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Improving the efficiency of district heating systems as a way to achieve decarbonization goals in the municipal sector

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Abstract. The results of research on the justification of methods for decarbonizing municipal energy by increasing the efficiency of centralized heat supply systems and reducing energy losses in the municipal sector are presented. The tasks of determining energy efficiency indicators and factors that influence them are comprehensively considered. For the first time, the existing changes in meteorological climate characteristics that occurred in the period after the establishment of outdoor air standards in Ukraine were studied. The impact of meteorological characteristics on heat supply indicators for heating and ventilation needs, as well as associated CO₂ emissions, was determined. The magnitude of energy losses at all stages of operation of centralized heat supply systems was analysed. Losses in the process of heat supply regulation were considered for the first time. The methodology of the work is based on an analytical analysis of the operation of existing heat supply systems, theoretical studies and the results of an energy audit of heat supply systems. The obtained dependencies make it possible to prevent unproductive heat losses and solve decarbonization problems. Scientific and practical results of the work make it possible to implement decarbonization in the municipal sector by reducing the use of fossil fuels.

1. Introduction

Decarbonization refers to the process of lowering greenhouse gas emissions, especially carbon dioxide (CO₂), within district heating systems, and it represents a critical scientific and practical challenge today. The significance of district heating is expected to grow, with projections indicating that by 2050, it will account for 50% [1-3] of the total heat supply across Europe. Currently, approximately 60% of the population has access to district heating services [4]. In the European Union, district heating systems are responsible for 42% of primary energy consumption [5], with a substantial 75% of this energy derived from fossil fuels. Evaluating the volume of greenhouse gases and working towards their reduction is a vital part of developing national greenhouse gas inventories, enterprise reporting, the implementation of the Carbon Border Management Mechanism (CBMM), and managing quota trading systems [6].

The European Union's strategy, articulated through the European Green Deal [7] in late 2019 by the European Commission, outlines a set of ambitious objectives aimed at promoting sustainable development within the community. A key goal of this strategy is to make Europe the



first continent to achieve climate neutrality, targeting zero net greenhouse gas emissions by the year 2050. Additionally, Ukraine has expressed its intention to align with these progressive initiatives. Through a decree issued by the Cabinet of Ministers on September 3, 2014 (No. 791) [8,9], Ukraine committed to embracing the European Parliament's directives on decarbonization and is dedicated to reaching environmental neutrality by 2050.

A comprehensive approach to addressing this issue involves shifting the municipal heating sector away from conventional fossil fuels toward renewable energy options such as heat pumps, biomass, or fuels that rely more on hydrogen than on carbon [10, 11]. This transition allows for a significant reduction in specific CO₂ emissions, decreasing from 0.105 to 0.371 kg CO₂/MJ when using fossil fuels, down to as low as 0.0318 to 0.0519 kg CO₂/MJ when harnessing geothermal energy through heat pumps [12, 13]. Furthermore, low-carbon intensity sources like waste heat can produce emissions ranging from 0.0012 to 0.0017 kg CO₂ E/MJ [14], while solar energy contributes emissions of approximately 0.0595 to 0.0694 kg CO₂ E/MJ [15].

An equally critical aspect of addressing decarbonization challenges in the municipal sector is enhancing the efficiency of heat supply systems and minimizing the fuel consumption required for generating heat used in building heating and ventilation. Reducing greenhouse gas emissions from heat generation is fundamentally connected to these improvements [1, 16]. The overall emission of greenhouse gases during the heat generation process can be expressed through a specific relationship:

$$CO_2 = Q \cdot KB, \quad (1)$$

where CO₂ is the amount of CO₂ emissions into the atmosphere, t;

Q is heat release for heating and ventilation needs in the district heating system, MWh;

KB is CO₂ emission factor, which determines the mass amount of CO₂ that is formed when generating a unit of thermal energy, KB = 0.151 t/MWh (when burning natural gas) [17].

Dependence (1) shows that reducing the need for heat Q for heating and ventilation linearly affects CO₂ emissions.

