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METHOD FOR ASSESSING THE EFFICIENCY OF THE DISTRICT HEATING SYSTEM UNDER MARKET CONDITIONS

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Abstract. *In response to global warming and the critical need for sustainable energy solutions, district heating systems (DHS) have emerged as an area of significant focus due to their potential to enhance resource efficiency, reduce carbon emissions, and improve economic outputs. This research addresses the critical issue of establishing a methodological framework for evaluating the efficiency of DHS as market relations evolve within the heating sector. The study's aim is to develop and validate methodological principles that assess the operational, economic, and technological dimensions of DHS in a competitive market landscape. The framework encompasses the complex interplay of regulatory frameworks, market dynamics, production technologies, and consumer engagement strategies. Key objectives include analyzing current challenges in implementing competitive market structures, justifying the non-linear nature of cost functions for energy producers, and developing criteria for the equitable distribution of thermal energy losses. The overarching goal is to strategically propel DHS towards greater efficiency and sustainability by using renewable energy sources (RES). The research utilizes simulation modeling in a case study of Irpin city, Ukraine, employing machine learning and computer vision technologies through the "Solvergy: Buildings" mobile application to provide rapid, detailed energy performance assessments. Results from the simulation in "Solvergy: Systems" software indicate benefits from the market conditions functioning in DHS, quantified at $727,120 per year, and highlight the cost-saving potential of the RES-based supply diversification structure. The relative market efficiency at 28.05% suggests that the market delivers high potential economic value relative to a scenario without market conditions. The study concludes that transitioning to market relations and integrating independent energy producers can lead to substantial system efficiency improvements, lower thermal energy prices, and enhanced sustainability in DHS. Suggested policy measures advocate for the modernizing of infrastructure and the implementation of efficient technologies within a competitive, consumer-oriented market environment, thereby facilitating the decarbonization process and optimizing system performance.*

Key words: *district heating system, district heating market, thermal energy loss, renewable energy sources, competitive bidding and auctions, multifactor optimization.*

МЕТОД ОЦІНЮВАННЯ ЕФЕКТИВНОСТІ СИСТЕМ ЦЕНТРАЛІЗОВАНОГО ТЕПЛОПОСТАЧАННЯ В УМОВАХ КОНКУРЕНЦІЇ

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З огляду на глобальне потепління та критичну потребу в стійких енергетичних рішеннях системам централізованого теплопостачання приділяють особливу увагу через їхній потенціал до підвищення ефективності використання ресурсів, скоро-

чення викидів вуглецю та покращення економічних результатів. У цьому дослідженні розглядається важливе питання створення методологічної основи для оцінювання ефективності систем централізованого теплопостачання (СЦТ), оскільки ринкові відносини розвиваються в секторі теплопостачання. Метою дослідження є розробка та перевірка методологічних принципів, які оцінюють операційні, економічні та технологічні аспекти СЦТ у конкурентному ринковому ландшафті. Структура охоплює складну взаємодію нормативно-правової бази, динаміки ринку, технологій виробництва та стратегій залучення споживачів. Серед основних цілей – аналіз поточних викликів у впровадженні конкурентних ринкових структур, обґрунтування нелінійного характеру функцій витрат для виробників енергії та розробка критеріїв для справедливого розподілу втрат теплової енергії. Основна мета полягає в тому, щоб стратегічно підштовхнути СЦТ до підвищення ефективності та стійкості за рахунок використання відновлюваних джерел енергії (ВДЕ). У дослідженні використовується імітаційне моделювання в прикладі міста Ірпінь, Україна, з використанням технологій машинного навчання та комп'ютерного бачення через мобільний застосунок «Solvergy: Buildings» для надання швидких детальних оцінок енергоефективності. Результати моделювання в програмному забезпеченні "Solvergy: Systems" вказують на переваги функціонування СЦТ у ринкових умовах, які кількісно оцінені в 727 120 доларів США за рік, і підкреслюють потенціал економії витрат структури диверсифікації постачання на основі ВДЕ. Відносна ефективність ринку на рівні 28,05 % свідчить про те, що ринок забезпечує високий економічний потенціал порівняно зі сценарієм без ринкових умов. У дослідженні зроблено висновок, що перехід до ринкових відносин та інтеграція незалежних виробників енергії сприятиме істотному підвищенню ефективності системи, зниженню цін на теплову енергію та підвищенню стійкості в СЦТ. Запропоновані політичні заходи спрямовані на модернізацію інфраструктури та впровадження ефективних технологій у конкурентному, орієнтованому на споживача ринковому середовищі, тим самим полегшуючи процес декарбонізації та оптимізуючи продуктивність системи.

Ключові слова: *система централізованого теплопостачання, ринок централізованого теплопостачання, втрати теплової енергії, відновлювані джерела енергії, конкурентні торги та аукціони, багатофакторна оптимізація.*

List of Abbreviations and Symbols:

DHS – district heating system

DHM – district heating market

SQP – sequential quadratic programming

RES – renewable energy sources

Introduction and task statement. In the context of global warming and the pressing need for sustainable energy solutions, the efficiency of district heating systems (DHS) has garnered significant attention. The transition to market relations within the heating sector presents both opportunities and challenges for enhancing operational efficiency, sustainability, and customer satisfaction. Evaluating the effectiveness of reforms in DHSs is essential for policy development, strategic planning, and the technological advancement of district heating infrastructures. Such assessments have the potential to optimize resource use, reduce carbon emissions, and improve economic outcomes for both suppliers and consumers. Establishing a methodological framework for evaluating the efficiency of DHSs amid the formation of market relations is a critical issue for assessing the feasibility of transitioning to more competitive, efficient, and environment-friendly centralized DHSs.

The effectiveness of a district heating system can be assessed through various economic, ecological, and technological efficiency indicators. However, each of these approaches must consider the current state of energy in the region to identify the most effective strategies for enhancing system efficiency. In Ukraine, for instance, the transformation of DHSs should focus on the utilization of renewable energy sources (RES) and customer-centric strategies, emphasizing the significance of strategic, sustainable, and feasible reforms aimed at improving energy efficiency, operational reliability, and financial stability [1, 2].

