Article

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Abstract

The transition to energy independence requires the application of flexible approaches and the diversification of distributed energy generation technologies. This article substantiates the feasibility of using a hybrid power supply system incorporating renewable generation sources and a cogeneration plant to enhance the reliability of power supply to centralised heat supply boiler houses. Criteria and approaches to structuring and balancing the hybrid system are proposed, based on an analysis of the nature of electricity consumption and the nature of generation by its structural elements, using the example of Ukraine's district heating enterprises. The structure of the hybrid system has been determined, taking into account seasonal variations in operation and the stochastic nature of load and generation, whilst applying economic and environmental approaches in accordance with the institutional requirements of the European Union and Ukraine. A discrete mathematical model of the energy balance with a system of technical constraints is proposed to justify the parameters of the hybrid system's components. It is proposed that the parameters of the structural elements of the photovoltaic power station, wind power station, storage battery and cogeneration plant be determined on the basis of actual electricity consumption data from a district heating boiler house. Operating modes of the hybrid power supply system have been established depending on technological requirements and conditions for integration with the centralised electricity grid. The results obtained can be used in the design of hybrid power supply systems for district heating enterprises.

Keywords: hybrid power supply system; distributed energy generation; renewable energy sources; district heating enterprises; energy security; sustainability; cogeneration plant; storage battery; energy balance; energy management system; power supply stability

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1. Introduction

The diversification of renewable energy generation sources and methods of integrating them into the centralised power supply system forms the basis for establishing energy independence and ensuring the sustainability of energy security. 'In the European Union, short-term measures starting in 2022 include the recommissioning of coal-fired power stations and nuclear power stations, promoting the transition to renewable energy among households, and imposing restrictions on industry's use of fossil fuel resources. The next stage involves phasing out Russian gas imports by 2027, upgrading energy infrastructure, introducing energy-efficient technologies (heat pumps), generating electricity from renewable sources (biomass, wind power and solar power), and a 30% reduction in gas consumption by 2030' [1]. At the same time, one of the most effective ways to resolve the issue of insufficient generation capacity in the integrated energy system within the shortest possible timeframe is the introduction of distributed generation with guaranteed capacity, as well as the modernisation of the grid infrastructure for the transmission and distribution of electricity.

In the wake of Russian missile attacks, ensuring the reliability of electricity supply to Ukraine's district heating enterprises is a pressing issue given the damage to centralised power grid facilities, as centralised heat supply boiler houses and central heating stations are critical components of the infrastructure. The distributed energy generation technologies developed in Ukraine can serve as models for the development of distributed energy generation in other countries, helping to build energy-independent networks and strengthen the resilience of energy security against potential risks.

The energy crisis currently unfolding in Ukraine, characterised by a shortage of reserve capacity and critical damage to distribution networks, dictates the need to transition to a fundamentally new architecture for the energy supply of life-support facilities. According to the Report [2], the deployment of distributed generation based on cogeneration plants allows for a significant reduction in total primary energy consumption compared to the separate production of heat (in boilers) and electricity (from the grid). For Ukraine, the deployment of distributed generation has become a strategic priority against the backdrop of critical infrastructure damage. According to the Report [3], as of the end of 2023, direct losses in the energy sector had reached US$10.6 billion, while total reconstruction needs are estimated at US$47.1 billion. These figures demonstrate the critical scale of infrastructure damage and the need for comprehensive modernisation of the power system. It is local cogeneration based on municipal boiler houses that guarantees the energy resilience of communities. The specific nature of district heating plants as electricity consumers lies in the operation of powerful pump units, which create significant dynamic loads and require high-quality electricity — parameters that a cogeneration plant provides far better than renewable sources, whose generation is stochastic in nature. The technological integration of a cogeneration plant into such systems not only ensures autonomy but also creates a synergistic effect, radically increasing fuel utilisation efficiency.