And reducing the amount of heat Q by the simplest methods can be achieved by reducing unproductive heat losses in the heat supply system, or by implementing more investment-intensive projects for thermal modernization of heated buildings.

Historically, heat supply systems in European Union countries are categorized into different generations, ranging from 1st generation to 5th generation, with the majority classified as third generation (3GDH) [18]. The incorporation of heat storage solutions and the digital transformation of district heating networks enhance the ability to integrate renewable energy sources and utilize waste heat effectively. This integration plays a significant role in lowering emissions and improving system reliability [19].

Thermal energy storage systems provide the capability to accumulate heat and release surplus thermal energy during periods of lower demand, which helps to reduce operating costs and diminish reliance on peak generation facilities [20]. One effective strategy for minimizing the carbon footprint within district heating systems involves lowering the temperature of the heating water, transitioning from approximately 100 °C typical in 3GDH systems to within the range of 50 to 70 °C seen in 4GDH systems [21]. This adjustment leads to reduced heat losses, improved energy efficiency, and a decrease in associated carbon dioxide emissions.

However, implementing this lower temperature approach is often not feasible for heating systems in Ukraine. Instead, alternative methods focused on enhancing energy efficiency are necessary to address decarbonization challenges during the restoration of Ukraine's heating infrastructure.

2. Research methodology

The selection of approaches to tackle the decarbonization challenge within municipal energy systems hinges on the design, operational state, and technologies utilized in heat supply infrastructures. In Ukraine, a notable shift is occurring from the centralized heat supply systems established in the 20th century toward advanced 3rd and 4th generation systems. The support provided by international organizations in rebuilding these systems, which have been affected by the conflict, plays a significant role in facilitating this shift. The initiatives aimed at reconstructing and enhancing the energy efficiency of heat supply systems are extensive infrastructure undertakings that involve the construction sector, energy generation and distribution facilities, and heat supply management. To achieve optimal outcomes, including environmental benefits, it is crucial to thoroughly assess the present condition of the existing heat supply systems.

The focus of this article is on creating strategies and initiatives aimed at enhancing energy efficiency to facilitate decarbonization in district heating systems. This analysis considers the existing conditions of these systems in Ukraine, as well as the climate changes that have transpired since the implementation of regulatory frameworks that define the design parameters for external climate conditions.

This research explores strategies aimed at minimizing heat generation and, consequently, lowering fuel consumption through enhanced system efficiency and the mitigation of unnecessary heat losses. The study's objective is to identify key projects and initiatives focused on decreasing heat losses within the heating supply system, as well as to evaluate their effects on climate change resulting from the greenhouse effect.

The authors employed various research methods, including a comparative critical analysis of existing literature and relevant regulatory documents. They utilized analytical techniques to examine distinct elements of heat transformation processes within district heating systems, such as generation, transportation, and implementation. Additionally, the authors drew on their own theoretical insights and experimental investigations conducted during energy audits and the formulation of heat supply schemes for cities in Ukraine. This approach was also applied when designing projects and strategies aimed at decarbonizing the municipal energy sector, ensuring compliance with established requirements [22].

3. Results and discussion

The survey of heat supply systems during the performance of energy audit work and the preparation of heat supply schemes showed that unproductive heat losses in them consist of losses at the heat generation stage, ΔQ_{gen} ; losses during the transportation of the coolant from energy sources to consumers, ΔQ_{trans} , as well as heat losses that occur when regulating the release of heat to consumers when the outside air temperature changes, ΔQ_{reg} .

This makes it possible to write the heat balance equation for the system when performing its energy audit in the following form:

$$VQ_h^f = Q_{hd} + Q_{hv} + \Delta Q_{gen} + \Delta Q_{tr} + \Delta Q_{sp} + \Delta Q_{reg}, \quad (2)$$

where V is the fuel consumption for the period of energy audit, m^3 ;

Q_h^f is the fuel combustion heat, kWh/m^3 ;

Q_{hd} is the heat demand for heating consumer buildings, MWh ;

Q_{hv} is the heat demand for ventilation consumer buildings, MWh .

