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Increasing the efficiency of low and medium-capacity bioenergy complexes as part of the fuel and energy complex of Ukraine

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ABSTRACT

The rapid increase in the share of renewable energy sources within the Unified Power System of Ukraine necessitates the integration of high-flexibility energy storage systems to compensate for their inherent variability. However, the implementation of battery-based storage systems significantly raises the overall cost of the energy infrastructure, complicating investment decisions for potential consumers. Key drivers stimulating the deployment of renewable energy include the pursuit of energy independence, improved reliability, ownership of generation assets, and the escalating and volatile costs of electricity supplied by centralized systems. This study proposes the utilization of biogas plants as high-maneuverability energy storage units. It is envisaged to leverage existing gas transportation and distribution networks for the accumulation and storage of biomethane. At the initial stage, biomethane is intended to be exported to EU countries, with production targets set to reach 8 billion m³ and beyond. According to the Bioenergy Association of Ukraine (UABIO), economic viability is typically achieved by biomethane plants with an annual production capacity of at least 3 million m³. A critical factor influencing the decision-making process for small and medium-sized biogas plant operators is the availability of predictive data on the energy efficiency of the proposed decentralized energy supply system in comparison with existing centralized alternatives. In this work, the assessment of energy efficiency indicators is conducted through an analysis of the share of renewable energy utilization, the type and cost of energy derived from both renewable and centralized sources. Given the capability of biogas plants to produce multiple forms of energy (electric, thermal, mechanical, etc.), it is recommended to consider both the share and the total volume of these energy types when designing the system. The proposed methodological approach is advised for use during the technical specification development phase, as it provides a rationale for investment decisions regarding the construction or modernization of energy supply systems.

Keywords: biogas plant, biomethane complex, combined energy supply, economic effect.

INTRODUCTION

According to a resolution adopted by the United Nations General Assembly, economic progress – largely driven by the rapid advancement of scientific and industrial processes – has been achieved predominantly through the intensive exploitation and depletion of fossil-based natural energy resources. These resources, primarily oil, natural gas, and coal, form the backbone of centralized energy supply systems. However, their use presents significant disadvantages: fossil fuels regenerate at an extremely slow rate and emit substantial quantities of greenhouse gases during combustion, thereby exerting harmful effects on both the environment and global climate systems [1].

In response to these challenges, the international community ratified the Paris Agreement in 2020, committing to the reduction of greenhouse gas emissions. This landmark accord has been endorsed by 186 countries, reflecting a collective effort to mitigate climate change. The situation has been further exacerbated by the military aggression of the Russian Federation. As a consequence of widespread destruction and territorial occupation, Ukraine's energy infrastructure has suffered considerable losses: approximately 43% of nuclear power generation capacity, 78% of thermal generation, around 73% of thermal power plant capacity, nearly 80% of wind power, and more than 20% of solar power capacity have been rendered temporarily inoperative, as shown in Figure 1.

For reliable damage control and mitigation of operational risks within the power system, it is necessary to develop a new, predominantly decentralized electricity generation infrastructure. Renewable energy sources (RES) generally meet modern environmental and technological requirements; however, the inherently variable nature of solar and wind power plants often results in imbalances between electricity supply and demand.

The power sector in Ukraine is currently evolving under the conditions of parallel operation between the Unified Power System (UPS) of Ukraine and the Union for the Coordination of Transmission of Electricity (ENTSO-E) in Continental Europe [3]. This development is characterized by an increasing share of RES in the national energy mix and the ongoing liberalization of the electricity market [4]. Additionally, the rapid growth in electricity generation from renewable sources, combined with infrastructure destruction caused by military conflict and challenges in accurately forecasting electricity consumption [5], leads to significant imbalances in the operation of the UPS of Ukraine. As a result, there is a growing need for reserve capacities and operational planning tools, particularly through ancillary services provided by electricity producers [6, 7].

Against the backdrop of the rapid expansion of wind and solar power generation, the issue of balancing their fluctuating outputs has become increasingly important for maintaining grid stability. A key operational characteristic of wind and solar power plants is their dependence on meteorological conditions, which introduces variability and unpredictability into power production [8, 9]. Research indicates that enhancing the flexibility of the power system – the ability to adjust electricity generation and consumption in response to fluctuations in RES output – is the most effective approach to address this challenge [9].