Among the challenges confronting DHSs in Ukraine are outdated infrastructure, a high dependence on natural gas, financial constraints, the necessity for modernization, and significant air pollution stemming from emissions produced by energy facilities [3]. Key strategies for enhancing the efficiency of DHSs in Ukraine include balancing heat demand with production and transportation capacities, integrating biomass as an alternative fuel source, and introducing competitive market dynamics to improve the quality and accessibility of heat supply services [4].

The adaptation of electricity market policies to DHSs is a particularly relevant area of study. Numerous researchers emphasize the necessity of establishing competitive conditions in DHSs that are akin to those found in electricity supply systems. For instance, market liberalization can motivate industrial heat producers to utilize waste heat as an additional resource within district heating networks. Under competitive conditions, the system can adopt pool and peer-to-peer (P2P) market models, wherein the integration of new participants into district heating systems emphasizes consumer choice through differentiated products, allowing consumers to select their preferred heat sources [5, 6]. Furthermore, various trading strategies available in the market may influence the feasibility of utilizing excess heat and the efficiency of centralized DHSs [7, 8].

It is also crucial to implement practices that regulate third-party access to the DHS from the production side, particularly through unilateral auctions. Adopting these measures could result in lower prices, draw in new consumers, and facilitate the decarbonization of the heat supply sector. Concurrently, significant attention should be directed towards the role of the regulatory framework, market structures, and pricing mechanisms [9]. The economic aspects of heat conservation and strategic system operation planning are vital, especially in the context of transitioning to RES. The study [10] underlines the need to revise municipal strategic energy plans and examines how local district heating tariffs can incentivize heat savings, thereby supporting the shift to fourth-generation district heating systems. By investigating the interactions between tariff policy, interest rates, and heat-saving initiatives, the study underscores the importance of aligning economic incentives with system efficiency, particularly amid technological advancements and market uncertainty. It is noteworthy that the introduction of competition in the DHS through market mechanisms, such as monthly auctions, can yield numerous economic and social benefits.

Research [11] demonstrates the feasibility and advantages of transitioning to a competitive market in DHSs, promoting the use of alternative energy sources, and enhancing the overall efficiency of the system. It also underscores the importance of robust political and regulatory support in advancing successful market liberalization initiatives. However, the introduction of market mechanisms is not without its challenges; various technical, regulatory, and economic problems accompany this process [12, 13]. Furthermore, there exists a divergence of opinions regarding the implementation of market conditions in DHSs, particularly concerning the economic justification of natural monopolies within energy sectors. A specific study [14] indicates a significant increase in district heating prices post-deregulation, resulting in public protests and debates. Therefore, the implementation of efficient operational practices within existing DHSs faces numerous obstacles, especially at the regional level, due to the presence of unique local conditions.

Factors such as the technological structure of the DHS, the conditions for utilizing energy sources, and weather variations can influence the efficiency of system operation under various models and regulatory approaches. Consequently, it is crucial to conduct system modeling to simulate the operation of the system in both static and dynamic modes, enabling the determination and optimization of efficiency indicators under suggested operational conditions. Among the primary efficiency criteria, three are often emphasized: economic, ecological, and exergetic (or technological). These indicators are subject to multi-objective optimization, which significantly enhances the stability and efficiency of district heating systems. Research [15, 16, 17] highlights the energy and exergy benefits of integrating RES into district heating, thereby advancing the application of the exergy principle in system optimization.

Research results [18, 19] indicate that district heating systems offer several advantages, including enhanced fuel efficiency, reduced heat production costs, and the potential for utilizing excess heat sources, positioning them as a viable and environment-friendly heating solution in densely populated areas. Consequently, there is a need for a systematic shift in focus towards creating or reforming complex regional centralized systems, as this could lead to a synergistic effect that enhances their operational efficiency. An increase in consumption volume encourages greater participation of third parties in the market, driven by the prospect of increased benefits, which may result in lower thermal energy tariffs for consumers. However, it is essential to consider each individual system on a case-by-case basis, taking into account local factors [20, 21]. Furthermore, the study [22] concludes that while DHS remains competitive in regions with high heat density, it may encounter challenges in areas with low heat density. The study underscores the importance of considering future market dynamics, the integration of RES, and urban planning decisions in shaping the long-term competitiveness of district heating systems. "Power-to-Heat" systems, which facilitate the use of energy from RES for heating and hot water supply, are gaining particular attention. These systems enable the scaling of DHSs and contribute to their flexibility, resulting in a synergistic effect from integrating electric and thermal energy markets. Research findings from studies [23, 24, 25, 26] indicate that the incorporation of "Power-to-Heat" systems diminishes dependence on fossil fuels during winter months and promotes a more stable operation of both DHSs and power supply systems.

Subject of study. The subject of this study is the methodological framework for evaluating the effectiveness of the DHS, particularly in the context of developing market relations. This encompasses a comprehensive analysis of existing district heating systems, the identification of efficiency indicators, and the assessment of how market dynamics influence these systems. The research emphasizes the interplay between the regulatory framework, market design, production technologies, and consumer engagement strategies, all of which collectively impact the efficiency and sustainability of heating systems.

Object of study. The focus of this study is on district heating systems functioning within a competitive market landscape. Specifically, it investigates the operational, economic, and technological dimensions of these systems, evaluating ways to optimize and sustain efficiency amid market liberalization. The research provides a comprehensive analysis of market functioning mechanisms, bidding strategies, regulatory policies, and technological innovations that aim to enhance both the efficiency and reliability of district heating services.

The purpose and objectives of the research. Develop methodological principles for assessing the efficiency of

DHSs in the context of establishing market relations among thermal energy producers.