Unproductive heat losses at the generation stage ΔQ_{gen} in dependence (2) depend on the efficiency of fuel combustion plants and do not exceed, as a rule, 8-12% of the thermal potential of the fuel. Heat losses at the transportation stage ΔQ_{tr} depend on the diameter of the pipelines of the heat networks, their condition and length. For the longest heat networks in Ukraine, this value does not exceed 12-13% of the thermal potential of the fuel [23]. This value of heat losses is normalized as the maximum possible for networks with a length of more than 1000 m. And its reduction is achieved by introducing well-insulated pipelines. The execution of these projects is primarily obstructed by the significant investment required for the pipelines, as well as the insufficient working capital available to heating supply companies. Therefore, the total, regulatory heat losses at the generation and transportation stages can reach values of 20...25% of the thermal potential of the fuel.

Special attention in the study was paid to heat losses from regulating heat release in connection with changes in outdoor air temperature.

In this issue, two tasks were considered:

- firstly - the range of regulating heat release according to the magnitude of changes in outdoor air temperature;
- secondly - analysis of methods of regulating heat release.

To assess the regulatory range, a study was conducted examining variations in meteorological conditions of the outdoor climate, as well as the alterations in calculated parameters relevant to engineering assessments of heat supply systems. This investigation specifically focused on the meteorological characteristics of Kryvyi Rih.

The analyzed meteorological parameters of the outdoor air that affect the indicators of energy activity for heating needs and, accordingly, the associated CO₂ emissions include the following:

- duration of the heating period;
- average temperature of the heating period;
- temperature of the coldest day;
- temperature of the coldest five-day period.

The values of the specified parameters specified in the regulatory documentation [24] were taken as the base ones. This document was approved in 2011. When compiling the DSTU, information from meteorological observations of weather stations for the period 1961-2005 was used.

Therefore, the studies of climate parameters from 2005 to 2025 performed in the work make it possible to expand and update meteorological characteristics for the period from the compilation of the DSTU to the current year for the selection of calculated climate parameters and determination of the main characteristics of engineering systems of heating, ventilation and heat supply.

Building a trend line of possible changes in meteorological climate parameters based on the change scenario from 2005 to 2025 makes it possible to predict the parameters of outdoor air as of 2050, by which time Ukraine is planned to achieve climate neutrality according to [25].

Table 1 shows the basic calculated parameters of outdoor air according to the current DSTU, which are used today, although determined based on the results of observations from 1961 to 2005.

Table 1. Normative current parameters of outdoor air for some cities of Ukraine [4]

City	Cold period temperature, °C				Period with average daily air temperature less than +8 °C	
	The coldest day of security		The coldest five-day period with security		duration, days	Average temperature, °C
	0,98	0,92	0,98	0,92		
Kyryvi Rih	-26	-23	-18	-17	171	0,2

The findings from the processing and analysis of climate parameters for the winter months in Kryvyi Rih, covering the years 2005 to 2025, are illustrated through graphs in Figures 1 to 4.

The anticipated length of the heating season is 141 days, a reduction from the previously estimated 171 days (Fig. 2).

The forecasted temperature for calculating heating systems is -13 °C for 2050 (Fig. 3).