The integration of high-capacity renewable energy sources into existing power systems presents additional challenges in ensuring both static and dynamic stability of grid operations. Notably, when the share of RES exceeds 2% of the total energy balance, existing grid infrastructure struggles to manage generation peaks and transmission congestion, necessitating comprehensive

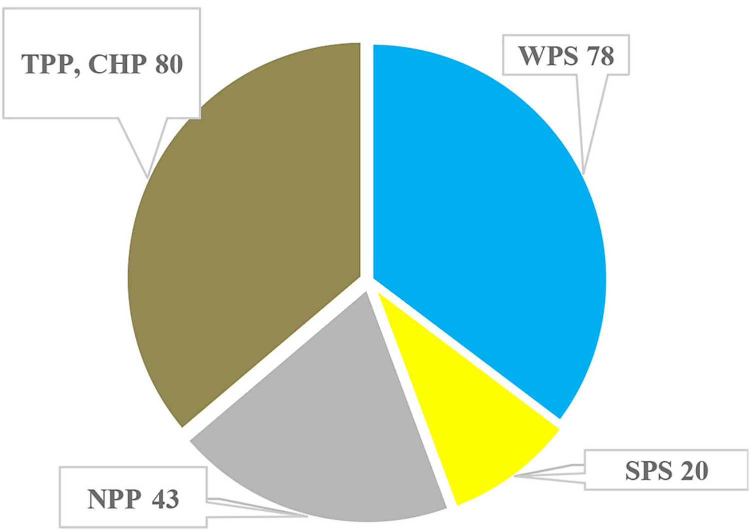

Figure 1. Direct infrastructure damage to power facilities [2]

modernization and reconstruction efforts [10]. Moreover, RES indirectly impact the damping properties of power systems, leading to reduced stability margins (e.g., decreased critical clearing times during faults) and degraded transient performance, such as increased generator rotor angle oscillations and diminished damping effects.

Presently, the global expansion of wind power entails the large-scale integration of wind turbines into national power grids, requiring centralized power supply systems to become increasingly "flexible". This transition demands the resolution of numerous complex scientific and technical challenges. One promising solution involves utilizing biogas plants (BGP) as flexible balancing resources to support wind and solar power operations. Biogas, which can be stored over extended periods, offers an effective means of stabilizing grid operations or meeting local energy demands [10]. Consequently, the initial phase of addressing this issue involves conducting an economic feasibility study of bioenergy complexes (BEC) within centralized power supply systems and substantiating their competitiveness as a balancing technology.

BACKGROUND

Traditional energy sources possess both advantages and disadvantages. Among the negative aspects are their adverse environmental impacts, the depletion of fossil fuel reserves, and the persistent trend of rising extraction and production costs. These challenges have accelerated the development and adoption of alternative, renewable energy sources in many developed nations, including the United States, the Philippines, Mexico, Japan, and several European countries such as Italy, Iceland, Germany, and Turkey [11, 12]. In Ukraine, the share of renewable energy in the gross final electricity consumption currently stands at approximately 14%, which remains significantly below the average European level of over 40%, as reported by Eurostat (Figure 2). Within the structure of renewable energy, biomass energy occupies a particularly important role. Notably, in the European Union, approximately 14% of total energy demand is met through biomass annually.

A significant policy development occurred in May 2024 when the Government of Ukraine enacted legislation permitting biomethane trading. This legal framework opens new avenues for the advancement of the bioenergy sector, contributing to the diversification and sustainability of the country's energy system. According to data from the Bioenergy Association of Ukraine (UABIO), as of today, three biomethane production facilities with a combined annual capacity of 11 million m³ are operational in Ukraine (Figure 3). In 2024, an additional seven biomethane plants are scheduled for commissioning, with a projected total production volume of 111 million m³ per year (Table 1).

A study conducted by UABIO [11] estimates the average market price for biomethane in Europe at approximately €900 per 1.000 m³. Given a production cost of around €500 per 1.000 m³, this pricing structure allows for an optimistic profitability margin of up to 28%. Comprehensive technical and economic parameters for a typical biomethane production plant are presented in Table 2.

The technical and economic performance of biomethane plants is influenced by a range of factors, including the cost, composition, and type of feedstock, capital expenditures, connection type