Global experience in recent years has shown that cogeneration plants provide an ideal basis for integrated solutions. Firstly, cogeneration plants enable the full potential of secondary heat recovery to be realised. In particular, the use of industrial heat pumps to extract energy from the flue gases of a cogeneration unit allows the thermal capacity of facilities to be increased by 18.5% without burning additional gas, as confirmed by the successful coverage of a load of 2,930 MW [4]. Secondly, cogeneration is becoming a cornerstone of hybrid power grids. Combining a cogeneration plant with solar panels and buffer batteries provides consumers with a level of electricity self-sufficiency of up to 78%, whilst the overall efficiency of such an energy system exceeds 91.5% [5].

In an international context, the concept of sectoral energy integration is being actively implemented in Denmark within the Power-to-Heat (P2H) model, where surplus electricity from wind farms is directed to district heating systems via high-capacity heat pumps, electric boilers and thermal energy storage systems. According to analytical calculations, the potential for utilising wind-generated electricity allows for the provision of heat to between 18,100 and 63,380 households, depending on the market development scenario, confirming the effectiveness of integrating renewable energy sources, heat pumps and thermal storage systems into the structure of heating

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networks [6]. An analysis of the implementation of high-temperature heat pumps for waste heat recovery demonstrates the high energy efficiency of such solutions: replacing gas boilers with MVR-type pumps allows for the generation of approximately 100 MW of thermal energy whilst consuming only 26.9 MW of electricity, confirming the potential of the electrification of heat supply [7]. Ultimately, a cogeneration plant transforms the economics of heat supply, becoming a flexible tool for energy balancing. Modelling of the district heating system shows that integrating high-capacity heat pumps into hybrid systems enables high equipment utilisation: optimising load distribution ensures up to 3,500–4,000 hours of operation per year at full capacity, making this technology a key element of the net-zero emissions strategy [8]. Research into hybrid district heating systems shows that the success of their integration critically depends on the choice of control strategy. Taking external factors, such as electricity market volatility, into account allows such units to be transformed into effective tools for balancing the power system, adapting their operation to current grid conditions [9–11].

2. Literature Review

The operation of hybrid systems integrating renewable sources, particularly in the context of power-to-heat, district heating and algorithms for stable grid operation, is of interest to researchers in the context of the transition to distributed energy generation. In particular, attention is drawn to the use of renewable sources for distributed energy generation and the quality of electricity in distributed renewable energy generation systems [12,13]. An 'economic analysis of distributed photovoltaic generation projects has been conducted, and profitability indicators such as the internal rate of return (IRR) on investment in the project, the cost of investment in the project, and the payback period for investment in the project have been calculated' [14]. The implementation of the Microgrid-as-a-Service (MaaS) model, discussed in [15], is considered a promising direction. The authors define a microgrid as a technological complex with a single control loop that integrates generation and consumers. This approach allows for the optimal balancing of electricity supply and demand, transforming a utility energy facility into a flexible local system, and enables modernisation without significant initial capital investment.

In [16], a comprehensive comparative analysis of thermal energy storage (TES) technologies is conducted, which are a critically important element for balancing supply and demand in hybrid systems. The authors have developed an interactive platform for selecting the optimal type of storage based on criteria of efficiency, cost and temperature regimes, which allows for the informed integration of renewable energy sources into municipal heating systems. In [17], based on dynamic modelling, it was demonstrated that weather variability is a critical factor for the effective balancing of hybrid systems (solar-wind-battery): under unstable conditions, the probability of load loss (LOLP) increases from 0.8% to 12.4%. The authors conclude that the physical capacity of batteries is insufficient to cover prolonged generation outages; therefore, the implementation of predictive control based on artificial intelligence is necessary for system reliability. The technological basis for balancing is thermal energy storage (TES) systems, the optimisation of which is presented in [18]. The authors have developed maps combining different types of storage systems (in particular, molten salt and solid particle systems) with thermodynamic cycles, demonstrating that such solutions provide the necessary flexibility for the integration of renewable sources.