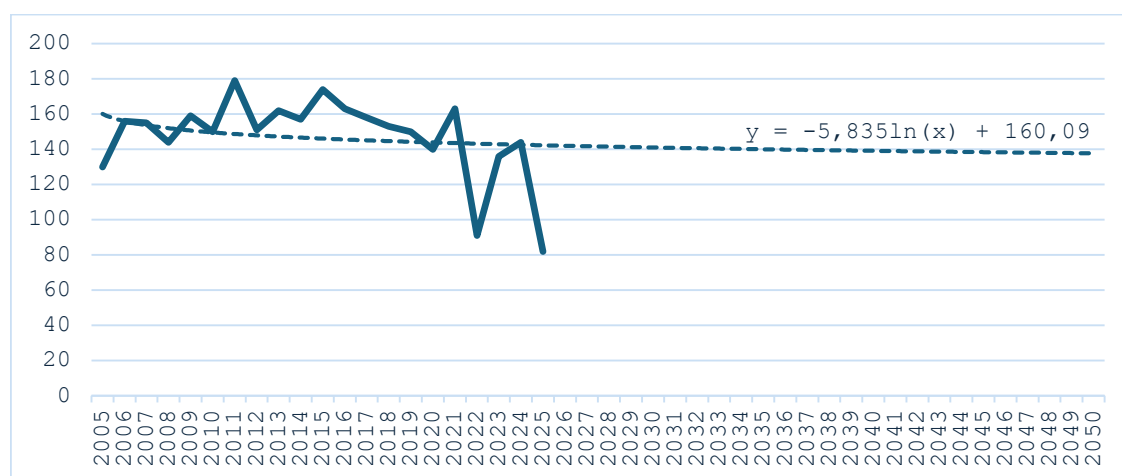


Figure 1. Findings from the evaluation and prediction of the heating season duration between 2005 and 2025.

The analysis of meteorological data revealed notable shifts in climate, indicating a warming trend. This change affects the heating requirements of systems, highlighting the necessity to broaden the regulation of heat output.

Analysis of climatological data of the cold period of the year over the past 20 years shows that the selection of equipment for heating systems according to meteorological characteristics

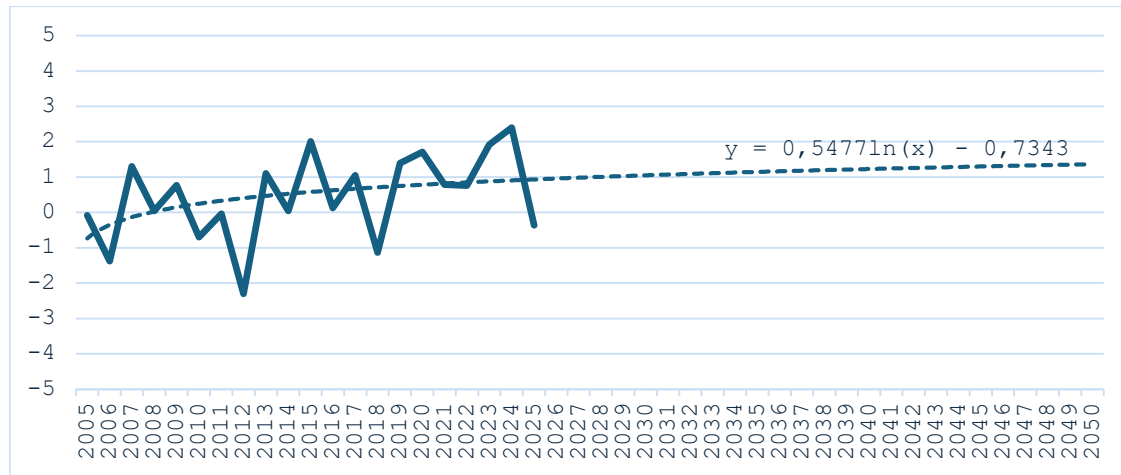


Figure 2. Analysis and prediction of average heating period temperatures between 2005 and 2025.