To achieve this goal, it is essential to address the following tasks:

- Analyze the current challenges facing DHSs from the perspective of implementing and operating under competitive conditions, and explore methodological approaches for evaluating the effectiveness of these systems, considering both economic and technological implications.
- Determine the functional structure and operational principles of the DHS amidst competition among thermal energy producers.
- Justify the non-linear nature of cost functions for thermal energy producers and heat transport organizations.
- Propose methodological principles for evaluating the equitable distribution of thermal energy losses among producers within the DHS during market operation.
- Develop methodological principles for assessing and optimizing the efficiency of the DHS in competitive conditions.

The novelty of the study is determined by the systematic solution of the high thermal energy price problem for consumers by developing a detailed methodological framework for assessing the efficiency of district heating systems in the context of market liberalization. This includes the formulation and validation of non-linear cost functions for thermal energy producers and heat transport organizations, which are critical for accurately evaluating and optimizing business activities within DHSs.

The practical relevance of this study is to provide the practical management and strategic planning of DHS in various urban settings, particularly in the context of transitioning to market-based operational frameworks. This comprehensive assessment approach can be particularly beneficial for policymakers and regulatory bodies as they devise strategies to liberalize energy markets and implement competition within DHSs.

District heating system under market conditions formation. To comprehend the operational principles of a DHS based on competition, it is essential to present a straightforward mathematical model that effectively illustrates the necessity of implementing such system. This model assesses the efficiency of the district heating market (DHM) by comparing two alternatives: a scenario involving a single producer (monopoly) versus a scenario with multiple thermal energy producers within the DHS (competition) [27, 28].

The term "district heating market" generally refers to a network of economic interactions involving fuel and energy suppliers, equipment vendors, energy service providers, heat-generating organizations, heat network operators, regulatory authorities, and thermal energy consumers. In contrast to a monopolistic DHS, where companies oversee the functions of production, transportation, and distribution of thermal energy, DHM provides for legal, financial, and property separation of the municipal vertically integrated monopolist. The primary aim of this separation is to foster competitive conditions in the thermal energy production phase, enabling independent producers to connect to heat networks and compete with other thermal energy producers, including utilities, based on self-determined pricing [29, 30].

It is important to note that energy sources that produce electricity can be utilized alongside other technological methods to generate thermal energy. Furthermore, electric boilers have emerged as an efficient and increasingly popular means of producing heat from RES, particularly in the context of district heating systems. These systems can harness electricity generated from RES such as wind, solar, hydro, and geothermal energy. Powerful electric boilers can be installed at a central station, where electricity generated from RES feeds the boilers to produce substantial volumes of hot water or steam. Thanks to smart grid technologies and real-time monitoring, the system can balance the load by predicting demand and regulating the boilers accordingly. This synchronization with other energy sources ensures optimal efficiency and minimal costs for both electrical and thermal energy production. Moreover, such approaches can mitigate issues related to system frequency instability and capacity reservation inherent in RES, thereby enhancing economic efficiency, reliability, and environmental impact [24, 31, 32].

Each energy resource, according to its intrinsic properties, will influence the nature of the cost function. Additionally, for a production company that supplies thermal energy to the heating supply system and manages multiple heat generation facilities within the market, the total cost function can become quite complex. It encompasses all costs associated with the production of thermal energy as a consumable product. The total cost function can be categorized into several components, each representing a specific type of expense incurred by the company.

To effectively minimize costs, carbon dioxide emissions, and exergy throughout the year, it is crucial to utilize a diverse array of energy sources, including RES such as solar collectors, air source heat pumps, and cogeneration plants. However, several challenges need addressing, particularly in balancing technical efficiency with economic incentives and institutional regulations as the market for district heating becomes more competitive [33]. Specifically in Ukraine, the approach to evaluating efficiency criteria may be inadequate due to unique conditions within the DHSs, such as monopolistic structures, distinct operational characteristics of heat networks, and the absence of a comprehensive regulatory framework that promotes competition within DHSs.

Methodological principles for assessing the efficiency of the DHM. To evaluate the effectiveness of implementing and functioning market relations within DHSs, a simulation model has been developed. This model allows for a quantitative assessment of the operational viability of DHM in a specified district heating system. The assessment can be based on various factors, including the configuration of existing heat networks, the volume of thermal energy consumption, and the density of demand, among others.

The model identifies three types of entities within the system: thermal energy producers, thermal energy consumers, and sections of heat networks that are integrated into a cohesive system for transporting thermal energy from producers to consumers.

Thermal energy consumers are characterized by their annual thermal energy consumption. The aggregation of this metric across all consumers constitutes the total thermal energy consumed within the DHS and is determined by the following formula:

$$Q^D = \sum_{i=1}^{n} Q_i^D , \quad (1)$$

where Q^D is the amount of annual thermal energy consumption by all consumers in the analyzed system, GJ; Q_i^D is the amount of annual thermal energy consumption by the i-th consumer, GJ; n is the number of thermal energy consumers in the system.

The responsibility for the transportation and supply of thermal energy primarily falls to the transportation organization within the system. Each section of the heat network, which consists of both a supply and a return pipeline, is characterized by several parameters, including the internal diameter of the pipeline, the method of installation (above ground, underground, or in a channel), the type of insulation, and the thickness of the insulation coating. These parameters are utilized to calculate heat and hydraulic losses in the heat network, thereby evaluating the impact of the spatial configuration of the system components.

Heat losses in heat networks are defined as the total of thermal energy losses resulting from water leakage from pipelines and the thermal energy losses due to the cooling of the coolant within the pipelines:

$$Q^L = Q^O + \sum_{j=1}^{n} q_j^S \cdot l_j , \quad (2)$$

where Q^O is amount of thermal energy losses with water leakage from pipelines, GJ; q_j^S is linear thermal energy losses due to coolant cooling in the j-th section of the pipeline, GJ; l_j is the length of the j-th section of the pipeline, m.