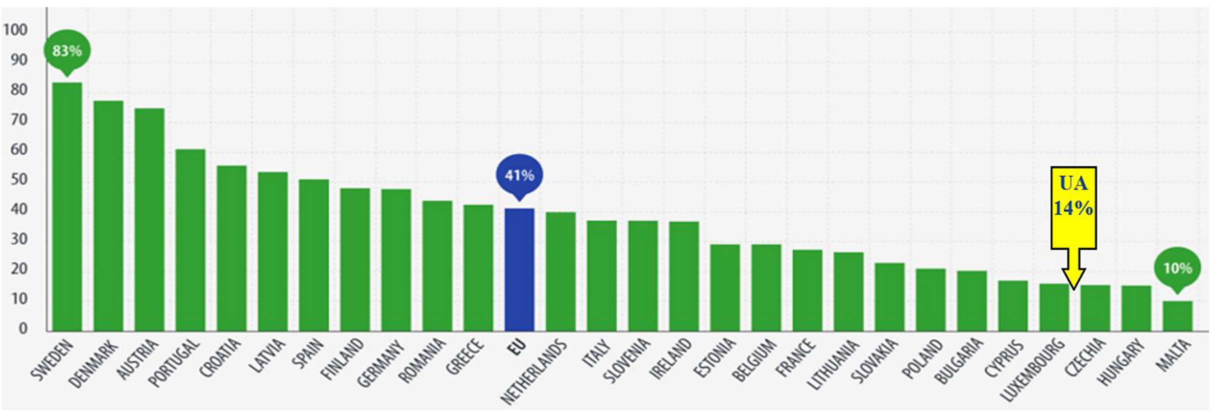

Figure 2. Share of renewables in gross final electricity consumption in the EU in 2022

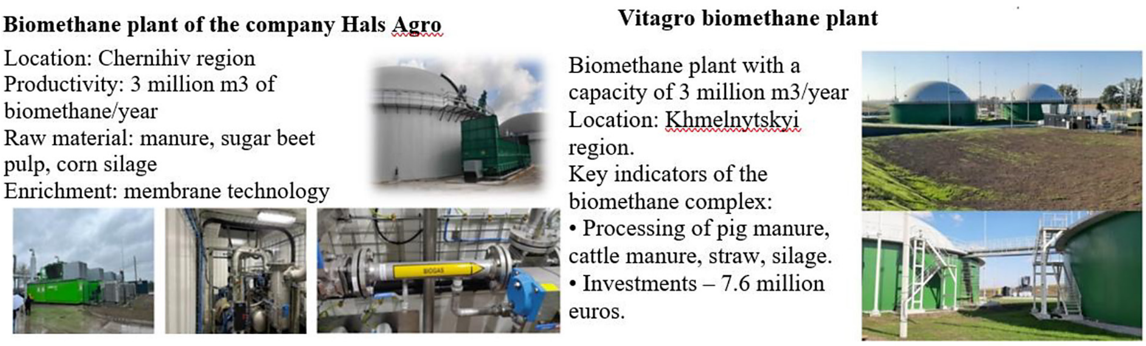

Figure 3. Operating biomethane plants in Ukraine

Table 1. Biomethane projects planned for launch in Ukraine in 2024 (UABIO)

No.	Name of the biomethane plant	Arrangement	Capacity, million m³/year	Accession
1	LLC "Gals Agro"	Chernihiv region	3.0	GDN
2	Group of companies VITAGRO	Khmelnytsky region	3.0	GDN
3	LLC "Teofipolskaya Energy Company"	Khmelnytsky region	56	GTN
4	LLC "Gals Agro"	Kyiv region	3.0	GDN
5	LLC "YUM LIQUID GAS"	Vinnytsia region	11	Bio LNG
6	MHP	Vinnytsia region	24	Bio LNG
7	MHP	Dnipropetrovsk region	11	GDN
Total			111	

Table 2. Feasibility study of a typical biomethane plant

Parameter	Parameter	Connecting to GDN	Connecting to GTN
Design capacity	m³/h	1000	1000
Raw material	-	Animal manure 15%, wheat straw/corn stalks 35%, corn silage – 50%	
Raw material processing method		comminution	
CAPEX	million euro	16.27	17.47
Raw material cost	Euro/t	40	40
Gas network pressure, at a distance of 0.5 km	bar	to 8	to 55
Raw material component of the cost of biomethane	€/1000 m³	195	
Full current cost of biomethane	€/1000 m³	523	550
Biomethane sales price in the EU	€/1000 m³	900	
NPV	million euro	32.1	29.86
IRR	%	28.4	25.7

to the gas network, operating and maintenance costs, as well as the costs associated with biomethane purification and marketing. According to [12], the production cost of biomethane can vary substantially, ranging from €300 to €1100 per 1000 m³, depending on these parameters.