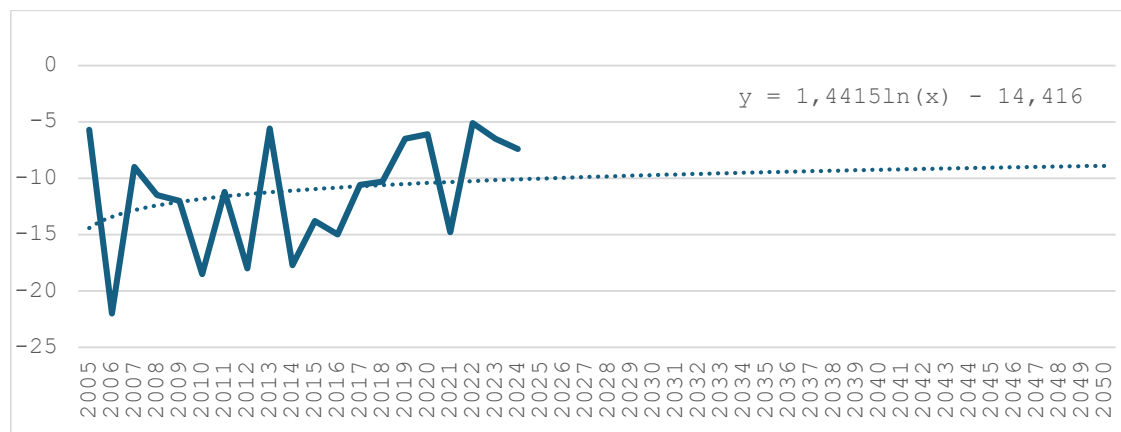


Figure 3. Analysis and prediction of the lowest temperature five-day Span, utilized for assessing heating system heat demand.

leads to the fact that the largest period of equipment operation falls on the period when the outdoor air temperature is in the range from 0 to +5 °C.

The duration of equipment operation in the nominal operating mode is only about 0.7% of the total duration of the heating period. At the same time, 70% of the equipment operating time falls on the period when its heat output is within 25–40% of the nominal values. The heat output regulation coefficient for the fuel-ignition equipment is in the range of $K = 2.5\text{--}4.0$. When the equipment operates within this range, it results in substantial unproductive losses and a decline in efficiency in efficiency. For example, it is known that deviations in the load of heat generators in the direction of decreasing from the nominal for every 10% reduce the net efficiency of boilers by 1–1.5%.

Adjusting the calculated parameters for external air based on up-to-date data, along with carefully selecting the heating capacity of heat supply system equipment, can effectively address this issue. Such measures have the potential to greatly lower fuel and electricity usage in the municipal sector. Additionally, this approach will contribute to a decrease in the emissions of carbon dioxide, a significant greenhouse gas.

Calculations indicate that adjusting the estimated outdoor air temperature—specifically the lowest five-day period—upward by only 5°C (e.g., changing from -20°C to -15°C) can significantly diminish the heating demand. For buildings that have not undergone thermal modernization and possess an average conditional heat transfer coefficient of $K = 1 \text{ W/m}^2 \cdot ^\circ\text{C}$, this adjustment can lead to a reduction in heating heat flow or connected heat load of $\Delta Q = 0.5 \text{ MW}$ per 100,000 m² of heated space. Consequently, the required heat load for this area would decrease from 3.8 MW to 3.3 MW, representing a reduction of 13% along with its associated implications.

The examination of meteorological climate characteristics indicated that the energy system responsible for heat generation for heating purposes exhibits a degree of self-regulation concerning anthropogenic CO₂ emissions. Specifically, the use of high-carbon fuels for heating buildings results in increased CO₂ emissions. These emissions contribute to the greenhouse effect, leading to a warming trend and more favorable climatic conditions. Consequently, this shift reduces the demand for heating, which in turn decreases fuel consumption and subsequently lowers CO₂ emissions.

The following studies were devoted to the analysis of methods for regulating heat output.

The most common method at heat supply enterprises in Ukraine is the qualitative (temperature) method of central regulation of heat output, during which the coolant temperature changes depending on the outdoor air temperature under the condition of constant coolant consumption. There are not enough standardized local control devices in houses using automatic weather-controlled individual heat points in Ukraine.