Thus, the simplified form of the total costs function for the organization of transportation and supply of thermal energy can be presented as follows:

$$TC^T(Q^T) = A_T + B_T \cdot Q^T + C_T \cdot (Q^T)^2 , \quad (3)$$

where TC^T is total cost of thermal energy transportation for the year, \$; A_T is constant costs for the year, which do not change depending on the amount of transferred heat, \$; B_T is the linear part of the cost of transporting thermal energy per year, which is correlated with variable costs that scale directly with the amount of heat supplied, \$/GJ; C_T is coefficient that characterizes the nonlinearity of the total cost function of thermal energy transportation, \$/GJ^2; Q^T is the amount of thermal energy transported per year, GJ.

The total amount of thermal energy that will be produced in the system for a year will be the sum of heat losses in the DHS network and the amount of annual thermal energy consumption by consumers:

$$Q_\Sigma = Q^T = Q^D + Q^L \quad (4)$$

In the DHM model, the concept of market share is introduced as a constraint, signifying the maximum amount of thermal energy that each producer is permitted to release each month. The market share for the i-th manufacturer (excluding the primary one) is computed using the market share coefficient:

$$Q_k^{max} = Q_\Sigma \cdot MS , \quad (5)$$

where Q_k^{max} is value that represents the market share as the maximum amount of thermal energy production per year for the k-th producer, GJ; MS - market share coefficient.

Each technological installation for thermal energy production can be characterized by indicators of maneuverability, particularly regarding changes in production capacity and the minimum capacity required to maintain the heat-generating station in standby mode. The minimum annual thermal energy requirement can be represented as an additional constraint for each producer within the objective function:

$$Q_k^{min} = N_k \cdot \vartheta_k \cdot n_{hs} \cdot 86{,}4 , \quad (6)$$

where Q_k^{min} represents the market share as the minimum amount of thermal energy production per year for the k-th producer, GJ; N_k is installed capacity of heat-generating equipment, MW; ϑ_k is coefficient that characterizes the minimum possible production capacity of the installation; n_{hs} is the number of days of operation of the heat generation facility in the DHS per year.

A non-linear total cost function for a heat production facility is warranted due to the complexities and variations inherent in operating costs, maintenance costs, fuel expenses, capital investments, and material costs. These factors are interrelated and cannot be accurately or effectively represented by a simplistic linear model. Therefore, the general form of the total cost function for each thermal energy producer can be expressed as follows:

$$TC_k^G(Q_k) = A_G + B_G \cdot Q_k + C_G \cdot (Q_k)^2 , \quad (7)$$

where TC_k^G is total cost of thermal energy production for the year of the k-th producer, \$; A_G is constant costs for the year, which do not change depending on the amount of thermal energy produced, \$; B_G is the linear part of the cost of thermal energy production per year, which is correlated with variable costs that scale directly with the amount of heat supplied, \$/GJ; C_G is coefficient that characterizes the nonlinearity of the total cost function of thermal energy production, \$/GJ^2; Q_k is the amount of thermal energy produced per year by the k-th producer, GJ.

Accordingly, each producer, possessing a complete cost function and a target profit level, calculates a forecasted price for the sale of thermal energy, considering market conditions and the actual quantity of thermal energy available for sale. This projected price is then included in their auction bid. The formula for calculating the forecasted price for thermal energy for each producer is as follows:

$$T_k^f = \frac{TC_k^G(Q_k^{max}) + P_k}{Q_k^{max}}, \quad (8)$$

where T_k^f is forecast price for thermal energy for the k-th producer, \$/GJ; P_k is expected annual profit for the k-th thermal energy producer, \$.

Manufacturers' bids for the auction, which specify the parameters T_k^f and Q_k^{max}, are evaluated, and the winners are determined. These winners will sell thermal energy at the tariffs and in the amounts as proposed in the submitted bid.

The total thermal energy losses in the system can be divided into two conventional components: intrinsic losses for each producer and losses in the system attributable to each producer. Thus, the total thermal energy losses in the system can be expressed using the following formula:

$$Q^L = \sum_{k=1}^{m} Q_k^L = \sum_{k=1}^{m} \left(Q_k^{LO} + Q_k^{LS}\right), \quad (9)$$

where Q_k^L is total thermal energy losses of the k-th producer for the year, GJ; Q_k^{LO} is own thermal energy losses of the k-th producer for the year, GJ; Q_k^{LS} is thermal energy losses in the system are attributed to the k-th producer for the year, GJ.

Each thermal energy producer, upon connecting to the heat network, will possess a designated section of the heat networks for the purpose of transferring thermal energy into the DHS. Heat losses can be attributed to a specific heat generation entity, allowing them to be classified as fixed or determined. The losses attributable to the k-th thermal energy producer will be calculated using the following formula:

$$Q_k^{LO} = Q_k^{ON} + C_k^{LO} \cdot Q_k, \quad (10)$$

where Q_k^{ON} is thermal energy losses for the heat generation facility's own needs for the year, GJ; C_k^{LO} is coefficient that characterizes the share of thermal energy losses from the total volume of released thermal energy by own heat networks; Q_k is the actual value of the amount of thermal energy released by the k-th producer, GJ.

The integration of independent producers into the DHS under market conditions generates uncertainty regarding the equitable distribution of thermal energy losses. Accurately attributing the costs of heat loss to various producers is both challenging and essential for economic justice. Given these considerations, the thermal energy losses in the system attributable to the k-th producer will be calculated using the following formula [34]:

$$Q_k^{LS} = (Q^{LS} - \sum_{k=1}^{m} Q_k^{LO}) \cdot (\omega_\varphi \cdot \varphi_k + \omega_\alpha \cdot \alpha_k + \omega_\beta \cdot \beta_k), \quad (11)$$

where ω_φ is the weight of the criterion $\varphi_k = \frac{l_k}{\sum_{k=1}^{m} l_k}$ is the weight of the distance of the k-th producer to the centroid of the DHS; l_k is the distance of the k-th producer to the centroid of the DHS; m is the number of thermal energy producers in the DHS; ω_α is the weight of the criterion $\alpha_k = \frac{Q_k - Q_k^L}{\sum_{k=1}^{m}(Q_k - Q_k^L)}$ is the weight of the amount of thermal energy consumption produced by the k-th producer; ω_β is the weight of the criterion $\beta_k = \frac{S_k}{\sum_{k=1}^{m} S_k}$ is the weight of the unevenness of the paths of transportation and supply of thermal energy in relation to the distance to the centroid in the system of objects of thermal energy consumption for the k-th producer of thermal energy; S_k is the level of unevenness of the paths of transportation and supply of thermal energy for the k-th producer.