Thus, the main factors contributing to the export of Ukrainian biomethane to Europe include:

- economic feasibility, which is achieved due to the higher price of biomethane in Europe than the cost of natural gas in Ukraine (European Biogas Association (EBA), Ukrainian Exchange UEEX – natural gas prices);
- Europe's interest in paying for biogas to Ukraine as the main supplier due to proximity, large agrobiomass resources and the presence of a gas transportation network (GTM), which contributes to achieving the climate goals of the Green Deal, Net Zero (IEA – Biogas and Biomethane Market Overview 2023);
- formation of guarantees of origin for biomethane, which operate in the EU and allow

the sale of not only biomethane, but also certificates of environmental value, which is not yet regulated in Ukraine (RED II Directive (2018/2001/EU);
- imperfect regulation of the biomethane market in Ukraine: there is no stable policy, tariffs or incentives for household consumers; difficulties with the introduction of biomethane into the Ukrainian gas distribution network (GDN) (certification, quality requirements, infrastructure are required), the draft Law of Ukraine on Biomethane No. 5464 was adopted in 2021, but it is at the implementation stage and at the present time there is no commercial market for biomethane;
- foreign exchange earnings, which will allow Ukraine to receive foreign exchange, which is important for the economy, especially in wartime (Ministry of Economy of Ukraine - Balance of Payments Forecast 2025);
- investment attractiveness, since the European market is more predictable for investors, unlike the Ukrainian one (European Investment Bank – Green Fuel Investment Roadmap).
- In addition, Ukraine has a competitive position in the European biomethane market due to its well-developed infrastructure for gas transportation and storage. Here are some additional factors that positively affect the potential for the development of biomethane technology in the country:
- biomethane is currently considered the most economical among renewable gaseous fuels;
- biomethane plants produce digestate as a by-product, which is a valuable organic fertilizer and necessary for restoring soil fertility in Ukraine;
- the country can offer some of the lowest prices for raw materials for biomethane production, positioning itself as a viable competitor in the international biomethane market;
- Ukraine has an extensive and reliable gas network infrastructure;
- there is significant potential for biomethane exports to the premium European market, especially given the ambitious EU initiative REPowerEU, which envisages the production of 35 billion m³ of biomethane annually by 2030. Ukraine can potentially provide up to 20% of this goal.However, the economic efficiency of biomethane plants is closely tied to their capacity.

According to [12], the specific capital investment required for biogas upgrading facilities with a production capacity of 100 m³/h is 2.5–4 times higher per unit of produced biogas compared to facilities with a capacity of 1000 m³/h. Consequently, the construction of plants with biomethane output capacities of at least 8000 m³/h is considered economically advisable.

To date, Ukraine has commissioned and operates over 70 small and medium-sized biogas plants, each with a capacity exceeding 100 m³/h. These facilities primarily utilize biogas for internal consumption, electricity or heat generation, or as vehicle fuel [13–15]. Small and medium-sized biogas plants offer a number of advantages over large-scale ones, including lower transportation costs for both organic raw materials and the energy produced. Such integrated energy supply systems are more resilient to external factors, which is especially important during martial law. Biogas plants operate locally, without requiring centralized logistics. Even during shelling and disruptions, they can power critical infrastructure – schools, hospitals, pumping stations. In addition, biogas complexes can function as an adaptive and multi-vector tool to increase the resilience of Ukraine's energy system, especially in conditions of military operations and the absence of maneuvering (regulating) capacities. Thus, the main motivation for integrating biogas plants as energy storage into Ukraine's energy system is flexibility, balancing, and energy security. Nevertheless, this class of biogas plants has not been widely used in Ukraine, partly due to the widespread perception of their limited economic feasibility.

Therefore, it is essential to substantiate strategies and design measures that can demonstrate and secure the forecasted economic benefits of such projects during the initial planning stages.

JUSTIFICATION OF THE POSITIVE ECONOMIC EFFECT OF BGP IMPLEMENTATION

The study will be conducted for a combined power supply system (CPSS). As illustrated in Figure 4, this system enables the consumer to connect either to a centralized power supply (CS) or a local supply (LS) via an automated energy redistribution unit (AERU). The CPSS concept promotes the integration of high-maneuverability loads (HML), which have the capability