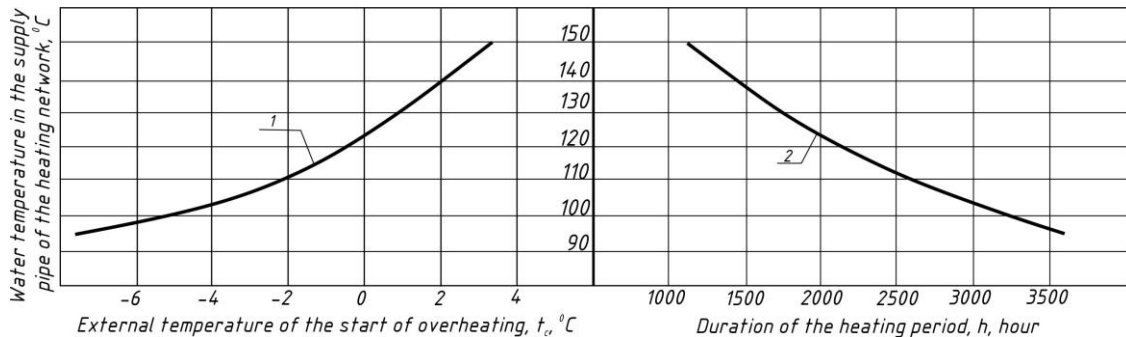
The control process is carried out using a temperature schedule for heat release. The presence of hot water supply systems connected to centralized networks, as well as restrictions on the temperature at the inlet to the boilers, lead to the presence of a "breakpoint" in such schedules, which corresponds to the temperature of hot water in the supply pipeline of about 60 – 65 °C. This temperature is attained at varying outdoor air temperatures, which are influenced by the specific type of temperature schedule employed.

The primary issue arises during the "cut-off" period, specifically when outdoor air temperatures range from +8°C up to the break point temperature T_s' . During this time, a phenomenon known as "overheating" occurs. This is attributed to the fact that the temperature difference defined by the "cut-off" schedule remains constant, while the heating schedule necessitates a reduction in this difference as outdoor temperatures rise. Consequently, there is a requirement for either central control or localized adjustments in heat output to meet heating demands during the "cut-off" temperature schedule. However, such regulatory measures are currently not implemented in Ukraine.

This results in significant heat losses associated with the lack of weather-based regulation of heat release and significant overheating.

The length of time a heating system operates in "overheating" mode is greatly influenced by the specific temperature schedule for heat distribution. Figure 4 demonstrates the relationship between the duration of operation in "overheat" mode and the outdoor air temperature at the "breakdown" point, as it relates to the water temperature in the supply lines of the heating networks.

As can be seen from the above graphical dependencies at hot water temperature and the use of high-temperature temperature graphs, for example, 150/70°C, the duration of the



4. Dependence of the temperature at the "break" point and the duration of the "overheating" period on the calculated temperature in the supply pipeline (temperature graph view) for the meteorological conditions of the city of Kryvyi Rih.

"overheating" period is only 1159 hours, and the "break" of the graph occurs at an outdoor air temperature of about +3.5°C, which reduces the amount of unproductive heat losses to 1.7% of the annual volume of heat sold.

But when switching to low-temperature graphs, which is typical for modern heat supply systems in Ukraine, the situation changes.

Releasing coolant based on reduced schedules results in a notable escalation of heat losses due to the inability to control the heat output effectively. As illustrated in Figure 5, when the hot coolant temperature decreases from 150 °C to 95 °C, the duration of the reheating process extends significantly from 1159 hours to 3600 hours. Additionally, the loss of central quality regulation occurs when the outdoor air temperature reaches -7.5 °C or higher, aligning with the system operating in reheating mode for up to 3600 hours of 4400 hours of the heating period. And unproductive heat losses and fuel overconsumption increase to 18% of the annual volumes (Fig. 5).

The easiest way would be to avoid such high losses by returning to an increased coolant temperature. But this is no longer possible, because the transition to low-temperature heat release schedules is a trend of modern 4th generation heat supply systems. Additionally, this involves implementing processes for effectively cooling combustion byproducts by harnessing the heat released during their condensation. But the European requirement for the transition to a low-temperature coolant should have been accompanied by a mandatory standardized transition to condensing boilers and compliance with the requirements for eco-design of heat generators, as well as a low temperature of the combustion products after the boilers (60-70 °C) [25]. But unfortunately this was not done.

