community to continue living and working even under conditions of complete autonomy.

The main goal of our methodology is to find the optimal balance between external power grids and our own energy production from biofuels. We strive to transform the community from a passive consumer, completely dependent on external circumstances, to an active and self-sufficient system.

To take into account the real bioenergy potential of each territory, we have developed an economic and mathematical model that divides generation facilities into two key levels:

1. Small generation (capacity up to 1 MW)—a segment focused on the concept of individual self-sufficiency. We calculated that for such facilities, the optimal radius of raw material collection (crop residues or household waste) should not exceed 10 km. This approach allows the community to find an energy resource practically “under its feet”, minimizing transportation costs and at the same time solving the problem of local garbage.

2. Medium generation (from 1 to 20 MW)—facilities such as powerful biogas plants or bio-CHP plants are considered by us as strategic capital of the entire community. The proposed methodology helps to find the best location for them, taking into account the logistical “shoulder” of biomass delivery within 10 to 15 km. This allows for the creation of a stable energy hub capable of powering social facilities and local enterprises. The objective function of the model (Z) is focused on minimizing total costs, taking into account the risk component and the effect of loss prevention:

$$Z = \sum(C_{gen} + C_{log} + CAPEX_{risk}) - VoLL \rightarrow \min \quad (1)$$

where C_{gen} —energy generation costs; C_{log} —bio-raw material logistics costs; $CAPEX_{risk}$ —capital expenditures adjusted for the war risk factor; and $VoLL$ (Value of Lost Load)—the cost of “unsold energy”, which reflects the socio-economic losses of the community in the event of an energy outage.

It is pertinent to observe that the range of 1–20 MW corresponds to the classification of distributed generation in the general energy network according to the regulatory framework of Ukraine. However, for agricultural decentralized biogas systems, the upper limit of 20 MW is critically excessive, since the creation of such a massive industrial facility (such as, for example, the Ladyzhyn biogas complex in Vinnytsia region—Separate Subdivision “Biogas Ladyzhyn” of Limited Liability Company “Vinnytsia Poultry Farm”, Ukraine) requires a transport radius of biomass delivery of tens or hundreds of kilometers, which destroys logistical profitability and the idea of local autonomy. Therefore, within the framework of the developed concept of “energy islands” of territorial communities, the emphasis is shifted to micro- and small-scale decentralized generation (from 0.1 to 1.5–2.0 MW). This allows for limiting the logistical radius of agricultural waste collection within 10–15 km, which fully corresponds to the objective function of cost minimization Z given in the work.

When building the “energy island” model, we pay special attention to the structure of the fuel base, since it is a reliable raw material base that determines the viability of the entire system. The system of constraints we have developed is not just a set of mathematical formulas, but a reflection of the real living conditions of the community. It includes resource parameters that take into account the volume of available biomass, taking into account its seasonality, technical characteristics of the throughput of local networks and complex logistical routes.

The implementation of the results of this modeling allows the territorial community to confidently move to the architecture of an autonomous “energy island”. In such a structure, the share of its own generation in the total energy balance is calculated in such a way

as to guarantee the coverage of most of the needs of critical infrastructure facilities, such as hospitals or water supply systems.

The choice of the Vinnytsia region as an object for empirical verification of the developed model is due to its role as a strategic regional reference point and a baseline with the highest bioenergy potential in Ukraine. Numerous studies confirm that the region is an absolute leader in terms of agricultural production volumes, agribusiness density and biomass concentration [26–30].

The presence of a powerful sugar beet cluster, developed industrial crop production and livestock breeding creates a unique, maximally saturated raw material base. Thus, the choice of this region allows for testing the operability of the economic and mathematical model of “energy islands” in optimal high-performance conditions, forming a reference matrix of decentralized energy supply for further scaling in other regions of Ukraine.

The implementation of a strategy aimed at minimizing total costs within the proposed objective function becomes possible only if a number of critical parameters are strictly observed. These indicators determine the limits of the physical and economic capacity of the entire energy system. In view of this, we supplemented the mathematical apparatus of the model with a system of boundary constraints that take into account the agricultural specifics of Vinnytsia, the capacity of engineering networks and existing logistical barriers. A detailed systematization of these constraints, as well as an analysis of their direct impact on the sustainability of the local energy system of the community, are presented in Table 2.

Furthermore, the bioethanol potential was calculated from sugar beet waste (molasses) and grain surpluses, biodiesel from rapeseed waste, and solid biofuel from corn/sunflower straw and stalks, which are included in the gross crop harvest described in the methodology.

Table 2. The system of model boundary constraints and their impact on the community’s energy balance parameters.

Type of Restriction	Model Parameters for Vinnytsia Region	Researched Impact on System Sustainability
Resource (Raw materials)	Arable land: 15–20 thousand ha; availability coefficient (η): 0.3–0.7	Defines the physical limit of biofuel facilities’ capacity; ensures environmental safety of soils through controlled removal of residues.
Balance (Energy)	Forecast demand (D): 100%; reserve coefficient (k): 0.2–0.3	Ensures uninterrupted power supply to critical infrastructure and eliminates VoLL losses during peak loads.
Logistics (Transport)	Micro-level: $R \leq 10$ km; Meso-level: $R \leq 70$ km	Limits the growth of Clog costs; when the radius is exceeded by 20%, the project’s profitability falls below the critical level of 15%.
Risk (Capital)	Risk coefficient (β): 0.15–0.25	Forms a financial buffer for projects in areas of potential instability, which allows avoiding liquidity shortages.

A systematization of these constraints and an analysis of their direct impact on the sustainability of the local energy system of a typical community in the region are presented in Table 3.

Table 3. Comparative characteristics of community energy supply scenarios.

Model Level	Fuel Type	Radius (R), km	Energy Output (Gcal/year)	Gas Substitution Potential, %	Stability Coefficient (Rindex)
Small (micro)	Straw, pellets, garden waste	0–10	4500	12–15	0.85
Medium (meso)	Biogas (silage + manure), wood chips	10–40	18,000	35–40	0.92
Regional	Biomethane, energy crops	40–70	45,000	20–25	0.70

In the initial state of complete dependence on external networks, the community bears critically high costs for energy security, estimated at forty-five million hryvnias annually; however, the implementation of even the first ten to twenty percent of biofuel generation allows for radical reduction of these risks with a relatively short payback period of investments, not exceeding three-and-a-half years.

Achieving the economic optimum zone at forty percent ensures the minimization of the objective function of total costs to the level of thirty-eight point three tenths of a million hryvnias, since it is at this stage that the maximum balancing of growing capital expenditures and the rapid decline in the price of energy risk occurs.

Further increasing the share of biofuels to 50% allows for stabilization of the system and ensures its strategic sustainability with a payback period of 5.2 years, which is the optimal indicator for municipal energy projects of medium-term planning.

At the same time, we consider it appropriate to systematize the algorithm of economic and mathematical modeling based on the description of the stages (Table 4).

Table 4. Algorithm for conducting economic and mathematical modeling of the community's energy balance.

Modeling Stage	Description of the Content of the Work and the Sequence of Actions	Stage Result
1. Diagnostics and profiling of energy consumption	At the initial stage, data on the actual consumption of electricity and heat energy by a typical community of Vinnytsia region is systematized, with special attention paid to identifying the critical load of social and engineering infrastructure facilities.	Formation of a baseline energy demand profile and determination of parameters for calculating the VoLL indicator.
2. Resource inventory of biofuel potential	The second stage involves conducting a detailed audit of available bioresources in the agricultural sector within the specified logistics radii (10 km for small and 70 km for medium generation), taking into account the energy density of the raw material and the coefficients of its seasonal availability.	Estimation of the gross and technically available volume of local energy resources to replace imported fuels.
3. Iterative calculation of the objective function	The modeling process proceeds to multiple calculations of integral costs (Z) for scenarios with a step increase in the share of own generation of 10%, which allows for comparing the dynamics of capital investment growth with the rates of reduction in the cost of energy risks.	An array of calculated data reflecting the correlation between the level of autonomy and the total costs of the community.
4. Optimum search and stability verification	The obtained curves are analyzed to identify the financial and energy break-even point, where total costs are minimized and the payback period of projects remains within the investment attractiveness for the municipal sector.	Justification of the optimal share of biofuel generation at the level of 45–55% for creating an “energy island”.

The proposed algorithm is based on an iterative approach that provides a consistent transformation of the initial statistical data on the resource potential of the Vinnytsia re-

gion (or other regions by analogy) into an applied model of energy security of the territory. The modeling process is initiated by the stage of accumulation of data on the energy intensity of critical infrastructure facilities, after which the information obtained passes through a filter of logistical constraints that determine the differentiation of small and medium generation facilities depending on the radius of transportation of bio-raw materials.

The algorithm guarantees a high level of scientific reliability of the results, as it allows for clearly verifying the boundary between the zone of effective autonomy and the area of excess investment. This makes it possible to identify a critical point after which further expansion of generating capacities loses economic feasibility and ceases to generate additional benefits for the community.

To ensure high accuracy of modeling and the possibility of scientific verification of the obtained results, a two-level system of transformation of primary data was used in the study. The transition from official statistical indicators of the gross harvest of agricultural crops and livestock to the volumes of the region's net energy potential was carried out using a system of technical and technological conversion coefficients. This approach allows for taking into account real limitations on biomass collection and the specifics of the yield of dry organic matter for different types of substrates.