At the same time, the organisational aspect is explored in the study [19] on sector integration. Using Germany as an example, it is shown that for the effective integration of heat supply and the electricity sector, it is necessary to overcome sectoral isolation and introduce a systematic approach to planning, which will minimise investment risks during the electrification of boiler houses. The paper [20] justifies the feasibility of creating hybrid nodes based on centralised heating substations. An analysis of modernisation scenarios (combining heat pumps with photovoltaic systems) demonstrates that such a configuration is the most economically advantageous, allowing for the balancing of energy costs and a reduction in dependence on the external grid through self-generation.

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Particular attention in the scientific literature has been paid to the problem of balancing hybrid systems under conditions of uncertainty or the absence of historical load data. In [21], an approach is proposed where the balancing process is viewed as a superposition of random generation and consumption processes. Such mathematical modelling allows the required capacity of energy storage devices to be determined with sufficient accuracy to cover power deficits, which is critically important for a reliable power supply to public facilities with unstable operating schedules.

When designing hybrid systems for boiler houses, it is critically important to consider the balance not only of active power but also of reactive power, which affects the throughput capacity of inverters. In [22], a methodology was developed for assessing the reactive load of frequency-controlled electric drives of pump units. It has been demonstrated that the asynchronous motor remains the primary consumer of reactive energy, whilst the influence of the frequency converter itself is negligible; this must be taken into account when selecting the capacity of autonomous power sources. A fundamental step in ensuring power balance is the optimal selection of hybrid system component parameters. In [23], calculation methods are analysed that allow the capacity of renewable sources and backup units to be selected in such a way as to guarantee coverage of all the facility's load profiles at minimum capital and operating costs. An important aspect of balancing is the use of the complementary nature of solar and wind generation modes. In [24], based on mathematical modelling, it is demonstrated that the hybridisation of these sources allows for a significant increase in the reliability of the facility's autonomous power supply and achieves an economically attractive cost of electricity (at $0.17/kWh), even when operating in 'off-grid' mode.

The source prioritisation algorithm, investigated in [25] using a solar air-conditioning system as an example, is important for balancing. The authors developed and tested a control logic in which the photovoltaic system acts as the primary source (base load), whilst the external grid or diesel generator is connected automatically only during periods of insufficient solar generation, thereby minimising operational costs. The fundamental principle of power balancing is explored in [26] using an analysis of global experience in the deployment of solar power stations (thematic studies spanning 12 years). The authors argue that, under conditions of unstable solar radiation, hybridisation is the most effective solution, as it implements a mechanism of mutual compensation: the 'weakness' of one source is automatically offset by the operation of another, thereby guaranteeing system stability.

The regulatory framework for the implementation of balancing technologies is provided by EU institutional documents [27]. This document obliges EU Member States to ensure access to energy markets for demand response. In particular, the Directive prioritises the modernisation of district heating systems through the integration of high-efficiency cogeneration and renewable sources, creating a legal framework for transforming boiler houses into active participants in the energy system.

Therefore, despite the existence of a significant body of work on hybrid power supply systems for various facilities, there has been insufficient research into approaches to determining the parameter structure and power balancing methods for such systems specifically for municipal heating plants, taking into account actual electricity consumption schedules, seasonality and peak loads in the context of the transition to distributed energy generation. The objective basis for solving this problem lies in the development of a structural-functional model of a hybrid power supply system for municipal heating plants, which accounts for the stochastic nature of pump equipment operation, seasonal variability in thermal load, and the possibility of integrating local cogeneration with renewable energy sources and storage systems. In this context, it is reasonable to propose the hypothesis that optimising the configuration of the hybrid system, taking into account actual electricity consumption profiles, will increase the capacity utilisation factor, reduce peak loads on the external grid, and ensure the stability of voltage and frequency parameters under variable load conditions. This hypothesis is complemented by the assumption that combining a small-scale cogeneration plant with electrical and thermal storage buffers can minimise the impact of variability in renewable energy sources and reduce the specific energy consumption associated with heat transfer in district heating networks.