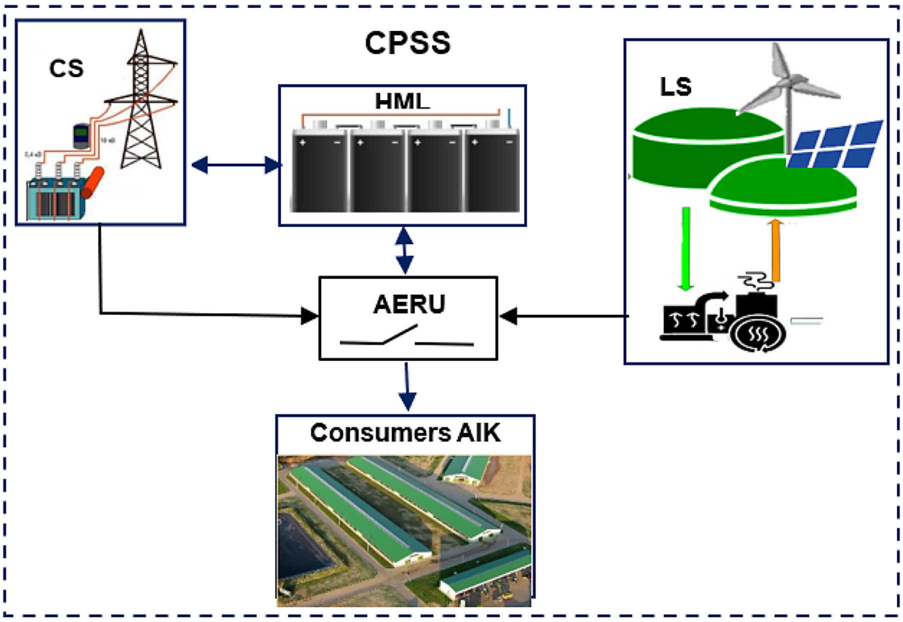

Figure 4. Flowchart CPSS

to accumulate energy from renewable energy sources (RES) while also serving as a backup power source for both the consumer and the centralized grid.

The economic effect (E_t) of operating the CPSS, as determined in accordance with DSTU 3886-99 "Energy Saving" is influenced by the operational time of the consumer from either the CS or LS, the revenue generated from energy sales (R_t), and the associated costs of construction and operation (C_t):

$$E_t = R_t - C_t \tag{1}$$

The projected positive economic effect ($E_t > 0$) should be established at the design stages by substantiating the threshold monetary values R_t. The value of R_t is primarily dependent on the cost and volume of energy produced locally by the consumer and the market price of energy supplied from the centralized system. A key challenge arises in the preliminary design phase, where predicting the revenue (R_t) is particularly complex – especially for bioenergy facilities capable of producing multiple energy types. When electricity constitutes the primary energy product, it is advisable to base the substantiation of the economic effect (E_t) on the corresponding electrical load schedules. In this study, the active electricity consumption schedule of the State Enterprise "Hontarivka" is employed as a representative example. The mathematical model describing this consumption pattern, defined by Equation 2, will subsequently underpin the optimal operational strategy for the AERU:

$$N_{\text{кс}(jt)} = N_{t0} + N_1 \frac{t_j}{T} + +N_2 \sin\left(\frac{\pi t_j}{T}\right) + + N_3 \sin\left(\frac{2\pi t_j}{T}\right) + \ldots + N_{n+1} \sin\left(\frac{n\pi t_j}{T}\right) \tag{2}$$

where: N_{t0} – the starting value on the electricity meter, measured in kilowatt-hours (kWh); N_1 – the recorded meter reading at the end of the day, in kWh; N_2, N_3,..., N_i – coefficients representing the variable part of the load, which reflect the pattern of daily electrical load fluctuations, in kWh; t_0, t – the start and end times of the electricity consumption measurement period, in hours (h); t_j – the specific hour within the measurement day, in hours (h); T – the total duration of the schedule, with $T = 24$ hours.

Assuming that the consumer receives electricity from the CS or LS at predetermined time intervals:

- From - CS - in hours $0 \le t \le 8$ and $21 \le t \le 24$ days;
- From - LS - at $8 \le t \le 21$ days.

The total amount of electricity produced by CS and LS per day is determined by the system of equations:

$$N_{CS}(t) = \begin{cases} N(t),\ 0 \le t < t_1 \\ N(t_1),\ t_1 \le t < t_2 \\ N(t) - [N(t_2) - N(t_1)],\ t_2 \le t < 24 \end{cases} \tag{3}$$

$$N_{LS}(t) = \begin{cases} 0, \; 0 \le t < t_1 \\ N(t) - N(t_1), \; t_1 \le t < t_2 \\ N(t_2) - N(t_1), \; t_2 \le t < 24 \end{cases}$$

where: $N_{CS}(t)$, $N_{LS}(t)$ – the amount of electricity received from the CS and PS respectively for t hours, kWh; $N(t_1)$, $N(t_2)$ – the amount of electricity received by the consumer respectively for hours t_1 and t_2, kWh.

The process of changing electricity consumption from the CPSS corresponds to the proposed Equation 4:

$$N_{CPSS}(t) = N_{CS}(t) + N_{LS}(t) \quad (4)$$

The dynamics of electricity consumption from the centralized power supply system (CPSS) are described by the proposed Equation 4. The justification for the coefficients in Equation 2, denoted as N_2, N_3, …, N_n, is performed using the built-in Linfit function available in the MATHCAD software environment [10]. For illustration, Figure 5 presents the algorithms employed for calculating these coefficients (N_n) based on the daily load profile of the Hontarivka State Enterprise [1, 16–18]. These coefficients correspond to the operational characteristics of the enterprise during the spring season:

N_2 = –28.442; N_3 = 0.644; N_4 = 4.655; N_5 = –31.512.