The calculation was differentiated according to two key vectors of the formation of the raw material base of communities: crop and livestock waste.

For crop waste, the potential yield of by-products P_{crop} was calculated using the formula:

$$P_{\text{crop}} = V \cdot K_{\text{mp}} \cdot K_{\text{av}} \cdot K_{\text{dry}} \quad (2)$$

where V is the gross yield of the main crop (t); K_{mp} —the ratio of the main and by-products (for example, for eared cereals—1.0–1.2, for grain corn—1.3, for sunflower—1.9); K_{av} —the availability coefficient for harvesting (taken at the level of 0.6–0.8); and K_{dry} —the dry matter content in biomass [31].

For livestock waste, the output of excrement and the potential volume of biogas (P_{ls}) pozpax were calculated based on the average daily manure output per head:

$$P_{\text{ls}} = N \cdot q \cdot 365 \cdot K_{\text{met}} \quad (3)$$

where N is the number of animals (heads); q —the average daily manure yield per head (kg/day); and K_{met} —the coefficient of specific biomethane yield per ton of organic dry matter (according to standards for cattle, pigs and poultry). The energy potential is converted into TJ and million m^3 of natural gas equivalent using the lower heat of combustion of methane (35.8 MJ/ m^3).

The component of the model responsible for calculating potential economic losses from energy supply shortages (Z_{los}) is based on the concept of the value of expected undersupplied energy (Value of Lost Load—VoLL). The VoLL coefficient determines the number of financial losses of local consumers and critical infrastructure of the territorial community in the event of an emergency shutdown or blackout (calculated in euros or UAH per 1 kWh of unsupplied energy). Mathematically, the loss component looks like this:

$$Z_{\text{los}} = \Delta E \cdot \text{VoLL} \quad (4)$$

where ΔE —the amount of undelivered energy for the billing period (kWh).

At the same time, to verify the adequacy of the developed economic and mathematical model, we conducted calculations for three territorial communities with different types of economic specialization, which allowed us to take into account the variability of the resource base of the region. As part of the study, the author's coefficient of energy

island sustainability (I_{sred}), was introduced, which quantitatively describes the effectiveness of investments in decentralization through the prism of minimizing socio-economic losses of the community.

For an integrated assessment of the capital intensity of the formation of “energy islands”, an indicator of average specific investment capacity (I_{sred}) has been introduced. It reflects the efficiency of capital investments relative to the volume of substitution of external energy resources:

$$I_{sred} = \frac{\sum_{i=1}^n CAPEX_i}{\sum_{i=1}^n E_{bionet_i}} \quad (5)$$

where $CAPEX_i$ —the amount of investment in the creation of the i -th biogas or other bio-fuel production in the community; E_{bionet_i} —annual amount of clean energy generation (in equivalent) by the specified facility.

At the same time, an integral assessment of the total bioenergy potential was carried out by aggregating the calculated potentials of all types of primary agricultural substrates. To bring heterogeneous raw materials resources (solid biofuels, bioethanol, biodiesel, biogas/biomethane) to a single comparison system, their metric volumes were transformed into energy equivalents—terajoules (TJ) and tons of oil equivalent (toe) according to the formula:

$$E_{total} = \sum_{j=1}^m M_j \cdot LHV_j \quad (6)$$

where M_j —net available volume j -th type of biofuel (t or m^3), obtained based on formulas for calculating plant residues and animal excrement;

LHV_j —lower heating value for the relevant energy carrier according to international standards IEA (in particular: for biomethane—35.8 MJ/ m^3 , for straw—14.2 MJ/kg, for bioethanol—26.8 MJ/kg, and for biodiesel—37.2 MJ/kg).

3. Results

3.1. Analysis of Resource Supply and Logistics Chains for Biofuel Production at the Regional Level

The effectiveness of the implementation of small and medium biofuel generation in territorial communities directly depends on the stability and availability of the resource base, as well as on the optimization of the processes of its movement from the place of formation to the point of energy conversion. Under conditions of martial law, when traditional logistical routes for the supply of fossil fuels are vulnerable or destroyed, the development of local value chains based on biomass becomes strategically important for ensuring the survivability of critical infrastructure of communities.

The analysis of resource provision at the local level requires an integrated approach, which involves assessing the theoretical, technical and economic potential of biomass (agricultural waste, forestry residues and the organic fraction of municipal waste). At the same time, the logistics component is a key factor in the competitiveness of biofuels, since the low energy density of raw materials (especially solid crop residues and raw organic matter for biogas) limits the economically feasible transportation radius.

Analysis of the dynamics of sown areas for the period from 2016 to 2024 indicates significant structural transformations in the Ukrainian agricultural sector, caused by both economic factors and the impact of a full-scale war (Table 5). The total area under grain and leguminous crops has undergone a significant reduction of 3185 thousand hectares, which is the largest drop among all categories.

The largest losses were recorded in wheat and barley crops, which decreased by 1316 and 1500 thousand hectares, respectively, with the main decline occurring after 2021. Corn for grain demonstrated relative stability compared to other cereals, although after the peak year of 2021 its area also began to gradually decrease. In contrast to the grain sector,

industrial crops showed an overall increase of 312 thousand hectares, which indicates a reorientation of farms to more profitable products.

Table 5. Sown areas of agricultural crops, thousand hectares.

Crops	2016	2017	2018	2019	2020	2021	2022	2023	2024	Deviation, +, −
Grains and legumes	14,324	14,605	14,810	15,292	15,392	15,995	12,171	10,985	11,139	−3185
Wheat	6208	6362	6623	6643	6596	7096	5435	4665	4892	−1316
Barley	2901	2506	2471	2552	2395	2476	1775	1496	1401	−1500
Corn for grain	4252	4477	4557	4987	5432	5522	4325	4113	4036	−216
Industrial crops	9064	9163	9262	9320	9224	9244	8292	8910	9376	312
Sunflower	6088	5961	6057	5928	6457	6622	5293	5220	5020	−1068
Rapeseed and colza	456	788	1037	1282	1127	1006	1186	1436	1251	795
Sugar beet	291	311	280	221	220	227	184	250	254	−37
Soybean	1859	1989	1708	1579	1351	1311	1559	1842	2720	861

Source: systematized based on [32].

Analysis of the dynamics of the number of farm animals in Ukraine for the period 2016–2024 indicates a deep structural restructuring of the industry, which is accompanied by a significant reduction in livestock in all key groups (Table 6).

Table 6. Number of farm animals by farm category in 2016–2024, thousand heads.

Animal Categories and Species	2016	2017	2018	2019	2020	2021	2022	2023	2024	Deviation, +, −
Farms of all categories										
Cattle	3750	3682	3531	3337	2874	2644	2307	2156	2302	−1448
including cows	2167	2108	2018	1928	1673	1544	1353	1263	1155	−1012
Pigs	7079	6669	6115	6025	5876	5609	4848	5034	4521	−2558
Sheep and goats	1325	1315	1309	1265	1140	1004	941	906	843	−482
Poultry, million heads	204.0	201.7	205.1	211.7	200.6	202.2	180.5	184.7	187.6	−16.4
Enterprises										
Cattle	1270	1245	1195	1147	1008	1003	942	920	932	−338
including cows	505	493	474	468	424	425	394	382	386	−119
Pigs	3704	3450	3291	3385	3629	3577	3144	3307	2935	−769
Poultry, million heads	112.0	110.3	115.2	123.5	109.7	113.5	101.8	106.2	110.1	−1.9
Households										
Cattle	2480	2437	2336	2190	1866	1641	1365	1236	1370	−1110
including cows	1662	1615	1544	1460	1249	1119	959	881	769	−893
Pigs	3375	3219	2824	2640	2247	2032	1804	1727	1586	−1789
Poultry, million heads	92.0	91.4	89.9	88.2	90.9	88.7	78.7	78.5	77.5	−14.5

Source: systematized based on [32].

In Table 7, we present a quantitative assessment of the energy potential of agricultural residues and energy crops, converted into millions of tons of oil equivalent (MTOE) for a standardized comparison of the energy efficiency of different types of biomasses.

In the structure of the presented data, there is a significant difference between the physical volume of residues and their real energy value, where, for example, the largest residues by mass of winter wheat and corn, which together amount to more than 18 million tons, provide a relatively low energy yield of 0.326 and 0.344 MTOE, respectively.

Table 7. Energy potential of post-harvest residues in terms of oil equivalent.

Crop	Volume of Post-Harvest Residues, Million Tons	In Terms of Million Tons of Oil Equivalent
Winter rapeseed	6.9	0.434
Sunflower	4.519	0.714
Soybean	3.358	0.83
Winter wheat	9.2115	0.326
Corn	9.062	0.344
Main products		
Miscanthus	2.53	1.213
Switchgrass	1.725	1.78
Total	37.306	5.641

Source: calculated by authors [17,31].

The table data indicate that the total biomass volume of 37.306 million tons allows for replacing 5.641 million tons of oil equivalent, emphasizing the priority of using energy plants to achieve maximum energy independence.

In Table 8, we present the author's calculation of the theoretical bioenergy potential of the livestock sector, based on a detailed analysis of the livestock of the main species of farm animals and poultry.