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The aim of this article is to justify approaches to determining the structure, parameters and balancing method of a hybrid power supply system for district heating enterprises as a means of distributed energy generation. The study is based on an analysis of actual electricity consumption profiles, as well as an assessment of the impact of the proposed configuration on the technical and economic performance of the system.

3. Methodology

The research was conducted using a load-oriented approach: the structure and capacity of the hybrid system's components (photovoltaic plant, wind farm, battery bank and cogeneration plant, grid) are determined on the basis of actual electricity consumption profiles of the boiler house and a discrete energy balance model with a time step of Δt (for daily calculations – Δt=1 hour).

Stages of the study:

1. Input data generation: annual/monthly/hourly electricity consumption profiles of the boiler house were used (Tables 1–3).

Table 1. Data on the annual electricity consumption of a district heating plant heating plant.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Electricity, kWh	85,651	75,074	65,693	9,601	4,560	9961	9121	9121	8881	23286	41422	61727

Table 2. Data on monthly electricity consumption at the district heating plant.

Date	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Electricity (kWh)	3500	3300	3400	3500	3300	2000	2000	3400	3300	3300	3500
Date	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Electricity (kWh)	3500	2000	2000	3500	3400	3500	3300	3300	2000	2000	3500
Date	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**-**	**-**
Electricity (kWh)	3400	3300	3300	3500	2000	200	3500	3400	3300	-	-

Table 3. Data on average daily electricity consumption for the coldest monthly consumption of a centralised heating plant.

Time of day	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**
Electricity, kWh	175	175	175	175	175	175	175	145
Hours of the day	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**
Electricity (kWh)	135	135	135	135	135	125	125	135
Hours of the day	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**	**00:00**
Electricity (kWh)	145	175	175	175	175	175	175	185

2. Load analysis: profile indicators (peak load, schedule fill factor, seasonality index, proportion of night-time dip) were calculated as requirements for the system structure.

3. Mathematical modelling: a discrete-time energy balance model and a system of technical constraints were constructed for the photovoltaic plant/wind farm/battery/cogeneration plant/grid (Equations (1)–(10)).

4. Development of operating modes: the operating logic of the energy management system has been defined for normal, night-time, emergency and grid integration modes.

Assessment of the controllable reserve (cogeneration plant): the potential of the cogeneration plant has been assessed based on the criterion of annual technical and economic benefit using a demonstration example. In particular, the following notation is introduced:

$t \in \{1, \dots, T\}$ – time interval number;
$P_{L,t}$ – electrical load of the boiler room during time interval t (kW);
$P_t^{PV}, P_t^{WT}, P_t^{CHP}$ – capacity of the photovoltaic plant, wind farm, and cogeneration plant (kW);
P_t^{imp}, P_t^{exp} – import/export to/from the grid (kW);
P_t^{ch}, P_t^{dis} – battery charge/discharge (kW);
SOC_t – battery charge status (kWh).

Design parameters (capacity/size): $P_{nom}^{PV}, P_{nom}^{WT}, P_{nom}^{CHP}, E_{nom}^{BAT}, P_{nom}^{BAT}$.

A sampling interval of $\Delta t = 1$ hour is used for daily calculations. The load profile is defined using actual hourly/monthly/annual data (Tables 1–3). Generation from the photovoltaic plant and wind farm is supplied via normalised profiles derived from meteorological data or reference series for the boiler house location; this allows for the stochasticity of renewable energy sources to be accounted for without being tied to a single 'ideal' day.

For each t, the power balance is calculated [19]:

$$P_t^{PV} + P_t^{WT} + P_t^{CHP} + P_t^{imp} + P_t^{dis} = P_{L,t} + P_t^{ch} + P_t^{exp} \quad (1)$$

Since the output of renewable energy sources is stochastic in nature, normalised generation profiles $k_t^{PV} \in [0; 1], k_t^{WT} \in [0; 1]$ are introduced, which are determined by meteorological data/reference series for the boiler house location. Then:

tt

$$0 \le P_t^{PV} \le P_{nom}^{PV} k_t^{PV}, 0 \le P_t^{WT} \le P_{nom}^{WT} k_t^{WT} \quad (2)$$

k_t^{WT} if the wind speed is v_t, the curve $P_t^{WT} = f(v_t) P_{nom}^{WT}$.