At the same time, additional constraints for the objective function will be the following expressions:

$$\omega_\varphi + \omega_\alpha + \omega_\beta = 1, \quad (13)$$

$$p_\varphi^{min} < \omega_\varphi < p_\varphi^{max}, \quad (14)$$

$$p_\alpha^{min} < \omega_\alpha < p_\alpha^{max}, \quad (15)$$

$$p_\beta^{min} < \omega_\beta < p_\beta^{max}, \quad (16)$$

where p_φ^{min}, p_α^{min}, p_β^{min}, p_φ^{max}, p_α^{max}, p_β^{max} *are* minimum and maximum values of the criterion weighting coefficients, which need to be individually determined within the context of the DHS under consideration, to ensure that all criteria are fairly accounted for.

The objective function for minimizing the weighted average price of thermal energy in a DHS operating under competitive conditions is presented as follows:

$$T_w^M = \frac{\sum_{k=1}^{m} (TC_k^G(Q_k) + P_k + (AC^T(Q_\Sigma) + \frac{P_T}{Q_\Sigma}) \cdot Q_k^L(Q_k))}{Q^D} \to min, \quad (17)$$

where T_w^M is the weighted average price per unit of thermal energy as a result of the operation of the DHM, \$/GJ; AC^T is the function of the average costs of the heat transport organization in the DHS, \$/GJ; P_T is the planned profit of the heat transport organization for the year, \$; P_k is planned profit of the k-th thermal energy producer for the year, \$.

Given the non-linearity present in the cost functions of thermal energy producers and transportation organizations, the proposed solution to the problem involves the use of Sequential Quadratic Programming (SQP) for non-linear optimization within the MATLAB software environment.

The benefits for consumers arising from the introduction of DHM must be evaluated by comparing the cost of consumed thermal energy with the weighted average tariffs for thermal energy, both during its operation and in its absence. This difference constitutes one of the components of the objective function for optimizing the operation of DHM, where the market share coefficient serves as a constraint.

In the absence of DHM, the projected tariff for the main producer is:

$$T_1^{MP} = \frac{TC_1^G(Q_\Sigma^{MP}) + P_1 + AC^T(Q_\Sigma^{MP}) \cdot Q_1^L}{Q^D}, \quad (18)$$

where T_1^{MP} is annual tariff for thermal energy from the main producer without the operation of the DHM, \$/GJ; Q_Σ^{MP} is the total amount of thermal energy produced in the system for a year without the operation of the DHM, GJ.

The absolute efficiency of the DHM encompasses the total advantage to consumers resulting from the introduction of the DHM, the cumulative profits of independent producers, the earnings from the heat transport organization, and compensations for losses incurred by the primary producer, specifically when the condition U < 0 holds true. But, to compare the success of implementing competitive conditions in the DHSs of various cities, it is advisable to utilize the relative efficiency of DHM. This relative efficiency is defined as the ratio of the absolute efficiency of the market to the total cost of thermal energy consumed over the year, assuming a scenario where the market is not operational:

$$e = \frac{Q^D \cdot T_1^{MP} - \sum_{k=1}^{m} TC_k^G(Q_k) + Q_1^D \cdot T_1^f - TC_1^G(Q_1) + P_T}{T_1^{MP} \cdot Q^D} \quad (19)$$

where *e* is the relative efficiency of the DHM as a value that shows the ratio of the total benefits relative to the total cost of thermal energy in the DHS under monopoly conditions, which means that an increase in benefits in the numerator leads to an increase in the efficiency value.

Case study. District heating systems are vital components of urban infrastructure, particularly in temperate climates where seasonal heating demands are significant. This case study examines the district heating system in Irpin city in Ukraine, under market conditions where multiple heat producers compete in monthly auctions to supply energy.

The assessment was conducted to evaluate the thermal energy consumption of 19 buildings within a DHS in Irpin city, Ukraine. This study utilized the "Solvergy: Buildings" mobile application [35, 36], which leverages machine learning and computer vision technologies to rapidly analyze and determine the energy performance of buildings. Through AI-based mechanisms, this mode evaluates a building's energy class and characteristics within minutes. The objective was to determine various characteristics like total annual heat energy consumption, average and maximum heat energy power consumption, and specific thermal losses and gains through the building envelope. The calculation results were analyzed in detail, with indicators and graphs generated for each building. The example of building assessment process is presented on Fig. 1.

These results provided insights into the energy performance and highlighted areas where improvements could be made to enhance energy efficiency. Key characteristics of the obtained results are presented on Fig. 2.

The district heating system in Irpin city consists of three integral components: consumers, heating networks, and producers. On the first step, it is necessary to evaluate heat losses in the heating network during the heating period.

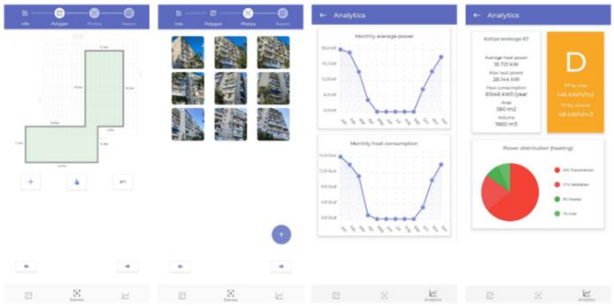

Fig. 1. The example of thermal energy consumption assessment process for a building in "Solvergy: Buildings" mobile application