The results of the calculations given in the table serve as a fundamental economic basis for the implementation of the “energy island” architecture, allowing the integration of livestock waste into a closed cycle of heat and electricity production within the framework of a circular development model of the region.

Table 8. Estimation of the potential for biogas production from livestock waste as of 2024.

Cattle, Thousand Heads	Pigs, Thousand Heads	Sheep and Goats, Thousand Heads	Poultry Million Head
2301.6	4521.1	843.3	187.7
Volume of organic residues (manure), t/head per year			
5	1.5	0.365	0.05
Manure output, thousand tons			
11,508	6781.65	307,805	9385
Biogas yield from 1 ton of manure, m3			
50	17	110	160
Volume of potential biogas production, million m3			
575.4	115.2881	33.85855	1501.6
Total, million m3		2.23	

Source: calculated by the authors [31,32].

Based on the data presented in Table 9 and Figure 1, it can be concluded that the regional structure of biofuel production potential in Ukraine is significantly uneven, which directly correlates with the agrarian specialization of the regions and the security situation under martial law.

The total annual energy potential of the country is estimated at 30.96 million tons of equivalent, where solid biofuels play a dominant role, accounting for more than 72% of

the total volume, which confirms the strategic importance of plant residues as the most accessible resource for decentralized energy supply.

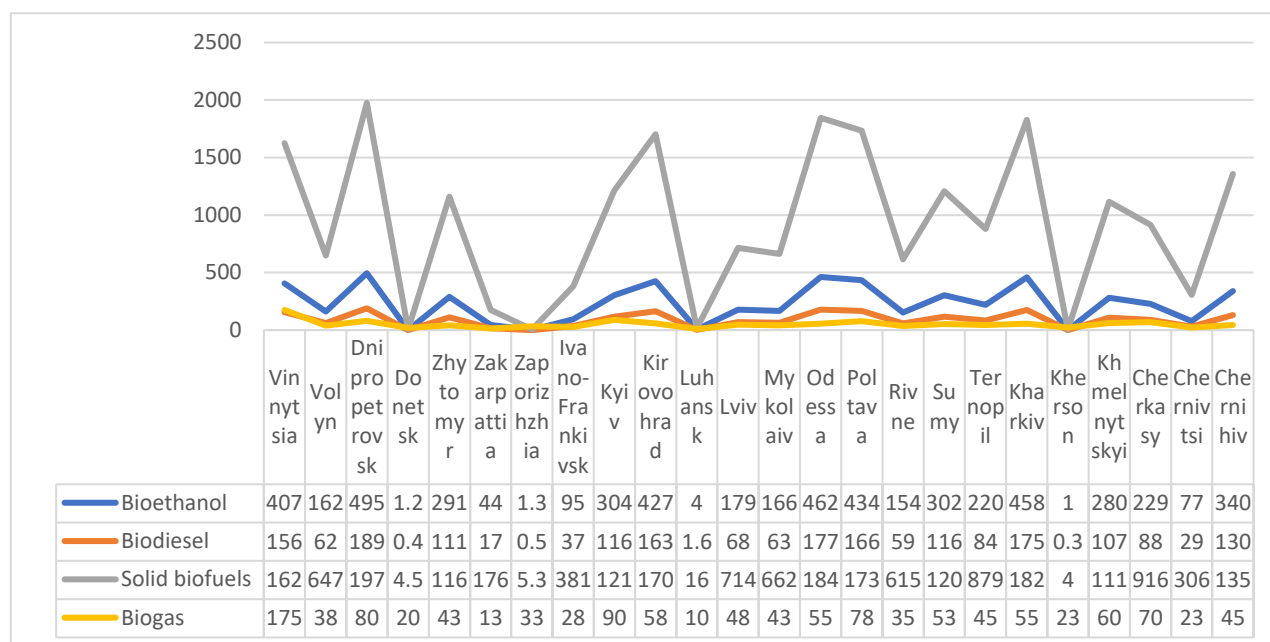


Figure 1. Regional structure of biofuel production potential in Ukraine in 2024 in terms of equivalent. Source: calculated by the authors based on data systematization [31,32].

At the same time, our analysis of the logistical aspects of biofuel production, presented in Table 9, allows us to state that the modern architecture of biofuel logistics chains in Ukraine has a multi-level structure, which varies from purely local to integrated regional models.

Table 9. Systematization of logistics models and existing biofuel projects in Ukraine.

Biofuel Type	Logistics Features	Centralization and Radius	Individual Projects
Solid biofuel	Decentralized model. Raw materials are collected and processed directly within the communities. Used for the needs of communal boiler houses and households.	Local. Radius up to 30–50 km. High dependence on seasonality.	Kernel Group of Companies (use of sunflower husks in CHP), municipal boiler houses on wood chips).
Bioethanol	Integrated model. Operates on the basis of distilleries. Raw materials (corn, molasses) are supplied in large batches by rail or road.	Regional. Radius over 100 km. Focus on exports and gas station networks.	Individual plants with dehydration lines: Agrofirma “Uzynska”, LLC “VEST-NOL”
Biodiesel	Fragmented model. Mainly operates as on-farm production within large farms for refueling their own agricultural machinery.	Intra-farm. Radius up to 10–20 km. Use of own rapeseed/soybean.	PP “Oliyar” (Lviv region), small farm plants in Ternopil and Khmelnytsky regions.
Biogas and biomethane	High-tech closed model. Raw materials (manure, silage) are supplied by pipelines or tanks. Biomethane is pumped directly into the gas transmission system or used to produce heat and electricity	Facility. Radius up to 10–15 km. Highest stability of supply.	MHP (Biogas complex “Biogas Ladyzhyn”), Vitagro (Vitagro), Teofipol Energy Company.

A key feature of the functioning of the solid biofuel sector is its decentralization, where the logistical shoulder is limited to 30–50 km, which makes this type of fuel the most adapted to the needs of territorial communities and the municipal sector.

It is important to emphasize that the effectiveness of each of the presented projects directly correlates with the density of the location of raw material sources relative to processing capacities.

Thus, the key determinant of the low efficiency of the sector in modern conditions is not the shortage of raw material resources, but the lack of stable logistics architecture capable of ensuring uninterrupted supply of fuel of standardized quality from primary generation sites to final power plants.

3.2. Research on Investment Attractiveness and Barriers to the Implementation of Small and Medium-Sized Generation Facilities

The results of the conducted economic and mathematical modeling of the optimal share of biofuel generation in the energy balance of the territorial community allow us to assert that the most effective development scenario is the formation of an “energy island” architecture with a level of autonomy within 40–50% (Figure 2).

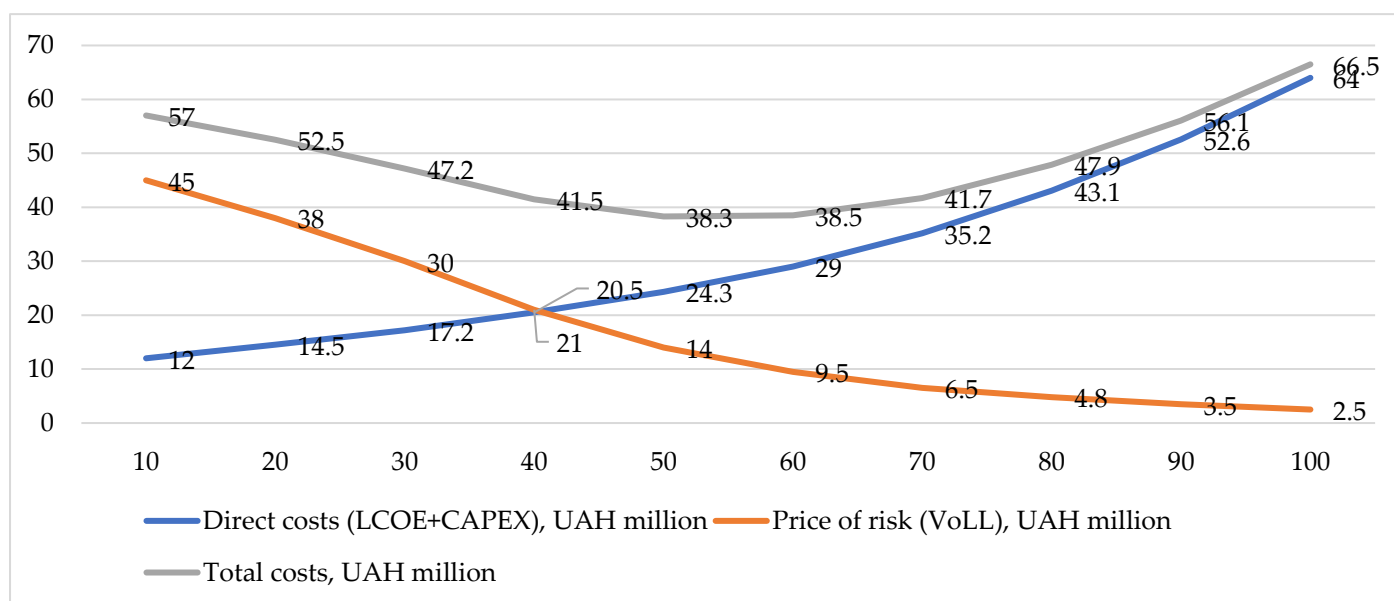


Figure 2. Optimization of the structure of the community’s energy balance based on the criterion of minimizing the total costs and risks of energy supply.