Charge dynamics:

$$SOC_{t+1} = SOC_t + \eta_{ch} P_t^{ch} \Delta t - \frac{1}{\eta_{dis}} P_t^{dis} \Delta t, \quad (3)$$

where η_{ch} (charging efficiency) – the charging efficiency (the proportion of the energy supplied for charging, that is actually stored in the battery). For example, if $\eta_{ch} = 0.95$, then ≈95 kWh will be stored from 100 kWh at the battery input; ηdis (discharging efficiency) – discharge efficiency (the proportion of energy in the battery that is actually delivered to the load/grid). For example, if $\eta_{dis} = 0.95$, then to deliver 95 kWh to the load, the battery will 'consume' ≈100 kWh of its reserve. Since the losses during charging and discharging are different (internal resistance, inverter, DC/DC converter, etc.), it is often standard practice to specify two coefficients separately. Furthermore,

$$0 \le SOC_t \le E_{nom}^{BAT}, 0 \le P_t^{ch} \le P_{nom}^{BAT}, 0 \le P_t^{dis} \le P_{nom}^{BAT} \quad (4)$$

To prevent battery degradation, a minimum permissible state of charge is also introduced:

$$SOC_t \ge SOC_{min} = \alpha E_{nom}^{BAT} \quad (5)$$

where α is the energy reserve, which remains 'untouched', $\alpha \in [0.1, 0.3]$ (within the range of 0.1–0.3 of the nominal capacity to prevent deep discharge and ensure stable system operation during transient conditions).

Cogeneration plant constraints:

$$0 \le P_t^{CHP} \le P_{nom}^{CHP} \quad (6)$$

If necessary, the minimum stable load level is taken into account:

$$P_t^{CHP} = 0 \text{ або } P_t^{CHP} \in [P_{min}^{CHP}; P_{nom}^{CHP}], \quad (7)$$

as well as the fuel component via the specific gas consumption b_{gas} (m³/kWh)

$$G_t = b_{gas} P_t^{CHP} \Delta t. \quad (8)$$

Network constraints:

$$0 \le P_t^{imp} \le P_{max}^{grid}, \ 0 \le P_t^{exp} \le P_{max}^{grid}, \quad (9)$$

where P_{max}^{grid} – is the maximum permissible power exchange with the centralised electricity grid at the connection point

In accordance with the approach adopted in this study, the choice of structure and capacity is determined by two groups of criteria:

1. Criteria based on consumption patterns (determined from actual boiler house load profiles (Tables 1–3):

- Peak load: $P_L^{Peak} = \max_t P_{L,t}$.
- Load factor: $LF = \frac{\overline{P_L}}{P_L^{Peak}}$.
- Seasonality index $S = \frac{\overline{E_{winter}}}{\overline{E_{summer}}}$ (based on monthly values).
- Proportion of the night-time dip: $N = \frac{\overline{P_{night}}}{\overline{P_{day}}}$ (for a 24-hour graph).

2. Criteria by generation type (based on the k_t^{PV}, k_t^{WT} profiles):

- Coefficients of installed capacity utilisation: $CF_{PV} = \frac{\sum_t P_t^{PV}}{P_{nom}^{PV} T}$, $CF_{WT} = \frac{\sum_t P_t^{WT}}{P_{nom}^{WT} T}$.
- Index of complementarity between renewable energy sources and load (reduction): $CI = 1 - \frac{\sum_t \max(0, P_{L,t} - (P_{nom}^{PV} k_t^{PV} + P_{nom}^{WT} k_t^{WT}))}{\sum_t P_{L,t}}$.