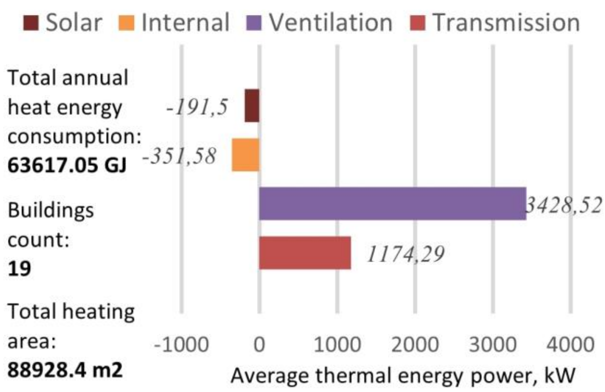

Fig. 2. Key characteristics of the provided assessment of the buildings in the DHS

The simulation was conducted using "Solvergy: Systems" software [35] as a comprehensive platform for technical and economic modeling of energy systems. This process aimed to quantify the heat losses to understand the amount that must be distributed between producers under market conditions. The district heating system under study includes 19 buildings (consumers), 130 segments of heating networks and 4 producers of the thermal energy. The simulation project in "Solvergy: Systems" software of the DHS in Irpin city is presented on Fig. 3.

Thus, the results of buildings assessment were imported to the energy system simulation as a part of Solvergy software "ecosystem". Heat demand profiles for each of the 19 buildings were established based on historical consumption data and weather conditions. As a result, the software performed a detailed calculation of heat losses across the network segments. The calculations were conducted on a temporal basis (annually, monthly, daily) to capture the dynamic nature of the heating period. The technical characteristics of the system after the calculations are showed in Table 1.

The district heating system under study operates within a market-based framework wherein thermal energy producers engage in monthly auctions to bid their price and quantity for the sale of thermal energy. This energy market adheres to a "single buyer" model, meaning that there is one central entity responsible for purchasing the energy produced by all participants. Currently, four distinct producers compete in this market, each utilizing different energy sources and possessing unique cost structures for their operations.

Fig. 3. Developed project for energy system simulation in "Solvergy: Systems" software

Historical weather data for Irpin was accurately integrated to model heat demand variations over the heating period.

The main producer in this system utilizes natural gas as its primary energy source. Historically, this entity functioned as a monopolist before the market paradigm was established. The environmental implications of natural gas consumption, such as greenhouse gas emissions, remain significant concerns. "Independent producer 1" thermal energy producer employs biomass in the form of wood pellets as its energy source. Biomass is often lauded for its renewable nature and its potential for reducing carbon emissions compared to fossil fuels. Wood pellets, in particular, are a compact and energy-dense form of biomass that can be easily transported and stored. "Independent producer 2" utilizes heat pump technology to generate thermal energy. Heat pumps are highly efficient devices that transfer heat from one location to another, often from the outside air, ground, or water into buildings. "Independent producer 3" relies on coal as its energy source. Coal has historically been a dominant source of energy due to its abundance and high energy density. However, the environmental impacts of coal have led to increased scrutiny and regulation.

In this competitive market, each producer's cost function plays a crucial role in their bidding strategies for the monthly auctions. As the market evolves, the interplay between these diverse energy sources and cost structures will shape the dynamics of the DHS, influencing both economic and environmental outcomes. The integration of RES such as biomass and heat pumps offer a pathway toward reduced carbon footprints, whereas the continuing use of fossil fuels like natural gas and coal underscores the challenges of transitioning to a more sustainable energy system. The nature of the total cost functions for each of the described producers is presented on Fig. 4.

Table 1. The technical characteristics of DHS in Irpin city, Ukraine

Name	**Total annual heat energy consumption**	**Total annual heat losses in networks**	**Average thermal energy power consumption**	**Maximum thermal energy power consumption**	**Electricity consumption for heat transmission**	**Network length**
Unit	GJ	GJ	MW	MW	kWh	km
Value	63617.05	3034.7	4.05	5.78	45959.27	6.42

Main producer, as the former monopolist, transitioning from a dominant player to one of several competitors, must adapt its strategies to remain viable in this newly structured market. As the largest actor in this market, the main producer's installed generation power is substantial, necessitating a baseline of minimum possible thermal energy generation annually to maintain operational efficiency and to meet market demand.

The simulation-based analysis demonstrates clear economic benefits from implementing market conditions in DHSs. The optimal distribution of thermal energy production among various producers and the resulting lower weighted average price underscore the potential for cost savings and efficiency gains. The model also highlights the importance of equitable loss allocation and the necessity for compensatory mechanisms for key producers. The optimization results of the DHS under market conditions are presented in Table 2.

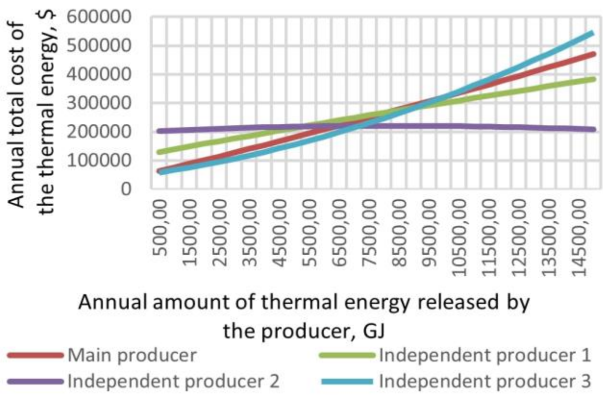

Fig. 4. Total cost function for each thermal energy producer

These results suggest a significant role for independent producers in meeting the overall thermal energy demand, highlighting the efficiency of a diversified supply structure.

Table 2. The optimization results of the distribution of thermal energy production and prices of thermal energy among the main and independent producers

Producer	Optimal Q_k, GJ	Optimal weighting factors			Monopoly price, $/GJ	Optimal weighted price, $/GJ
		ω_φ	ω_α	ω_β		
Main producer	16977	0.5	0.2	0.3	39.22	28.99
Independent producer 1	19996				-	
Independent producer 2	19996				-	
Independent producer 3	6649				-	

The optimal weighted price of thermal energy is significantly lower than the main producer's price, demonstrating the potential cost savings from implementing market conditions. At the same time, weighting factors reflect the relative importance of each criterion in the overall optimization process, indicating that distance to the centroid is the most significant factor in current DHS.