The practical implementation of bioenergy potential faces a number of systemic limitations—from the difficulty of attracting available financing to technical obstacles in connecting generation facilities to existing networks. Analysis of the investment landscape in the small and medium-sized generation sector makes it possible to identify growth points for local economies and justify the need for a transformation of state policy to eliminate barriers.

We present a systematization of barriers to the implementation of bioenergy generation facilities, indicating the presence of a complex of constraining factors, among which economic and financial aspects play a key role due to the high cost of capital investments and limited access to long-term lending (Table 10).

Table 10. Systematization of barriers to the implementation of bioenergy generation facilities.

Barrier Category	Specifics of Implementation	Impact on Investment Attractiveness
Economic and financial	High cost of capital investments (CAPEX) against the background of limited access to long-term lending. Significant currency risks when purchasing foreign equipment.	Extension of the payback period of projects to 7–10 years, which scares away private investors.
Regulatory and legal	Complexity and duration of procedures for obtaining construction permits and licenses for energy production. Instability of legislation on the “green” tariff and mechanisms for supporting biomethane.	Creation of corruption risks and bureaucratic delays, which increases the cost of the project at the launch stage.
Technical and infrastructure	Limited capacity of local electricity and gas networks. Lack of specialized equipment of Ukrainian production for small capacities.	Inability to connect facilities to the grid without expensive reconstruction work on the territorial communities infrastructure.
Raw materials and logistics	Lack of formation of a transparent biomass market. Risks of disruption of raw material supply chains due to changes in crop rotation or change in owners of agricultural enterprises.	Uncertainty regarding the cost of energy production (OPEX) in the long term.
Military and security	Risks of physical destruction of facilities due to shelling. Difficulties with insuring investments against military risks in frontline regions.	Rising insurance costs and general caution of international donors.

At the same time, our calculations indicate that more than 60% of the total investment volume (about 1.1–1.3 billion euros) is accumulated in 6–7 regions of Ukraine, where stable agro-industrial clusters have been formed (Table 11).

Table 11. Analysis of investment activity and volumes of investments in biofuel projects by region of Ukraine.

Region	Nature of Investment Activity and Key Projects	Investment Areas	Investment Volume (Million Euros)
Vinnitsia	High. Leader in biogas capacity (MHP, Yuzefo-Mykolaivska BC).	Biogas, pellets.	180–220
Volyn	Medium. Processing of industrial crops (VESTNOL LLC), export logistics.	Bioethanol, oils.	45–60
Dnipropetrovsk	High. Significant capacities of industrial biogas and landfill degassing.	Industrial biogas.	140–160
Donetsk	Critically low. Most assets destroyed or preserved.	Recovery.	<5
Zhytomyr	Medium. Development of municipal generation based on wood biomass.	Wood chips, pellets.	35–50
Zakarpattia	Low. Small generation for the recreational sector.	Wood biomass.	10–15
Zaporizhzhia	Critically low. Conducting hostilities and occupation of part of the territories.	Mobile generation.	<2
Ivano-Frankivsk	Medium. Biogas installations of agricultural holdings (e.g., Goodwell).	Biogas, wood chips.	40–55
Kyiv	High. New biomethane plants, modernization of utility networks.	Biomethane, pellets.	120–150
Kirovohrad	Medium. Energy utilization of sunflower husks at the SEZ.	Pellets, straw.	30–45

Luhansk	None. Full occupation, halt of all investment processes.	-	0
Lviv	High. Flagship projects of bioethanol (OKKO/EBRD) and biomethane.	Bioethanol, bio-methane.	150–190
Mykolaiv	Low. Containment due to military risks, specific agricultural projects.	Straw, renewable energy.	15–25
Odessa	Medium. Straw and viticulture potential, export hubs.	Bioethanol, straw.	40–55
Poltava	High. Biogas of sugar factories (“Astarta”), processing of crop residues.	Biogas, biomass.	110–130
Rivne	Medium. Woodworking and solid biofuel cluster.	Pellets, wood chips.	30–40
Sumy	Low. Border risks, focus on domestic energy consumption of territorial communities.	Straw, firewood.	12–18
Ternopil	Medium. Biodiesel capacities of farmers, biogas (Teofipol).	Biodiesel, biogas.	50–70
Kharkiv	Low. Decentralized solutions for communities under shelling.	Mobile boiler houses.	15–20
Kherson	Critically low. Consequences of occupation and mining of territories.	Recovery.	< 3
Khmelnitskyi	Medium. Development of biogas capacities and straw burning.	Biogas, straw.	45–60
Cherkasy	High. Energy-efficient projects of large agricultural producers.	Biomass residues.	70–90
Chernivtsi	Low. Small generation using firewood and wood waste.	Firewood, pellets.	8–12
Chernihiv	Medium. Export-oriented production of fuel pellets.	Forest biomass.	25–35

Source: systematized by the author based on [31–37].

The highest threshold for entry into an investment project is observed in the Vinnytsia and Kyiv regions due to the prevalence of capital-intensive biogas and biomethane technologies.

At the same time, the structure of investments indicates the dominance of private capital in agrarian regions, where in regions with a high level of capital investment, such as Vinnytsia and Poltava, the main share of financing, reaching 90%, belongs to large agricultural holdings (Table 12).

Table 12. Structure of investment resources in biofuel projects by source of origin (averaged across region clusters).

Cluster of Regions (By Investment Level)	Private Investments of Agricultural Holdings and Businesses (%)	International Technical Assistance and Grants (%)	Own Funds of Communities (%)	Key Financing Model
High level (Vinnytsia, Kyiv, Poltava, Cherkasy)	85–90%	5–10%	2–5%	Corporate is based on reinvesting the profits of large agricultural holdings in their own energy independence.
Export-oriented (Lviv, Volyn, Odesa)	60–70%	25–30%	5–10%	Mixed is based on the use of credit lines from IFOs (EBRD, EIB) + private capital to enter the EU market.

Average/Municipal (Zhytomyr, Rivne, Khmelnyskyi)	30–40%	40–50%	15–20%	Grant-municipal is based on the replacement of gas in the budget sector at the expense of donor funds (NEFCO, GIZ).
Critical/Frontline (Kharkiv, Sumy, Mykolaiv)	10–15%	70–80%	5–10%	Humanitarian-energy is based on the installation of mobile boiler houses as emergency assistance from international partners.

Source: systematized by the authors based on [31–40].

At the same time, the analysis of the cost structure shows that for biomethane and biogas electricity production projects, the costs of connecting to the grid account for a quarter, and sometimes a third, of the total investment, making this factor a powerful “filter” that cuts off projects with a low level of capitalization (Table 13).

Table 13. Analysis of the share of costs of connecting to the grid in the structure of capital investments (CAPEX) of biofuel production projects.

Type of Generation Facility	Connection Type	Share in Total CAPEX (%)	Specifics of the Impact on Investment Attractiveness
Cogeneration plants (biogas)	Electrical networks (0.4–10 kV)	15–25%	The need to build or modernize transformer substations and power lines (TL).
Biomethane plants	Gas distribution networks (GRM)	20–35%	The high cost of preparation, compression and construction of gas pipelines-inputs to the GDS.
Biomass boiler plants (small)	Heating networks	5–12%	Usually integrated directly into existing local heating systems of social sphere facilities.
Biomass CHP plants (medium)	Electricity and heating networks	25–30%	Double load due to the need for synchronization with the Unified State Electric Power System of Ukraine.

Source: systematized by the author based on [36–46].

It is worth noting that the analysis shows that “soft” barriers create a hidden financial burden on the project, which is difficult to assess at the business planning stage (Table 14).

Table 14. Analysis of managerial readiness and “soft” barriers to the implementation of bioenergy projects in territorial communities.

Factor Category	Current Status	Impact on Investment Risks
Investment planning	Only 15–20% of territorial communities have updated investment passports with allocated sites (brownfields/greenfields) for energy facilities.	The lack of prepared sites forces the investor to independently undergo the procedure for changing the purpose of the land (from 6 to 12 months).
Human resources	Acute shortage of technical specialists (engineers, energy specialists) in rural communities for the operation of biogas plants and complex CHPs.	High operating costs for attracting shift personnel from regional centers or the risk of equipment downtime due to improper maintenance.
Biomass audit	Lack of verified data on the energy potential of waste at the community level; audits are usually conducted “de facto” after the arrival of the investor.	Uncertainty of raw material security, which increases the cost of project insurance and deters bank financing.
Municipal management	Low capacity of local energy managers in developing feasibility studies and preparing applications for international grant funds.	Slowing down the pace of attracting donor funds, which are critical for small communities

Transparency and communication	Lack of clear algorithms for interaction between authorities and business (one-stop-shop) to simplify local approvals.	Increasing corruption expectations and the likelihood of conflicts with the local population (NIMBY syndrome).
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Source: systematized by the author based on [47–52].

In particular, the lack of specialists with appropriate qualifications in the community forces investors to budget additional costs for process automation and remote monitoring, which increases the cost of the technological part by 10–15%.