To obtain a unique solution, the problem of optimal selection is formulated as $\{P_{nom}^{PV}, P_{nom}^{WT}, P_{nom}^{CHP}, E_{nom}^{BAT}\}$ and of modes $\{P_t^{CHP}, P_t^{imp}, P_t^{exp}, P_t^{ch}, P_t^{dis}\}$ under a multi-criteria objective function:

$$F = \omega_1 \mathrm{C_{ann}} + \omega_2 \mathrm{CO_2} + \omega_3 \mathrm{ENS} \rightarrow \min, \qquad (10)$$

where $\mathrm{C_{ann}}$ – annual costs (capital + operating), CO_2 – emissions (mainly from CHP/grid), ENS – power supply deficit for critical load. The weights $\omega_1, \omega_2, \omega_3$ define the priorities: minimisation of the payback period (economic approach) and environmental constraints (environmental approach), which is consistent with the logic of the criteria applied in this work.

It should be noted that within the scope of this work (10) is presented as a formalisation of the problem formulation for further research; illustrative assessments have been carried out based on the model's criteria and constraints without a full numerical solution of the multi-criteria optimisation.

The presented model allows for the formalisation of the selection of a hybrid system's structure, the calculation of the potential of its components based on real load profiles, and the justification of the grid integration mode and the role of the battery/cogeneration plant in covering night-time and emergency intervals.

However, the proposed model is discrete in nature and uses normalised generation profiles from renewable energy sources; therefore, the accuracy of the results depends on the quality of the meteorological data and the representativeness of the selected modelling horizon. Further refinement of the methodology should be carried out using actual weather time series for a specific location and scenario analysis of emergency grid outages.

Table 1 presents data on electricity consumption by the process equipment of a district heating boiler house.

The data shows that the boiler room's electricity consumption exhibits a distinct seasonal pattern, divided into winter-spring and autumn-winter periods. This means that the hybrid power supply system will operate on a seasonal basis, and its components will be underutilised when operating in standalone mode. This applies primarily to the photovoltaic station, as it can generate the maximum amount of electricity during the spring-summer period. Therefore, to improve its efficiency, the hybrid power supply system must be integrated into the centralised electricity grid.

Table 2 presents data on the monthly electricity consumption of the boiler house's operational equipment electricity consumption of the centralised heating plant.

The data shows that the boiler house's electricity consumption follows a weekly cyclical pattern, with consumption remaining stable on working days, whilst on weekends it drops by almost half. Consequently, the monthly electricity consumption graph does not impose any particular requirements on the structure and capacity of the hybrid power supply system. At the same time, such a hybrid system can supply electricity to the centralised grid at weekends when the boiler house's electricity consumption decreases.

Table 3 shows data on average daily electricity consumption for the coldest monthly consumption of a centralised heating plant.

The data shows that the boiler house's electricity consumption falls by approximately 30% at night, but remains stable at all other times. At the same time, there is no photovoltaic generation at night, which may necessitate the consumption of electricity from the centralised grid. This means that to improve economic efficiency and reduce the payback period, the hybrid power supply system must be integrated into the centralised grid.

An analysis of these graphs provides a basis for determining the capacity of the hybrid system's components to meet peak loads; however, the seasonal nature of electricity consumption will result in structural generation being utilised inefficiently, and investment projects will have a significant payback period. On the other hand, there are institutional requirements from the European Union and Ukraine regarding the structure of hybrid power supply systems, which are primarily linked to environmental concerns. Accordingly, the hybrid power supply system for municipal heating plants should consist of the following components:

1) a photovoltaic power station – providing generation during the day and charging the storage batteries;

2) a wind power station – effective in the evening and at night, particularly in winter when heating demand increases;

3) storage battery – stores surplus energy for later use when generation is unavailable;

4) cogeneration unit – acts as the main backup power source during emergencies or at peak loads.

Thus, an overall concept is formed for the operation of a hybrid centralised power supply system for boiler houses as a complex of equipment that ensures uninterrupted power supply to process equipment by integrating several energy sources. Such a system can operate either integrated into the centralised grid or in stand-alone mode. Against a backdrop of growing demand for electricity and rising energy prices, this concept has the potential to reduce the load on the electricity grid and open up new opportunities for its development.