The economic benefits for market participants in DHM simulation are presented in Table 3.

Table 3. The economic benefits for market participants

Parameter	Unit	Value
Market share (*MS*)	%	30
Main producer loss (*U*)	$	0
Consumers benefit (*V*)	$	651120
Producers Benefit (*P*)	$	75000
Transportation Benefit (*H*)	$	1000
Absolute market efficiency (*E*)	$	727120
Relative market efficiency (*e*)	%	28.05

The simulation results indicate a considerable benefit to consumers from the introduction of market conditions, quantified at $651,120. Producers also realize a significant benefit of $75,000, while the transportation organization sees a modest gain of $1,000. The relative market efficiency of 0.2805 suggests that the market delivers 28.05% of the potential economic value relative to a scenario without market conditions.

Conclusions

The shift to market dynamics in DHSs is a strategic move aimed at optimizing system efficiency. Market liberalization introduces competitive pressures that can lower consumer prices, increase service quality, and drive technological innovation.

Policymakers should prioritize creating a supportive regulatory environment that encourages competition, protects consumers, and incentivizes the adoption of RES. Consideration of local conditions and unique characteristics of each DHS is crucial for the successful implementation and optimization of market-based heating systems.

The diversification of energy sources, as evidenced by the integration of biomass, heat pumps, and RES, can significantly bolster system efficiency and sustainability. This integration reduces dependency on fossil fuels, mitigating carbon emissions and advancing environmental objectives.

Methodological principles for determining and optimizing the weighted average price for thermal energy, as well as the efficiency of DHM, are proposed in the context of independent thermal energy producers competing within the system. This framework enables the modeling of DHSs from a market perspective, supporting strategic planning and decision-making for the implementation of such projects in real DHSs.

The case study of Irpin city, Ukraine, demonstrates the practical application of the developed methodological principles. The introduction of competitive market conditions in Irpin's DHS led to significant economic benefits for consumers, producers, and the transport organization, highlighting the potential gains from market liberalization.

REFERENCES

1. S. Bogut, D. White. White paper on transforming district heating in Ukraine: Assessment and recommendations, USAID, 2020. https://energysecurityua.org/wp-content/uploads/2021/04/050G-DH_White-Paper_for_DEC-2021-02-02-ENG.pdf
2. Tuchynskyi, B., Kudria, S., Ivanchenko, I., Ivanchuk, V. Inevitability of Ukraine’s transition to renewable energy. Vidnovluvana Energetika. 2020. (4(63), 6-21. https://doi.org/10.36296/1819-8058.2020.4(63).6-21
3. A. Zaporozhets, V. Babak, A. Sverdlova, L. Scherbak, Y. Kuts. Review of the state of air pollution by energy objects in Ukraine. System Research in Energy, 2022. Vol. 71, pp. 42-52. https://doi.org/10.15407/srenergy2022.02.042
4. K. Engelmann, M. Čavar, J. Buganova, S. Martinkrista, J. Čižman, M. Mladenović, K. Tomliak, M. Shlapak. Improving the performance of District Heating Systems in Central and Eastern Europe. 2020. https://keepwarmeurope.eu/fileadmin/user_upload/Resources/Deliverables/KeepWarm_D5.2_Development_of_Multi-level_policy_Plans.pdf
5. A. Faria, T. Soares, J. M. Cunha, Z. Mourão. Liberalized market designs for district heating networks under the

EMB3Rs platform. Sustainable Energy, Grids and Networks. 2022. Vol. 29. https://doi.org/10.1016/j.segan.2021.100588