At the same time, the analysis demonstrates a direct correlation between the technological complexity of the project and the return on investment period. Solid biofuel boiler houses have the shortest payback period (up to 5 years), which makes them an ideal tool for territorial communities that are focused on obtaining a quick socio-economic effect within one political cycle. In such projects, the main driver of profitability is the difference between the cost of imported natural gas and local wood raw materials (Table 15).

Table 15. Comparative characteristics of payback periods and investment profile of bioenergy projects.

Type of Generation Facility	Estimated Payback Period (years) Capital Intensity Level (CAPEX)	Estimated Payback Period (Years) Capital Intensity Level (CAPEX)	Typical Investor and Motivation
Wood chip/pellet boiler plants	3–5	Low. Relatively simple and affordable equipment.	Territorial communities, small businesses. Goal: rapid replacement of expensive gas and saving budget funds.
Biogas plants (electricity/heat)	6–8	Medium/High. Requires complex reactors and co-generation modules.	Medium-sized agricultural enterprises, farms. Goal: utilization of their own waste and obtaining stable income (RES).
Biomethane plants (biogas purification)	8–12	High. Expensive cleaning, compression and timing systems.	Large agricultural holdings, international corporations. Goal: export of biomethane to the EU, strategic decarbonization and high margin.
Biomass CHP plants (combined generation)	7–10	High. Complex turbine systems and extensive network infrastructure.	Industrial enterprises, energy service companies. Goal: full energy autonomy of large production sites.

Source: systematized by the author based on [53–56].

At the same time, municipal projects based on woody biomass are the most vulnerable, as they compete for resources with the local population, which, in the context of a shortage of other energy sources, creates not only an economic but also a social barrier (Table 16).

Table 16. Assessment of the risks of raw material competition and their impact on the viability of projects in the field of biofuel production.

Raw Material Type	Collection Radius (km)	Level of Competition Threat	Implications for the Investment Project
Wood chips/firewood	30–40	High. Competition from municipal boiler houses, private households and furniture production.	Rapid seasonal price growth (up to 50%), risk of generation shutdown due to resource shortage during the heating season.
Straw (cereal, rapeseed)	20–30	Medium. Competition between bioenergy and livestock (litter) or agronomic requirements (plowing).	The need to conclude forward contracts, increasing costs for pressing and storage.

Corn/sunflower waste	40–50	Low/Medium. The resource is usually in surplus, but competition increases with the emergence of large biomethane plants.	Lengthening of the logistics arm, which leads to an increase in the cost of Gcal/kWh due to the transport component.
Manure/silage (biogas)	10–15	Critical. Facilities are strictly tied to a specific farm.	Termination of the contract with one raw material supplier actually leads to a complete shutdown of the facility.

Source: systematized by the author based on [55,56].

Analysis of current capital raising conditions shows that the introduction of the CBAM mechanism radically changes the logic of investing in bioenergy. For exporting enterprises (agricultural holdings, cement or fertilizer producers) located in communities, the transition to biomass becomes a tool for maintaining competitiveness in the EU market.

In this context, an investment in a biomethane plant or biomass CHP is considered not as a separate business project with its own payback, but as an insurance premium to avoid a high carbon tax, which actually makes such projects viable even with long payback periods (over 10 years) (Table 17).

Table 17. The impact of insurance and climate regulation mechanisms on the investment attractiveness of bioenergy projects.

Impact Factor	The Essence and Current Status of the Instrument	Effect on the Investment Attractiveness of Territorial Communities
War risk insurance (MIGA, DFC)	Attraction of guarantees from the Multilateral Investment Guarantee Agency (MIGA) and the American Development Finance Corporation (DFC).	Allows us to unlock access to cheap Western capital even for regions with an average risk level, reducing the cost of raising funds by 3–5%.
Climate adjustment (CBAM)	An EU mechanism that provides for the taxation of the carbon footprint of products (metallurgy, fertilizers, energy) imported into the European Union market.	Transforms bioenergy from a “desirable” to a “mandatory” element of modernization for large exporters in communities, reducing the strategic payback period by avoiding fines.
National guarantees (ECA)	Expansion of the powers of the Export Credit Agency of Ukraine to insure direct investments against military risks.	Creates a “safety corridor” for domestic small and medium-sized businesses that do not have access to international financial corporations.
Carbon certificate market	The possibility of monetizing CO ₂ emission reductions through the sale of voluntary carbon units (VERs)	Creates an additional revenue stream that can accelerate the payback of biomethane and biogas projects by 1–1.5 years.

Source: systematized by the author based on [57–60].

The presented Table 18 systematizes the results of the multifactor analysis and suggests adaptive investment strategies for different types of territorial communities depending on their economic specialization and financial capacity. The matrix of strategic choice of bioenergy projects depending on the community profile allows for transforming the previously identified barriers and incentives into a specific decision-making matrix, where the technological choice of the community directly correlates with its resource potential and foreign economic goals.

Table 18. Matrix of strategic choice of bioenergy projects depending on the community profile.

Territorial Community Profile	Recommended Technology	Key Investment Driver	Priority Source of Financing
Small rural community	Chips/straw-fired boiler plants	Rapid payback (3–5 years), energy independence of the social sphere.	Grants, own funds, ESCO contracts.
Agrarian community (medium)	Biogas plants, pellet plants	Waste disposal, job creation.	Loans from Ukrainian banks, private agribusiness capital.
Industrial/Export territorial community	Biomethane plants, biomass CHP plants	CBAM compliance, energy sales to the network, fuel export.	Foreign direct investment, loans from IFOs (EBRD/EIB), MIGA insurance.

Source: own research.

For small rural communities, which are characterized by limited access to investment capital, the matrix determines the priority of implementing low-cost technologies for direct combustion of biomass, in particular boilers on wood chips or straw. In this segment, the key driver of attractiveness is a short payback period, which allows the community to obtain a quick socio-economic effect through a significant reduction in budget expenditures on energy carriers for the social sphere.

Since the own resources of such communities are minimal, the financial model here is based on a combination of international grant aid and energy service mechanisms, which allows for attracting professional operators to manage energy assets without excessive burden on the local budget. In medium-sized agricultural communities, the investment logic is shifting towards deep processing of agricultural waste through the construction of biogas plants or pellet plants. The main motivation for such projects is the implementation of the principles of the circular economy, where energy utilization of manure, silage or crop residues creates added value within the community and ensures energy independence of agro-industrial enterprises. The financing model in this cluster is based mainly on private capital of local businesses and credit lines of Ukrainian commercial banks, since the availability of their own raw materials and understandable energy sales markets make such projects classic investment assets with a medium level of risk. The highest level of technological and financial complexity is inherent in industrial and export-oriented communities, where bioenergy is considered as a tool for decarbonizing large production sites. The commissioning of biomethane plants and powerful CHPs in such communities is determined by the need to comply with CBAM requirements and maintain access to EU markets, which makes investments strategically mandatory despite the long payback periods. Due to the high capital intensity and complexity of connection to the main networks, the implementation of such projects requires attracting direct foreign investments and the mandatory use of international insurance mechanisms for military risks, which allows for integrating local energy capacities into global value chains.

Therefore, the effectiveness of implementing bioenergy projects in the territorial communities directly depends on the ability of local authorities to synchronize internal management processes with external security and climate incentives. The developed strategic choice matrix allows communities to clearly identify their technological profile and choose the most optimal financing models, which ensures the sustainable development of local energy as the foundation of national energy independence.

3.3. Economic and Mathematical Modeling of the Optimal Structure of the Community's Energy Balance, Taking into Account Biofuel Capacities

According to the objective function (1), justified in the methodology section, and the step-by-step optimization algorithm, the calculation of integral costs (Z) was carried out

for different scenarios of bioenergy autonomy of territorial communities. Integral costs include capital investments (CAPEX), operating and logistical costs (OPEX), as well as losses from undersupply of energy to critical infrastructure (Z_{mark}). The modeling showed that the integral cost function Z is nonlinear and reaches its minimum when ensuring the level of community autonomy within 40–50%.

At a low level of autonomy (less than 30%), the integral costs (Z) remain high due to the critical growth of the component (Z_{mark}) (economic losses and penalties due to the instability of the external network and blackouts).

At the optimum point (40–50% self-sufficiency), a balance is reached where the amount of investment in local biogas plants and logistics is minimal relative to the eliminated risks, and the total integral costs stabilize at the minimum basic level.

When trying to achieve absolute autonomy (70–100%), the value of the Z function increases exponentially. This is due to a sharp increase in the logistical radius of biomass delivery, the need to attract low-calorie substrates and excessive capital costs for capacity reservation.

The systematization of the taken-into-account potential and the results of calculating the Isred indicator are given in Table 19.

Table 19. Structure of bioenergy potential and assessment of the sustainability of the potential “energy island” of individual communities of Vinnytsia region.

Community (Type of Specialization)	Estimated Potential of Bioresources (Detailing of Sources)	Energy Equivalent (MWh/year)	Avoided Losses ($\Delta VoLL$), Million UAH	Stability Coefficient (Isred)
Illinets territorial community (Grain and technical)	The basis of the potential is corn crop residues and wheat straw (taking into account the removal of 30% of the gross harvest to preserve fertility), as well as waste from local production and elevator farming.	84,000	22.4	0.94
Trostanets territorial community (Agro-industrial)	The potential is based on organic waste from large poultry complexes and pig farms for biogas production, as well as on the processing of sugar mill pulp and the use of energy crops on low-yielding lands.	118,000	28.5	0.89
Severynivska territorial community (Horticultural and educational)	The calculation includes waste from sanitary cleaning of forest belts and gardens, wood chips, and straw from college educational farms, as well as the potential for installing micro-biogas plants for the needs of the social sphere.	21,500	6.8	0.78

Source: own research.