The process of forecasting electricity consumption from an energy source involves entering the appropriate parameters into the calculation algorithm or software tool. For example:

- $x \rightarrow t$ – time of day, from 0 to 24 hours;

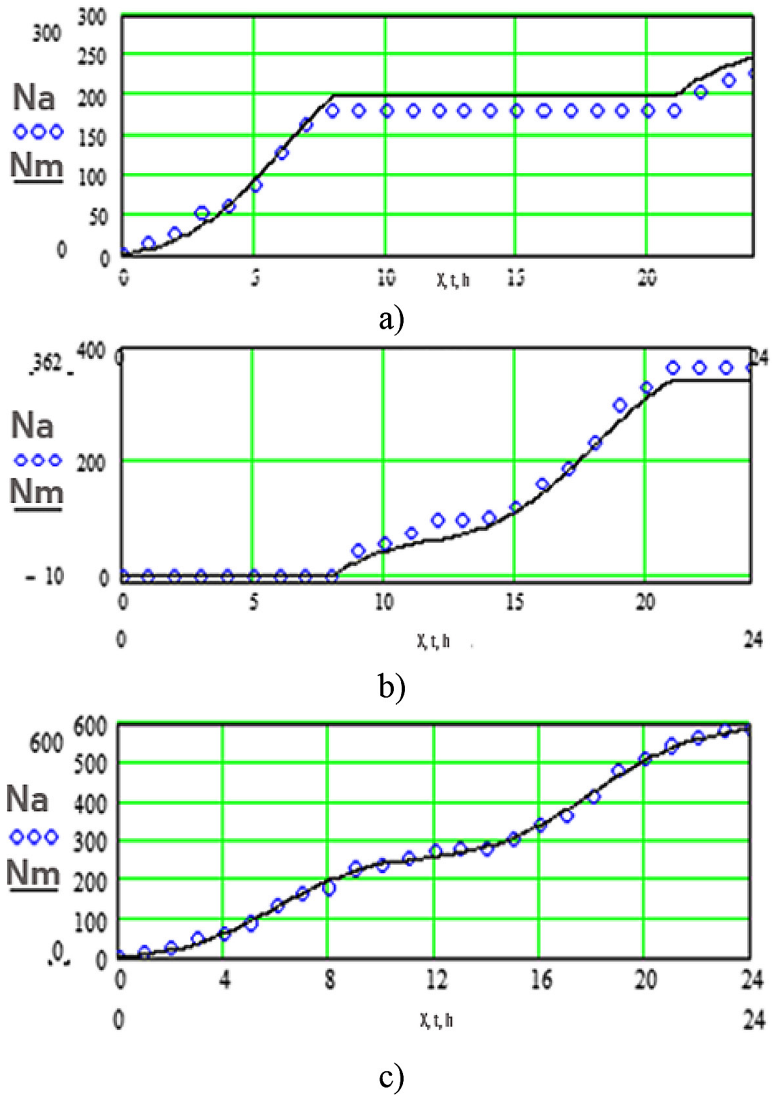

Figure 5. Graphical correspondence of active electricity consumption curves based on actual meter data (Na) and theoretical model (2) (Nm) for different power sources: (a) centralized source (CS); (b) local source (LS); (c) combined power supply system (CPSS)

- $i \rightarrow t_1, t_2$ – duration of energy use from LS and CS, respectively, hours;
- $y \rightarrow N_{CPSS}$ – hourly electricity consumption from the combined power supply system, kWh;
- $y_1 \rightarrow N_{CS}$ – hourly electricity consumption from a centralized source (CS), kWh;
- $y_2 \rightarrow N_{LS}$ – hourly electricity consumption from a local source (LS), kWh.

The initial (N_0) and final (N_1) values of the electricity meter readings are set to certain reference points during the day. In this case, they are defined as $N_0 = 0$ kWh and $N_1 = 589$ kWh. Details of seasonal fluctuations in electricity consumption at the Hontarivka Sub-State Enterprise are given in Table 3. According to the analysis, the average daily deviation between the actual electricity consumption of the "Hontarivka" State Enterprise of Regional Utilities (SERU) and the theoretical values, obtained through computer-based processing of dependence (2) and the system of Equations 3, does not exceed 5%. This result was established by calculating the root mean square deviation as defined by dependence (5).

$$\delta = \frac{\sqrt{\frac{1}{N}\sum_{i=0}^{S}(Ea-Em)^2}}{\frac{1}{N}\sum_{i=0}^{S}Ea} \cdot 100 \quad (5)$$

where: S – the number of samples, $N = 24$ s.o.