And the vast majority of boilers in the centralized heating system of Ukraine still operate in non-condensing mode with a high temperature of exhaust combustion products (higher than 120....130 °C). And there are no requirements for a gradual mandatory transition to the condensation mode of operation in Ukrainian regulations yet.

The research findings lead the authors to conclude that implementing a low-temperature heat release schedule is impractical if it is not accompanied by the installation of condensing heat exchangers on the exhaust gases of district heating system boilers. Additionally, maintaining the existing central control principles in boiler rooms further exacerbates the issue, resulting in a marked decline in the overall efficiency of the heating system.

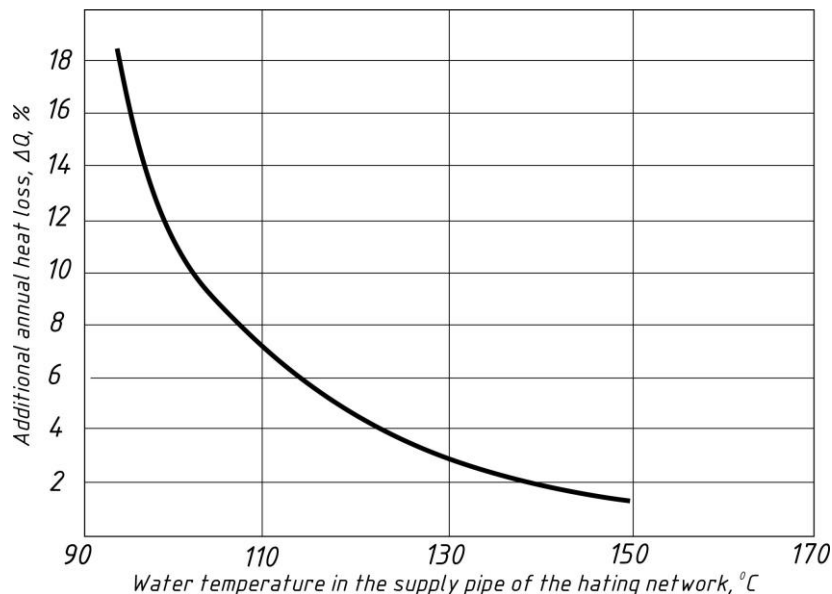


Figure 5. Dependence of annual heat losses when regulating heat release due to the rejection of the temperature schedule depending on the temperature in the supply pipeline of heating networks.

Heat losses during weather-dependent heating regulation can be minimized by adopting both quantitative and qualitative control methods. This approach involves primarily adjusting the coolant flow rate to manage the heat output for most of the operational period, instead of altering the temperature of the coolant. This makes it possible to almost completely solve the issue of seasonal overheats during the period of temperature schedule cutting, significantly reduce fuel consumption, reduce associated CO₂ emissions and achieve decarbonization goals.

A mandatory condition for implementing such regulation is the presence of automated individual heat points with weather regulation at heat consumers. Otherwise, thermal and hydraulic deregulation of the heat supply system cannot be avoided.

Regulation of coolant flow rate depending on the heat load can be performed according to the data in Fig. 6.

To achieve effective regulation of the heat load, which reflects the average temperature during the heating season (approximately 50% of the determined value), it is necessary to decrease the relative coolant flow to around 30% of the calculated consumption. This is relevant for a heating network designed with a heat release temperature schedule of 115/70 °C.

Equipping heat consumer buildings with modern automated ITPs and the accompanying transition to combined qualitative and quantitative central regulation on sources of heat energy generation requires the mandatory installation of automatic frequency drive regulators on network pumps of boiler houses, changes in the thermomechanical scheme of boiler houses, as well as optimization of the thermal power of boiler units in accordance with the connected thermal load. Such reconstruction of boiler houses must necessarily make it impossible to reduce the consumption of the coolant circulating through the boilers and ensure the separation of the boiler circuit and the circuit of the heating networks according to one of the known schemes.