The conducted study allows us to state that the Illinets community is characterized by the highest level of specific investment efficiency (Isred = 0.94), which is explained by the maximum concentration of cheap plant residues within a radius of up to 15 km from potential generation points. The high density of raw materials ensures minimal logistical costs, which makes the “energy island” scenario as close as possible to the theoretical ideal.

Thus, the calculated indicators confirm the author’s hypothesis that the optimal sustainability point for the communities of Vinnytsia is in the range of Isred values from 0.75 to 0.95, which corresponds to the share of biofuel generation in the energy balance at the level of 45–55%.

We also provide a detailed description of the components that allowed us to determine the final Δ VoLL indicator and the author's sustainability coefficient (Table 20).

The conducted study confirms the hypothesis that the structure of the community economy directly determines the value of the avoided losses indicator (Δ VoLL) and, as a result, determines the value of the author's Isred sustainability coefficient. The Illinets territorial community demonstrates a high level of avoided losses, which is due to the functioning of a powerful energy-intensive agro-industrial cluster on its territory. As a result, the cost of "unreleased energy" in this community is the highest among the studied agricultural objects, which directly increases the author's Isred coefficient to the level of 0.94. This indicator indicates the strategic need to invest in bioenergy capacities to ensure the viability of the industrial sector.

Table 20. Detailing of economic components of the sustainability effect for individual communities of Vinnytsia region.

Community	Basis of Calculation Ecrit (Critical Load)	Specific Cost of Risk, UAH/kWh	Estimated Outage Period, h/year	Final Δ VoLL, UAH Million
Illinetska	Waterworks, hospital, bakery, elevators (high share of industrial sector).	28.5	450	22.4
Trostianetska	Poultry farms (continuous cycle), sewage treatment plants, distillery.	32.4	450	28.5
Severynivska	College (heating), outpatient clinic, heating points, wells.	24.2	450	6.8

Source: own research.

Thus, the developed economic and mathematical model and the proposed Isred coefficient allow us to move from a subjective assessment of energy independence to a mathematically justified design of community energy systems. It is proven that for agro-industrial communities of the Vinnytsia region, the point of economic optimum lies within 45–55% autonomy, which ensures maximum stability of critical infrastructure with rational terms of investment payback. The results obtained become the foundation for the development of applied mechanisms for the implementation of bioenergy projects in the next section of the study.

Successful implementation of the "energy island" model and achievement of the calculated Isred sustainability indicators require not only technical re-equipment, but also the formation of appropriate human and scientific capital based on clusters of applied bioenergy developments.

3.4. Assessment of the Effectiveness of Medium-Generation Investment Projects Through the Prism of the "Cost of Energy Independence" and Avoidance of Economic Losses

During the research, the analysis of curves to determine the financial and energy break-even points was carried out based on the relationship between the scale of generation (the level of community autonomy) and the dynamics of capital and operating costs.

The financial break-even point was based on the analysis of the curve of total discounted costs and avoided financial losses (Z_{mark}). It determines the minimum level of substitution of external energy resources by own biogeneration (fixed at 30–35% autonomy), at which capital investments in biogas infrastructure are fully compensated by the economic effect of eliminating the risks of blackouts, downtime of local enterprises and reducing the fee for electricity imported from the network.

The energy break-even point (EROI) was estimated by analyzing the curve of the ratio of energy spent on the collection, logistics and processing of biomass (including fuel for machinery) to the volume of clean energy produced (electricity and heat). The break-even point ($EROI = 1$) is reached even at minimal processing volumes. However, the critical break of the curve (where energy costs for logistics begin to exceed energy efficiency) occurs when the delivery radius is expanded beyond 18–20 km, which corresponds to 55–60% of the total level of community autonomy.

It is the intersection of the boundaries of these two areas of financial and energy feasibility that mathematically determines the choice of the integral optimum of autonomy within 40–50%.

The results of the economic and mathematical modeling conducted in the previous section confirmed that the formation of the architecture of an “energy island” for the territorial communities of the Vinnytsia region is not only technically possible, but also a strategically justified step. It was established that the financial and energy turning point for most communities in the region (in particular, Illinets, Trostyanets and Severynivska) is within 45–55% autonomy, where the author’s Isred stability coefficient reaches its peak values. Under conditions of martial law and a permanent threat of destruction of centralized networks, classic investment efficiency indicators (NPV, IRR, DPP) lose their exclusive dominance, since they do not take into account the cost of “survival” of the community and the effect of preventing losses. That is why the assessment of investment projects of small and medium biofuel generation is carried out through the prism of the “cost of energy independence”. This approach is based on comparing capital expenditures with the monetized indicator of avoided socio-economic losses ($\Delta VoLL$), which allows us to consider energy autonomy as a specific type of insurance asset of the territory.

Thus, the assessment of the effectiveness of investments in biofuel generation within the framework of this study goes beyond the scope of purely commercial payback and is integrated into the overall strategy of increasing the institutional capacity of the community to autonomously function in conditions of prolonged energy deficits.

Systematization of the potential of the Chernyatyn Vocational College of the Ukrainian National Academy of Sciences allows for combining the resource capabilities of crop and livestock farming into a single model of energy autonomy of the cluster. Based on the calculated coefficients of by-product yield per unit area and biogas per unit of livestock, a summary table of energy potential was formed (Table 21).

Table 21. Total bioenergy potential of bioresources of the Chernyatyn Vocational College of the Ukrainian National Academy of Sciences.

Resource Source	Resource Volume (ha/Head)	Biofuel/Substrate Type	By-Product Yield Ratio	Gross Energy Potential (t/m ³)
Wheat (winter and spring)	171.5	Straw (for pellets/briquettes)	1.5 t/ha	257.25 t
Sunflower	177.0	Stems and baskets	1.8 t/ha	318.60 t
Winter barley	66.0	Straw	1.2 t/ha	79.20 t
Soybean	104.7	Plant residues	0.8 t/ha	83.76 t
Pig farming (total herd)	71 heads	Manure (for biogas)	1.5 t per year	5751 m ³ /year

Source: own research based on regulatory indicators [31].

Analysis of electricity costs for the functioning of the Chernyatyn Vocational College of VNAU indicates a significant financial burden on the institution’s budget, since the total annual consumption is 327,739 kW/h, which in monetary equivalent exceeds 2.7 million hryvnias.

Based on the conducted study of the structure of sown areas, livestock and actual electricity costs, the following is a systematization of the feasibility of implementing a combined bioenergy generation system for the Chernyatyn Vocational College of VNAU (Table 22).

Combining the two technologies allows the college to achieve full energy synergy: solid biofuel covers the main peak loads during the heating period, while biogas cogeneration provides sustainable electricity generation for administrative facilities and water supply throughout the year. This approach not only converts agricultural waste into a valuable energy resource, but also radically reduces operating costs, which were analyzed in the structure of the institution's energy consumption.

Table 22. Systematization of the feasibility of processing agricultural waste into thermal and electrical energy.

Comparison Parameter	Use of Solid Biofuels (Straw, Stalks)	Use of Biogas (Manure-Based Cogeneration)
Raw material	Over 730 t/year of by-products (sunflower, wheat, barley, soybeans).	Over 5800 m ³ /year of biogas from the existing pig population.
Technological solution	Installation of high-capacity solid fuel boilers for burning bales or pellets.	Installation of a cogeneration plant (internal combustion engine with generator).
Purpose	Meeting the needs for thermal energy for heating educational buildings and workshops.	Production of electricity for own needs and obtaining thermal energy as a by-product.
Economic effect	Replacing expensive natural gas or coal; using our own free raw materials.	Reduction in electricity purchase costs (savings up to 2.7 million UAH/year) and voltage stabilization.
Environmental benefits	Utilization of crop residues, which are often burned in the fields, reducing CO ₂ emissions.	Processing of manure, reduction in methane emissions into the atmosphere and obtaining biofertilizers (digestate).
Impact on the cluster	Creation of jobs in fuel procurement and processing (grinding, pelletizing).	Formation of a base for scientific and practical research in the field of renewable energy.

Based on data on actual natural gas consumption and raw material costs, a final systematization of the economic feasibility of creating a bioenergy cluster was carried out. This allows for a clear comparison of the institution's real costs with potential costs when switching to its own generation (Table 23).

Thus, the integrated model of the bioenergy cluster based on the Chernyatyn Vocational College of VNAU proves its capabilities: due to the synergy of crop production (heat) and livestock production (electricity and fertilizers), the institution achieves a significant reduction in operating costs and complete energy sustainability.

Table 23. Economic justification for the diversification of energy supply of the Chernyatyn Vocational College of VNAU.