In accordance with dependence (1), the conditions for achieving a positive economic effect are satisfied when $E_t > 0$, which corresponds to $R_t > C_t$. Based on this principle, the value of R_t can be equated to the marginal costs $\Delta C^{/}_t$ for the implementation and operation of LS for the corresponding period t [7, 18]:

$$\Delta C^{/}_t = C_{tcs} - C_{tc} = C_{cs} - (\Delta C_{cs} + \Delta C_{tl}) \quad (6)$$

where: C_{tcs} – annual electricity costs for the t-th year from the central source (CS), UAH; C_{tc} – year t electricity consumption costs sourced from the CPSS, UAH; ΔC_{tl}, ΔC_{tcs} – costs of electricity from, respectively, the local and central sources integrated into the CPSS for the t-th year, UAH.

The determination of the cost limit $\Delta C^{/}_t$ for the implementation of the CPSS was performed using actual daily electrical load data from the "Hontarivka" State Enterprise during the spring season. This process involved computer-based analysis of the system of Equations 7:

$$\Delta C_\tau{}^{/} = \Delta y \cdot (\beta_\tau - \alpha_\tau) = \\ = \left[\begin{cases} 0.0 \le t \le t_1 \\ N(t) - N(t_1), t_1 \le t \le t_2 \\ N(t_2) - N(t_1), t_2 \le t \le t_{24} \end{cases}\right] \cdot (\beta_\tau - \alpha_\tau) \quad (7)$$

where: Δy – amount of electricity received by LD within CPSS structure, kWh; β_τ, α_τ – respectively, the rate charged for electricity from the CS and the unit cost of electricity generation from the LS, UAH/kWh.

Further, employing the developed algorithms [1, 19] within the MATLAB software environment, a study was conducted to examine the temporal dynamics of $\Delta C^{/}_t$ values throughout the day. The interrelations between the program's algorithmic modules are illustrated in Figure 6.

The input data for the program includes the following components:

1. Specification of the coefficients E_0 to E_5 in (2), which characterize the load curves of the local supply (LS) system.
2. Input of Equation 7, which defines the cost limits $\Delta C^{/}$.
3. Introduction of the electricity tariff rates for the CS system, set at β = 10.4 UAH/kWh for industrial consumers, and for the LS system, where changes in α are taken in the range of 0–20 UAH/kWh.
4. Justification of the selected value for the cost limit $\Delta C^{/}$.
5. Justification of the primary technical and energy-related components of the LS devices.

After obtaining the nomogram (Figure 7), where the calculations are implemented in the mathematical package MATLAB [20, 21], the consumer can justify the limitations of financial costs for the implementation of LS systems under given operating conditions at the initial stages of design.

Table 3. Hourly change in electricity consumption at the Hontarivka Sub-State Enterprise from the CS (y_1) and LS (y_2)

t, h	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
y_1	0	13	26	52	61	87	129	164	182	182	182	182	182	182	182	182	182	182	182	182	182	205	218	227
y_2	0	0	0	0	0	0	0	0	44	57	75	93	97	101	119	159	185	231	296	328	362	362	362	362

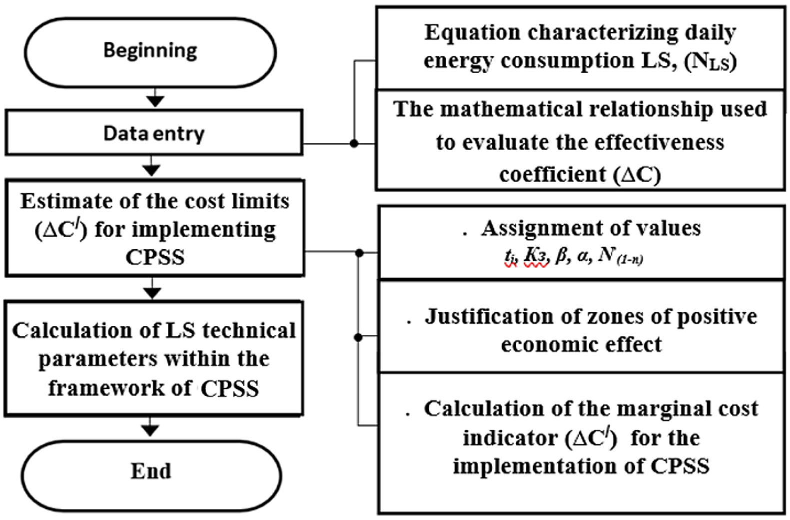

Figure 6. Block diagram of the algorithm used to calculate the cost threshold $\Delta C^{/}$ for CPSS deployment and operation