Accordingly, the architecture of a hybrid power supply system is formed, featuring an energy management subsystem (EMS) that ensures the coordinated operation of a photovoltaic power station, a wind power station, a battery bank, a cogeneration plant and the centralised power grid.It is capable of ensuring the stable and continuous operation of boiler houses and heat distribution points even in the event of a power cut to the centralised electricity grid. The use of photovoltaic solar systems and wind power generation as part of hybrid power supply systems is a technically sound and cost-effective solution for reducing energy consumption, lowering carbon dioxide emissions and improving environmental performance.

Key factors determining the potential for implementing hybrid systems:

1) existing heating infrastructure and stable demand for heat;

2) access to fuel resources (natural gas, biomass, biogas);

3) technical feasibility of synchronisation with the electricity grid;

4) economic viability of operating cogeneration modules with an electrical capacity of 0.5–5 MW.

Table 4 presents technical data for the proposed hybrid power supply system for municipal heating boiler houses.

Table 4. Technical data for the proposed hybrid power supply system for municipal heating boiler houses.

Technical data	Photovoltaic power station	Wind power plant	Cogeneration plant	Battery
Rated power	150 kW	50 kW	500 kW	100 kWh
Efficiency	21–22%	42%	88.5%	90%
Service life	25<	25<	25 <	18,600 cycles
Operating temperature range	-40/+85	-30/+50	+5/+40	-20/+55
Model	Risen RSM110-8-550M (Titan S)	RX-50DK	INNIO Jenbacher JGS 312 GS-N-L	Deye BOS-G (High Voltage)

The proposed hybrid power supply system utilises an ACRUX-200K-H inverter ( ) with a power rating of 200 kW, a maximum DC input voltage of 1500 V, a nominal AC output voltage of 800 V, a maximum output current of 144.3 A, and an IP66 protection rating.

4. Results and Discussion

This section presents the results of the analysis of the proposed architecture for a hybrid power supply system for boiler houses in municipal heating plants. The proposed system operates on the basis of an automatic control algorithm (EMS), which optimises energy flows depending on the generation from renewable energy sources (RES), the state of charge (SOC) of the batteries, and the current load on the boiler house's pumping equipment.

Simulation was carried out in the SciLAB software environment; the technical specifications of the laptop were: ASUS TUF GAMING A15 with an AMD Ryzen 5 7535HS processor with Radeon Graphics and 16 GB of RAM. The results obtained confirm the system's operational efficiency. This study examines normal operating conditions (balanced generation).

During the day, provided there is sufficient solar activity, the photovoltaic system (PV) acts as the primary energy source. Wind turbines (WT) perform a stabilising function, compensating for short-term dips in solar generation.

The power balance in this mode is described by the following logic: The total generated power of the hybrid power supply system is directed towards covering the boiler room's load. Excess energy is distributed by the EMS system according to priority. Specifically, charging the energy storage system (Battery) until the charge level reaches its maximum. Export to the external grid; in our case, this is permitted by the technical specifications. If the power generated by the hybrid system exceeds the boiler house load, the surplus is stored in the battery or exported to the centralised electricity grid.

The following is a demonstration assessment of the potential of a cogeneration plant using the example of the JGS 312 GS-N-L plant (electrical power 500 kW, thermal power 575 kW); the results are presented in Table 5. The potential was determined based on the criterion of annual technical and economic benefit.

Table 5. Potential of a cogeneration plant in a hybrid power supply system for a boiler house.

No.	Indicators	Unit of measurement	Volume,	Rate, UAH/unit	Value, thousand UAH
1	Gas consumption by boilers	m³	64,296	12.4633	771
2	Gas consumption by KGU for heat supply	m³	69,536	12.4633	862
3	Gas consumption by KGU for EE supply	m³	69,363	16.4428	1140
4	Boiler room electricity consumption	kWh	800042	10.1574	8120
5	Annual technical and economic benefit	thousand UAH	–	–	6,808

For the demonstration example of the JGS 312 GS-N-L cogeneration plant, the potential was determined based on the criterion of annual technical and economic benefit (Table 4). According to the data provided, the boiler house’s annual electricity consumption is 800,042 kWh, which, at a tariff of 10.1574 UAH/kWh, corresponds to costs of 8,120,000 UAH. The calculated benefit (6,808 thousand UAH/year) is comparable to the boiler house’s annual electricity costs, indicating significant potential for a controllable reserve under current tariff conditions.