Energy Supply Indicator	Current Status (Traditional Resources)	Resource Volume of Own Biogeneration	Forecast Status (Bioenergy Cluster)	Annual Effect, UAH
Heating (Natural gas)	1,008,000 UAH (36,000 m ³ at a price of 28 UAH)	738.8 t (straw and plant residues)	513,466 UAH (cost 695 UAH/t)	+494,534
Electricity (Year)	2,704,466 UAH (external networks)	5800 m ³ (biogas from manure)	2,591,666 UAH (reduction in purchases from the network)	+112,800
Raw material costs (Manure)	0 UAH	106 t (manure for biogas)	42,400 UAH (cost 400 UAH/t)	−42,400
TOTAL annual costs	3,712,466 UAH	—	3,147,532 UAH	+564,934

Table 24 shows the structure of investment costs adapted to the actual resource capacities of the community, where the total amount of capital investments (CAPEX) was adjusted downwards due to the use of a low-power biogas plant and a combined heat and power plant. The main source of payback within the bioenergy cluster remains the solid fuel complex, which generates over 87% of the total annual effect due to the high marginality of replacing natural gas with straw.

It is important to note that this model does not include the cost of the resulting digestate (high-quality organic fertilizers), the use of which can reduce agricultural enterprises' costs for mineral fertilizers by another 15–20%, further accelerating payback.

Thus, the creation of a bioenergy cluster based on the Chernyatyn Vocational College of the Ukrainian National Academy of Sciences is a strategically appropriate step that turns the theoretical potential of biomass into a real tool for the financial autonomy of the educational institution and the community.

Table 24. Estimated cost of creating bioenergy cluster infrastructure and its payback period.

Infrastructure Element	Technical Parameters	Estimated Cost (UAH Million)	Source and Amount of Payback (Year)
Solid fuel boiler complex	Power ~500–800 kW (on straw)	1.8–2.5	Replacement of 36 thousand m ³ of gas (savings of 494.5 thousand UAH/year).
Biogas plant + CHP	Electrical power ~5–10 kW	3.0–3.5	Replacement of electricity (112.8 thousand UAH/year) + fertilizers.
Crushing and baling line	Straw and residue preparation	0.8–1.2	Optimization of raw material cost (up to 695 UAH/t).
Networks and connection nodes	Local network modernization	0.5–0.7	Reduction in losses during energy transportation.
Total capital expenditure (CAPEX)	—	6.1–7.9	Total savings: 564.9 thousand UAH/year.

At the same time, the concept of “energy independence value” substantiated by us suggests a transition from a narrowly financial assessment of investments to a risk-oriented development strategy and, in the long term, of territorial communities by scaling the relevant clusters. Its essence lies in determining the real efficiency of bioenergy projects not only through savings on tariffs, but also through an integral comparison of capital expenditures with the monetized indicator of avoided losses (VoLL) arising from the power outage of critical infrastructure. This approach transforms the bioenergy cluster from a classic generation facility into a strategic asset insurance tool, where investment attractiveness is determined by the level of minimizing infrastructure risks and achieving the maximum stability coefficient of the facility under conditions of instability of centralized networks.

3.5. Formation of Mechanisms for Financial and Economic Stimulation of Diversification of Energy Supply of Territorial Communities During the Transition Period

Successful implementation of the strategy of diversifying the energy supply of territorial communities based on bioenergy solutions requires the formation of an effective financial and economic basis capable of activating investment processes in a difficult transition period. The foundation of such mechanisms should be the creation of conditions for safe entrepreneurship in the agricultural sector, since under modern conditions the energy component is a critical risk factor that directly affects the sustainability of business models [61]. An important tool for overcoming infrastructure barriers at this stage is the development of cooperation, which allows territorial communities and agricultural producers to combine resources to realize the potential of renewable energy sources, which is fully con-

sistent with the principles of the “green” course and ensures sustainable development of rural areas [62,63]. In the context of the post-war reconstruction of Ukraine, the role of local government as the central entity for managing energy transformations at the local level is of particular importance [64].

The practical implementation of financial incentives in the transition period should also be based on mechanisms for bioenergy utilization of waste, in particular agricultural residues and wastewater, which not only solves acute environmental problems, but also creates additional sources of income from the sale of by-products, such as organic fertilizers [65]. A deep transformation of the energy system under conditions of shortage of traditional resources actualizes the maximum involvement of local bioresources, which allows territorial communities to change the status of a passive consumer to an active energy producer [66]. The effectiveness of such transformations directly depends on the quality of communications and partnership between all market participants. Logosha R. [67] emphasizes the importance of forming models of marketing interaction, where agricultural enterprises act as key links in the chain of creating added value for biofuels.

The institutional aspect is of particular importance in this context. According to [68], system energy management is an integral part of the socio-economic and energy security of Ukraine, as it allows communities to monitor and rationally allocate resources, minimizing losses and increasing the overall efficiency of the local network.

The practical implementation of bioenergy initiatives can be based on the modernization of existing industrial facilities. In particular, [69] consider the production of biomethane at sugar refineries as a strategic direction that allows not only to ensure the energy security of the state, but also to transform traditional energy-intensive enterprises into modern bioenergy hubs. This approach creates a synergistic effect, combining agricultural production with high-tech energy [70].

The systematization of financial and economic incentive mechanisms allows us to differentiate support instruments into reactive (aimed at survival and autonomy during martial law) and proactive (aimed at market integration and sustainable development in the post-war period). This approach provides flexibility in managing energy transformations, where the priority is not only the direct payback of projects, but also the strategic sustainability of territorial communities (Table 25).

Table 25. Systematization of mechanisms for financial and economic stimulation of diversification of energy supply of territorial communities.

Direction of Stimulation	Martial Law Instruments (Focus on Sustainability)	Post-War Recovery Tools (Emphasis on Efficiency)	Target Benchmark (According to the Study)
Budgetary and tax levers	Municipal grants for cogeneration; exemption from land tax for small generation facilities.	Tax rebates for the implementation of Smart Grid technologies; Green community bonds.	Achieving a level of autonomy of 40–50% (optimum zone).
Investment mechanisms	Direct financing of “energy islands”; insurance of war risks through international funds (DFC/MIGA).	Preferential green lending; attracting private investment in biomethane production.	Maximizing the integral indicator of Isred sustainability.
Market instruments	Monetization of avoidable losses (VoLL) for critical infrastructure.	Implementation of the Net Billing system and sale of surplus energy at a green tariff.	Transformation of the community into an active energy producer.
Logistical incentives	Subsidizing the collection of local raw materials within a radius of up to 10 km for energy supply of communities.	Grants for the development of regional bioenergy clusters and digestate processing.	Closed cycle of production and restoration of soil fertility.
Institutional support	Creation of mobile energy management centers based on educational platforms	Creating a network of certified scientific and technical hubs and biomethane filling stations.	Personnel and technological support according to EU standards.

It has been established that to ensure the viability of communities under martial law, the priority is to transition from a purely commercial assessment of projects to a model of minimization of the cost of lost load (VoLL). The proposed typology of incentives allows us to distinguish between reactive measures (war risk insurance, direct financing of “energy islands”) and proactive tools of post-war recovery (Net Billing system, “green” bonds, incentives based on the integral sustainability indicator Isred).

To ensure the practical implementation of the developed optimization model, a closed engineering and technological architecture of a decentralized cluster has been formed. It is based on the principles of a circular economy and ensures the full utilization of waste from the local agro-industrial complex in order to generate multi-energy flows (electricity, heat and fuel) for the needs of the territorial community.

Figure 3 presents a schematic diagram of the technological process and logistical connections within the autonomous cluster.