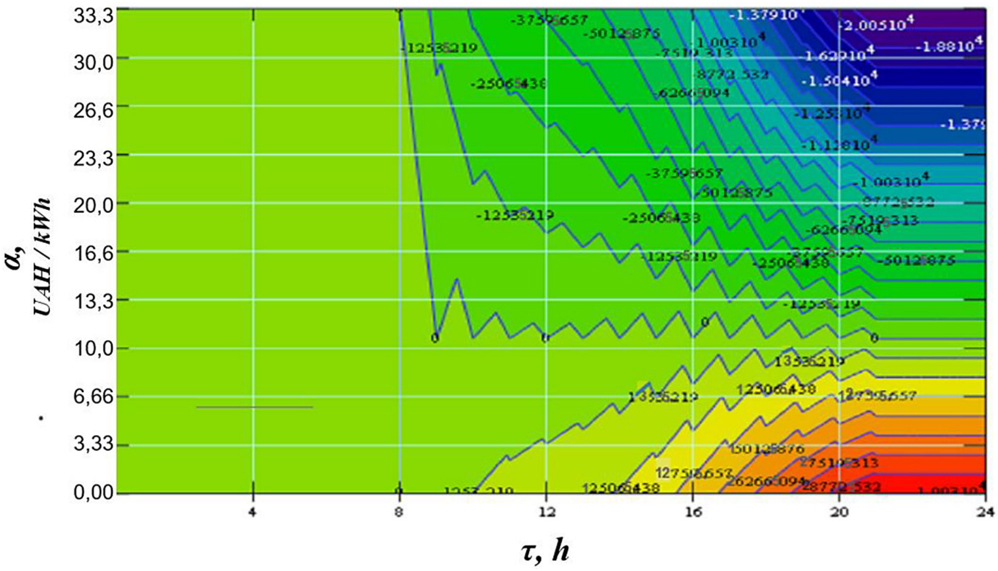

Figure 7. Dependence of marginal cost $\Delta C^{/}$ for CPSS implementation on electricity tariffs (α) and local sources service life during the day (τ)

Variations in operational conditions and external influencing factors can significantly affect the threshold at which a positive economic effect from LS implementation is anticipated [22]. The nomogram illustrates that the threshold for achieving a positive economic outcome corresponds to the equilibrium point between CS and LS electricity tariffs. For example, with the cost of electricity generated from a solar power plant α = 6.66 UAH/kWh, the electricity tariff for industrial consumers β = 10.4 UAH/kWh, and the period of connection of the consumer to the solar power plant from 8 a.m. to 9 p.m., the maximum financial investment in the construction of a solar power plant should not exceed 127,557 UAH per season, excluding operating costs. The average value of the marginal cost ΔC for the *j*-th season is also determined by the dependence:

$$\Delta C_j^{/} = \frac{\sum_{t_b}^{t_e} \Delta C_t^{/}}{N_j \cdot t_j} \tag{8}$$

where: ΔC_t – hourly cost limit values in the *j*-th season, UAH/h; t_e, t_b – respectively, the initial and final operating time of the consumer from LS per day of the *j*-th season, h; t_j – consumer connection time per day to LS in the *j*-th season, h; N_j – number of days in the *j*-th season.

The capacity for flexible adjustment of the cost limit during the early design phases makes it possible to align the anticipated economic effect with target values. This facilitates the purposeful selection of energy equipment for LS systems and the rational organization of local energy infrastructure by establishing economically justified constraints.

CONCLUSIONS

Today, Ukraine is considered a resource base in the bioenergy sector relative to the solvent EU market. Until there is a domestic policy to support biomethane, every project will focus on exports as a more profitable model. The discrepancy between existing and synthetically constructed load schedules does not exceed 5%, confirming their practical applicability for modeling load curves of varying types, and determining electricity consumption and generation volumes for diverse consumers at different times of the day.

The proposed methodology for justifying the economic effect of energy-saving measures minimizes economic risks in the construction of energy-saving systems by determining the values of marginal costs. This approach will allow justifying the composition and relationships between individual components of the relevant system in such a way that the existing costs do not exceed the marginal ones, which will allow predicting the economic effect and acceptable cost of energy produced from renewable sources, and is especially valuable for the development of small and medium-sized bioenergy projects.

The implementation of the proposed methodology will contribute to the development of an integrated power supply system based on small bioenergy complexes, which will ensure increased reliability and stability of the functioning of the Unified Energy System of Ukraine during natural disasters, emergencies and military aggression, etc., as well as the impact of difficult-to-control electromagnetic oscillations of wind and solar energy.

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