6. A. Faria, T. Soares, J. M. Cunha, Z. Mourão. Mutual-benefit of district heating market and network operation for prosumers integration. Energy Sources, Part B: Economics, Planning, and Policy. 2023. Vol. 18. https://doi.org/10.1080/15567249.2023.2280568
7. B. Doračić, M. Pavičević, T. Pukšec, N. Duić. Bidding strategies for excess heat producers participating in a local wholesale heat market. Energy Reports. 2022. Vol. 8, pp. 3692-3703. https://doi.org/10.1016/j.egyr.2022.02.307
8. I. Blanco, D. Guericke, A. N. Andersen, H. Madsen. Operational Planning and Bidding for District Heating Systems with Uncertain Renewable Energy Production. Energies. 2018. Vol. 12, p. 3310. https://doi.org/10.3390/en11123310
9. A. Pažėraitė, V. Lekavičius, R. Gatautis. District heating system as the infrastructure for competition among producers in the heat market. Renewable and Sustainable Energy Reviews. 2022. Vol. 169. https://doi.org/10.1016/j.rser.2022.112888
10. S. Djørup, K. Sperling, S. Nielsen, P. Østergaard, T. J. Zinck, P. Sorknæs, H. Lund, D. Drysdale. District Heating Tariffs, Economic Optimisation and Local Strategies during Radical Technological Change. Energies. 2020. Vol. 13, p. 1172. https://doi.org/10.3390/en13051172
11. D. Korsakaite, D. Bieksa, E. Bieksiene. Third-party access in district heating: Lithuanian case analysis. Competition and Regulation in Network Industries. 2018. Vol. 19, pp. 218-241. https://doi.org/10.1177/1783591719837410
12. V. Bürger, J. Steinbach, L. Kranzl, A. Müller. Third party access to district heating systems - Challenges for the practical implementation. Energy Policy. 2019, Vol. 132, pp. 881-892. https://doi.org/10.1016/j.enpol.2019.06.050
13. K. Bauermann. German Energiewende and the heating market – Impact and limits of policy. Energy Policy. 2016. Vol. 94, pp. 235-246. https://doi.org/10.1016/j.enpol.2016.03.041
14. D. Magnusson, J. Palm. Between natural monopoly and third party access - Swedish district heating market in transition. Monopolies: Theory, Effectiveness and Regulation. 2011. pp. 1-33. https://www.researchgate.net/publication/285726324_Between_natural_monopoly_and_third_party_access_-_Swedish_district_heating_market_in_transition
15. H. Dorotić, T. Puksec, N. Duic. Economical, environmental and exergetic multi-objective optimization of district heating systems on hourly level for a whole year. Applied Energy. 2019. Vol. 251. https://doi.org/10.1016/j.apenergy.2019.113394
16. L. Frölke. Market Design for Future District Heating Systems. DTU Wind and Energy Systems. 2023. https://doi.org/10.11581/dtu.00000253
17. J. v. Woerden. A conceptual model to grasp the district heating market. 2015. https://www.semanticscholar.org/paper/A-conceptual-model-to-grasp-the-district-heating-A-Woerden
18. C. H. Hansen, O. Gudmundsson. The competitiveness of district heating compared to individual heating. Green Energy Association. 2018. https://danskfjernvarme.dk/media/zulfbv0j/the-competitiveness-of-district-heating-compared-to-individual-heating.pdf
19. Kovalko O. M., Kovalko N. M., Yevtukhova T.O., Novoseltsev O.V. Communal heat and power engineering: energy efficiency, management structure, energy service services. Kyiv: NAS of Ukraine, In-stitute of General Energy. 2023. URL: https://web.nlu.org.ua/object.html?id=2196
20. P. Söderholm, L. Wårell. Market opening and third party access in district heating networks. Energy Policy. 2011. Vol. 39, pp. 742-752. https://doi.org/10.1016/j.enpol.2010.10.048
21. E. Landelius, M. Astrom. District heat price model analysis, Malardalen University Sweden, 2019. https://www.divaportal.org/smash/get/diva2:1325101/FULLTEXT01.pdf
22. U. Persson, S. Werner. Heat distribution and the future competitiveness of district heating. Applied Energy. 2011. Vol. 88, pp. 568-576. https://doi.org/10.1016/j.apenergy.2010.09.020
23. M. Schindler, L. Gnam, M. Puchegger, K. Medwenitsch, P. Jasek. Optimization-Based Operation of District Heating Networks: A Case Study for Two Real Sites. Energies. 2023. Vol. 16, № 2120. Pp. 1-15. https://doi.org/10.3390/en16052120
24. V. P. Babak, M. M. Kulyk. Increasing the efficiency and security of integrated power system op-eration through heat supply electrification in Ukraine. Science and Innovation. 2023. Vol. 19, № 5, Pp. 100-116. https://doi.org/10.15407/scine19.05.100
25. Derii, V., Teslenko, O., Lenchevsky, E., Denisov, V., Maistrenko, N. Prospects and Energy-Economic Indicators of Thermal energy Production Through Direct Use of Electricity from Renewable Sources in Modern Heat Generators. In: Zaporozhets, A. (eds) Systems, Decision and Control in Energy IV. Studies in Systems, Decision and Control. 2023.Vol. 454. Springer, Cham. https://doi.org/10.1007/978-3-031-22464-5_27
26. Leshchenko I., Shulzhenko S., Kaplin M., Maistrenko N., Shcherbina Ye. Assessment of the greenhouse gases reduction by the oil and gas sector of Ukraine to meet international climate agreements. In: Zaporozhets A., Popov O. (eds) Systems, Decision and Control in Energy IV. Studies in Systems, Decision and Control, Springer,

Cham. 2023. – vol 456. – P. 199-212. https://doi.org/10.1007/978-3-031-22500-0_13

27. V. Deshko, D. Karpenko. Analysis of conditions for the creation of the local thermal energy mar-ket in Ukraine. Municipal Economy of Cities. 2018. 7(146). pp. 68–76. https://doi.org/ 10.33042/2522-1809-2018-7-146-68-76
28. V. Deshko, D. Karpenko. Analysis of aspects and simulation modeling of the thermal energy mar-ket in Ukraine. Management of technological processes in energy technologies under the general editor-ship of Anatoliy M. Pavelko. 2019. Kielce, Politechnika Swietokrzyska, 7-4. http://bc.tu.kielce.pl/366/1/M-120.pdf
29. V. Deshko, D. Karpenko. Functional Structure of the Local Thermal Energy Market in District Heat-ing. 2019 IEEE 6th International Conference on Energy Smart Systems (ESS). 2019. Kyiv, Ukraine, pp. 343-346. https://doi.org/10.1109/ESS.2019.8764211
30. A. Mahnitko, Y. Veremiichuk, V. Deshko, D. Karpenko. Scenario Analysis for Increasing Efficiency Level of the Autonomous Generation Object in Central Heat Supply. 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Tech-nical University (RTUCON), Riga, Latvia. 2019. pp. 1-7. https://doi.org/10.1109/RTUCON48111.2019.8982299
31. M. K. Oleksandra Hotra, V. Babak, S. Kovtun, O. Zgurovets, J. Mroczka, P. Kisała. Organisation of the Structure and Functioning of Self-Sufficient Distributed Power Generation. Energies. 2024. Vol. 27. https://doi.org/10.3390/en17010027
32. Khilko, V. Measures to support renewable energy in Ukraine. Vidnovluvana Energetika. 2021. (3(66), 6-17. https://doi.org/10.36296/1819-8058.2021.3(66).6-17
33. Kuznietsov, M. Complex use of renewable energy sources – results of the scientific and practical conference 2023. Vidnovluvana Energetika. 2023. (2(73), 6-10. https://doi.org/10.36296/1819-8058.2023.2(73).6-10
34. D. S. Karpenko, T. O. Yevtukhova, O. V. Novoseltsev, O. I. Teslenko. Market features of heat pro-ducers contribution to losses in district heating system networks. Scientific notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences. 2024. Vol. 35 (3). https://doi.org/10.32782/2663-5941/2024.3.1/37
35. Innovative Tools for Energy Efficiency Assessment. Solvergy. (n.d.). https://solvergy.org/
36. P. A. Østergaard, A. N. Andersen, P. Sorknæs. The business-economic energy system modelling tool energyPRO. Energy. 2022. Vol. 257. https://doi.org/10.1016/j.energy.2022.124792