Table 5 also shows the structure of the fuel component (gas consumption by boilers and CHP units), which enables further scenario-based assessments of the sensitivity of the results to changes in electricity tariffs and the cost of natural gas. Further research into the structure and potential of a hybrid electricity supply system should focus on developing methodological approaches to determining the potential of renewable generation sources, namely photovoltaic power stations and wind turbines. With regard to cogeneration plants, research should focus on their operation when using gas from biogas plants, which may be associated with potential disruptions in the operation of gas transmission systems.

The research results show that the proposed hybrid system structure is capable of ensuring the energy self-sufficiency of boiler houses and heating stations during the transition to distributed energy generation. The integration of a cogeneration plant with renewable sources is a technically sound solution that allows for a reduction in the carbon footprint and operating costs.

Based on the analysis, the key performance indicators (KPIs) influencing the scalability of such systems have been identified:

- infrastructure compatibility: the availability of a stable heat load for the efficient utilisation of thermal energy from the cogeneration plant;
- resource base: availability of fuel resources (natural gas, biogas) and the potential of renewable energy sources in a specific region;

Technical integration: the ability to synchronise local generation with the external grid (Smart Grid ready).

Cost-effectiveness: The optimal power range for cogeneration units in district heating systems is 0.5–5 MW of electrical power, which ensures the shortest payback period.

6. Conclusions

As a result of the study, a coherent and methodologically consistent system of indicators for renewable energy development, environmental security, and the climate resilience of Ukraine’s energy system has been developed, based on the integration of national and international open data sources. The proposed system of indicators ensures the reproducibility of calculations and the international comparability of results, while enabling the quantitative identification of both structural transformations in the energy sector and the associated environmental and systemic effects. Particular emphasis is placed on intensity-based indicators that remain robust to changes in the scale of electricity generation.

This paper demonstrates the feasibility of using a hybrid power supply system for district heating boiler houses, utilising renewable sources of generation, battery storage, a cogeneration plant and integration with the centralised electricity grid. It is shown that the boiler room's electricity consumption profile exhibits pronounced seasonality and diurnal characteristics, which limits the efficiency of purely autonomous operation and justifies the need to operate in grid-integrated mode to improve economic efficiency.

Based on actual electricity consumption data (annual, monthly and hourly profiles), selection criteria for the structure and capacity of the hybrid system have been formulated, grouped by the following areas: reliability (power supply to critical loads and autonomy), cost-effectiveness (minimisation of levelised costs/payback period), environmental friendliness (reduction in fossil fuel consumption and CO_2 emissions) and technical feasibility (maintaining energy balance and operating mode constraints of components).

A mathematical model of the energy balance of a hybrid power supply system is proposed, which takes into account the stochastic nature of RES generation, restrictions on battery charging/discharging, the operating modes of the CHP unit, and the possibilities for power exchange with the centralised grid. The architecture of the hybrid power supply system is presented, and its main operating modes are described, which ensure an increase in the reliability of the power supply to the central heating plant boiler room in the event of disruptions in the centralised grid, with priority given to critical loads.

Using a cogeneration plant as an example, an assessment of potential was carried out based on the criterion of annual technical and economic benefit, demonstrating the possibility of practical application of the approach to justify the parameters of a controlled backup generation source within a hybrid power supply system for a boiler house.

It is also worth noting that a promising direction for further research is the application of intelligent energy management technologies, which will enable a transition from static potential assessment to adaptive planning and control of the hybrid system, taking into account the uncertainties and constraints of real-world operation.

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