It is essential to consider the additional funding needed for the renovation of boiler houses when planning projects that involve the installation of automated ITPs equipped with weather regulation systems.

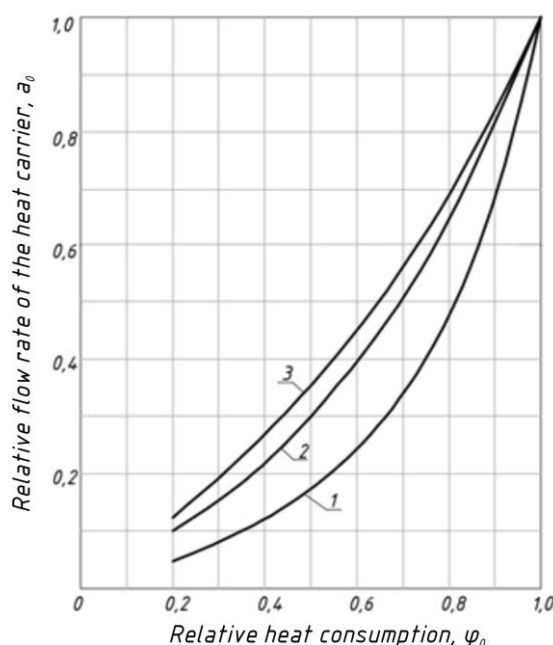


Figure 6. Quantitative control schedule and determination of relative coolant flow rate for the heat release temperature schedule 90/70 °C -1; 115/70 -2; 135/70 -3 °C

The complete transition to both quantitative and qualitative regulation can only occur once automated heat distribution stations equipped with mixing devices are installed in every building linked to the centralized heating system, without any exceptions.

Therefore, the choice of the final solution regarding the temperature schedule of heat release from the boiler room and the method of reducing heat losses during the period of "cutting" the temperature schedule must be carried out on the basis of a technical and economic calculation taking into account the technical characteristics of heat generators and equipment installed at consumers. But in any case, the reconstruction of heat release control systems in centralized systems of Ukrainian cities will make it possible to reduce unproductive heat losses by 18...20% of the fuel's thermal potential.

4. Conclusions

Enhancing the efficiency of centralized heating systems while minimizing unnecessary heat losses is a key strategy for advancing decarbonization objectives in municipal energy sectors.

Using European experience and implementing in Ukraine projects for the transition of centralized heating systems from the 1GDH or 2GDH generation to modern 3GDH ... 5 GDH should be carried out comprehensively, taking into account all accompanying conditions and requirements. Otherwise, a negative result will be obtained. For example, the transition to low-temperature release schedules without mandatory compliance with the requirement to reduce exhaust gases after heat generators (boilers) leads to significant heat losses during the temperature cut-off period.

Research on the meteorological features of the external climate has verified the reality of climate change. This has highlighted the necessity to revise the calculated parameters of outside

air, which are essential for assessing the thermal power and heating loads in ventilation and heat supply systems.

Analysis of meteorological climate characteristics also showed that the energy system in which heat is generated for heating needs and anthropogenic CO₂ emissions are to some extent self-regulating – high carbon fuel consumption for heat generation for heating buildings leads to increased CO₂ emissions into the atmosphere. As a result of the greenhouse effect, these emissions cause a warming effect and a softening of climate parameters, which in turn affects the reduction of heat demand for heating. This leads to a corresponding reduction in fuel consumption for heating and a reduction in CO₂ emissions.

A significant contribution to anthropogenic greenhouse gas emissions is made by unproductive heat losses in the process of weather-dependent heat regulation of centralized heat supply systems. The conducted studies have shown that changing the principle of regulation from qualitative to quantitative by changing the amount of coolant makes it possible to reduce the amount of unproductive heat losses and reduce the carbon footprint in municipal heat supply systems by 18...20%.

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