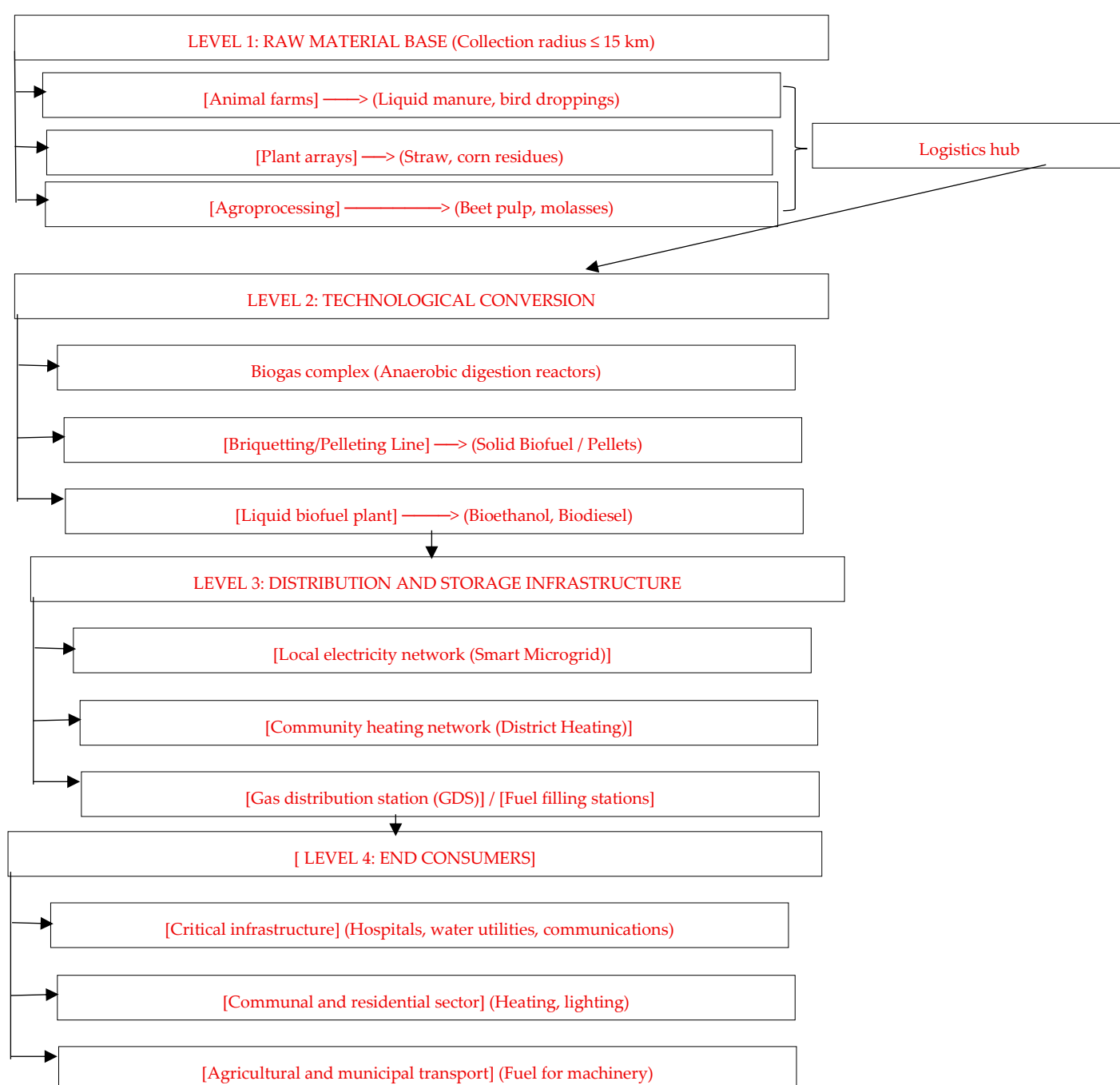


Figure 3. Technological and logistical architecture of the decentralized bioenergy cluster “energy island” based on the principles of a circular economy.

Thus, the presented empirical verification of the optimization model on the materials of the Vinnytsia region confirms the technical and economic feasibility of forming decentralized bioenergy clusters. System analysis of calculation coefficients and the formed engineering and technological architecture of the “energy island” clearly demonstrate that the integration of crop and livestock waste into a single circular cycle allows communities to achieve an optimal level of autonomy within 40–50%. The obtained values of the objective function of integral costs (Z) and the investment capacity index (I_{sred}), and taking into account the cost of undelivered energy ($VoLL$), prove that it is this scale of local generation that ensures maximum financial and energy break-even of the system, minimizing logistical risks and capital investments under the conditions of modern challenges.

4. Discussion

The results of our assessment of the regional and national bioenergy potential of Ukraine (Tables 7 and 8) correlate with the basic research of the Bioenergy Association of Ukraine (UABIO), as well as the fundamental works of domestic and European scientists [3,19,24,70]. However, there are certain discrepancies. While most previously published works assessed mainly the theoretical or technical potential of biomass without taking into account strict logistical constraints and military destruction, our study applied the coefficients of real availability (K_{av}) and took into account the regional factor of “safety islands”. This allowed us to obtain a more conservative, but economically justified estimate of the real volume of raw materials available for decentralized energy supply systems of territorial communities under modern conditions.

The integration of agricultural waste management with energetic autonomy models aligns heavily with recent scholarly findings that prioritize post-war transformation vectors. In particular, Zhuk et al. [26] emphasize the critical role of recycling, bioenergy, and fine-tuned export–import regulatory mechanisms in developing a composite economic efficiency index for Ukraine’s post-war agricultural sector. Their focus on macro-economic and regulatory stabilization tools complements our localized multi-level modeling approach, underscoring that micro-level community autonomy serves as a structural foundation for nation-wide green economic recovery.

Furthermore, the technological feasibility and grid-integration capabilities of such autonomous systems must be closely contextualized with specific biofuel formats, such as biomethane. Pimenowa [27] provided a comprehensive market assessment of biomethane derived from crop residues in Ukraine, detailing both techno-economic feasibility and strict environmental performance criteria. While our model utilizes a broad spectrum of local agricultural substrates within a strict 15 km localized radius to secure critical infrastructure, the insights from Pimenowa et al. [27] justify the mid-to-long-term integration of these decentralized “energy islands” into larger regional gas distribution networks.

However, the intensive extraction of agricultural post-harvest residues (such as corn stalks or wheat straw) for biofuel processing demands strict ecological oversight regarding soil quality. As verified by Razanov et al. [28], long-term cultivation of energy crops and massive residue removal can actively alter gray forest soil microbiota. Their research signals a critical boundary for circular bioenergy frameworks: the energetic optimization model must strictly balance biomass harvesting with soil biological sustainability. This directly justifies the usage of our resource availability coefficient (K_{av}) to prevent the over-extraction of organic residues and secure soil fertility.

In terms of regional prioritization and raw material composition, Alieksieieva et al. [29] focused on the specific energetic assessment of agricultural waste within circular

models, calculating total biofuel potential through localized crop and livestock dynamics. Their findings strongly support our empirical selection of the Vinnytsia region as a prime high-performance benchmark, establishing agricultural waste as a secure asset rather than an environmental liability.

Lastly, when adapting these frameworks to transitional crops and marginalized land usage, Geletukha et al. [30] highlighted the distinct economic and environmental characteristics of generating biomethane from intermediate crops in Ukraine. Their focus on intermediate and non-food biomass production formats provides a vital risk-mitigation pathway for our “energy island” architecture. If traditional post-harvest residues face seasonal deficits or structural supply chain disruptions under martial law, moving toward intermediate crops presents a highly stable, ecologically sound alternative to prevent potential socio-economic losses and stabilize the community’s overall energy balance.

An additional critical factor that significantly affects the final conversion efficiency under conditions of military conflict or prolonged logistical disruptions is the natural degradation and decomposition of biomass during excessively long storage. Similar to the model presented in [71], prolonged storage of raw materials in intermediate storage due to internal infrastructure limitations or blockage of logistical routes due to hostilities leads to a loss of dry organic matter and a decrease in the yield of biogas or bioethanol. As an emergency measure to minimize these risks and avoid fuel shortages, the architecture of the “energy island” provides for flexible diversification of biomass use. In the event of a threat of spoilage of wet raw materials or the impossibility of ensuring an uninterrupted technological process of bioconversion, the model provides for an operational reorientation of flows: for example, replacing complex bioethanol production with thermal combustion or briquetting of sustainable types of solid fuel, in particular energy crops (miscanthus or rod-shaped millet), which guarantees the preservation of the overall energy balance of the community.

In the broader context of the global scientific discourse, three main strategies are traditionally distinguished to solve the problem of raw material degradation and disruption of supply chains:

The technological conservation strategy (technical approach) is aimed at minimizing the moisture content of the raw material at the early stages (through torrefaction, rapid drying or ensiling), which slows down biological decomposition, but significantly increases operating costs (OPEX).

The geographical diversification and creation of surplus reserves strategy (logistical approach), which involves the formation of a network of geographically remote storage warehouses, which reduces the risk of simultaneous blocking of the entire raw material base, but increases capital investments (CAPEX).

The dynamic reprofiling strategy (management approach) which is based on flexible switching between different types of final energy depending on the current condition of the biomass.

The approach proposed in our study integrates elements of the strategy of dynamic reprofiling and logistical optimization, but translates them to the level of local autonomous systems—“energy islands”. Unlike most existing solutions that focus only on the commercial marginality of market operators, our model uses the VoLL (Value of Lost Load) coefficient as a key priority criterion. This allows us to make decisions about an emergency change in the technological cycle (for example, switching to burning miscanthus instead of producing bioethanol) not from the standpoint of maximizing the company’s profit, but from the standpoint of minimizing total economic losses and ensuring the survivability of the critical infrastructure of the territorial community. Such an integrated approach allows us to transform logistical risks and military threats into manageable parameters of local energy security.

5. Conclusions

The formation of decentralized “energy islands” based on circular bioenergy models is a strategic imperative for Ukraine under martial law, as it allows for effectively eliminating the risks of chronic power shortages, compensating for the destruction of centralized infrastructure, and ensuring autonomous operation of critical infrastructure facilities with a parallel reduction in operating costs by 15%. Based on the developed economic and mathematical model, it was established that the optimal level of energy autonomy of territorial communities is from 40% to 50%, because it is at this value that a rational balance is achieved between minimizing capital and logistical costs and reliable protection against socio-economic losses during blackouts, which is confirmed by the calculated Isred stability coefficient within 0.78–0.94.

The high efficiency of attracting local agricultural waste and phytoenergy crops with a total regional potential of up to 30 million tons of oil equivalent has been substantiated; however, to maintain the internal profitability of projects not below the critical limit of 15%, the logistical radius of biomass collection should be strictly limited and not exceed 15 km for microgeneration and 70 km for the meso level. The scientific novelty and practical value of the results obtained lie in the integration of the cost of unobtained energy *VoLL* indicator into the traditional investment analysis model, which allowed for successfully monetizing the avoided socio-economic losses from power outages and transforming ordinary commercial calculations into a comprehensive risk-oriented strategy for ensuring the energy viability of communities.

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