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Transformation of outdated district heating systems

Abstract. The transformation of outdated district heating (DH) systems is a pressing issue for countries with well-developed DH infrastructure, which was predominantly built in the previous century and designed for the use of fossil fuels. These systems face the simultaneous challenges of replacing obsolete equipment, improving fossil fuel efficiency, and substituting these fuels with renewable energy sources and waste energy resources. These challenges must be addressed while ensuring the stable supply of thermal energy to consumers. Solving such a complex and multifaceted task requires the development of a scientifically grounded strategy. The pace of modernization and decarbonization of DH systems varies significantly across countries. For Ukraine, which is among the countries with a developed but outdated DH infrastructure, the transformation and decarbonization of this vital energy system are being approached based on European experience, adapted to national circumstances. This study focuses on the methodological and techno-economic aspects of a transitional strategy for decarbonizing large, outdated DH systems, taking into account the specific features of the current state of such systems in Ukraine. It examines the necessity and content of transitional plans, the experience of DH system transformation in EU countries, key methodological considerations of transition planning, including temporal changes in DH systems, the current structure and condition of existing DH networks, the potential for fossil fuel substitution with renewable energy sources, criteria for comparing different decarbonization approaches, third-party access to district heating networks, and directions for further research into DH decarbonization. Natural gas is the main fuel used in existing outdated DH systems, and gas boilers are the primary source of thermal energy. These form the baseline for evaluating the economic efficiency of alternative transformation pathways. The study demonstrates the economic feasibility of replacing gas boilers with solar district heating plants equipped with seasonal thermal energy storage. *Bibl. 29, Fig. 9, Tab. 3.*

Keywords: methodology for transforming outdated gas-fired district heating systems, thermal hydraulic clusters, change in operating costs in district heating systems over time, threshold

values of heat load density and linear heat density indicators, current state of district heating in Ukraine, comparison of natural gas substitution technologies, hybrid district heating systems with local solar hot water systems, solar heating systems in combination with gas boiler houses, integrated approach to modernization of district heating systems and buildings.

Introduction

The transformation of outdated large-scale technical systems is a relevant research area that remains insufficiently explored [1, 2].

This area concerns technical systems such as electric power systems, district heating (DH) systems, water supply and wastewater systems, transportation systems, and residential building stocks of settlements. All these systems were mostly developed during the last century over several generations. Today, they have become obsolete and require fundamental modernization. Most studies focus on analyzing the current state and the future structure of these systems, but the transitional period has received insufficient attention, even though such research is highly relevant at present.

This study is dedicated to the transformation of outdated DH systems, which is especially important for countries with well-developed DH systems built during the previous century. Ukraine is one of these countries; therefore, this research is based on information regarding DH systems in Ukrainian settlements. However, the general methodological approach may also be useful for other countries that are actively developing DH systems and may face similar challenges in the future as discussed in this study.

Developing transition plans for the transformation of DH systems requires detailed consideration of the following aspects:

— assessment of the possibility (or advisability) of further operation of the existing outdated DH systems without significant transformation and evaluation of the consequences of such a strategy from technical, economic, environmental, and social perspectives;

— assessment of the scale of the existing systems, the scale of the necessary changes to be implemented, evaluation of the required financial resources, and comparison with actually available resources;

— definition of the timeframes, rational sequence of transformation steps, the scope, and cost of each stage;

— identification of priority objects for transformation based on clearly formulated criteria;

— determination of the role of conventional fuels, especially natural gas, in the process of their replacement by renewable energy sources;

— identification of priority technologies and options for combining different transformation technologies for outdated systems;

— interrelation between the transformation of outdated heating systems and other large systems related to DH.

These questions are addressed in more detail in this study.

Experience of transforming outdated district heating systems in EU countries

In 2019, the total installed solar district heating plants capacity in Europe reached 37 GW (th) [3]. The total available solar thermal energy storage (STES) capacity from solar thermal systems amounted to 185 GWh.

In 2017, there were 194 solar DH plants in European countries [4]. The largest numbers of these STES are found in Denmark, Austria, Germany, and Sweden (Figure 1).

An example of the construction of a seasonal thermal energy storage (STES) system for use in a city's DH system is shown in Figure 2.

One of the innovative projects in Germany is the waste and biomass incineration plant "Müllverwertung Borsigstraße GmbH" (MVB), whose main goal is to ensure safe waste disposal in Hamburg. The project envisions connecting the power plant directly to the DH system of the city of Hamburg. Depending on demand, the energy generated by burning waste and biomass can supply the DH network, while steam will be available for the "Hamburg Tiefstack" power plant. The implementation of this project is based on two main ideas: utilizing flue gas heat through condensation combined with absorption heat pumps on all three incineration lines (two waste lines and one biomass line), and recovering exhaust steam from the turbine, which is used to produce 20 MW of electricity. The exhaust steam will be condensed in a new heat exchanger. The combined additional thermal output amounts to 60 MW. This increase in available energy can reduce CO_2 emissions from the DH system

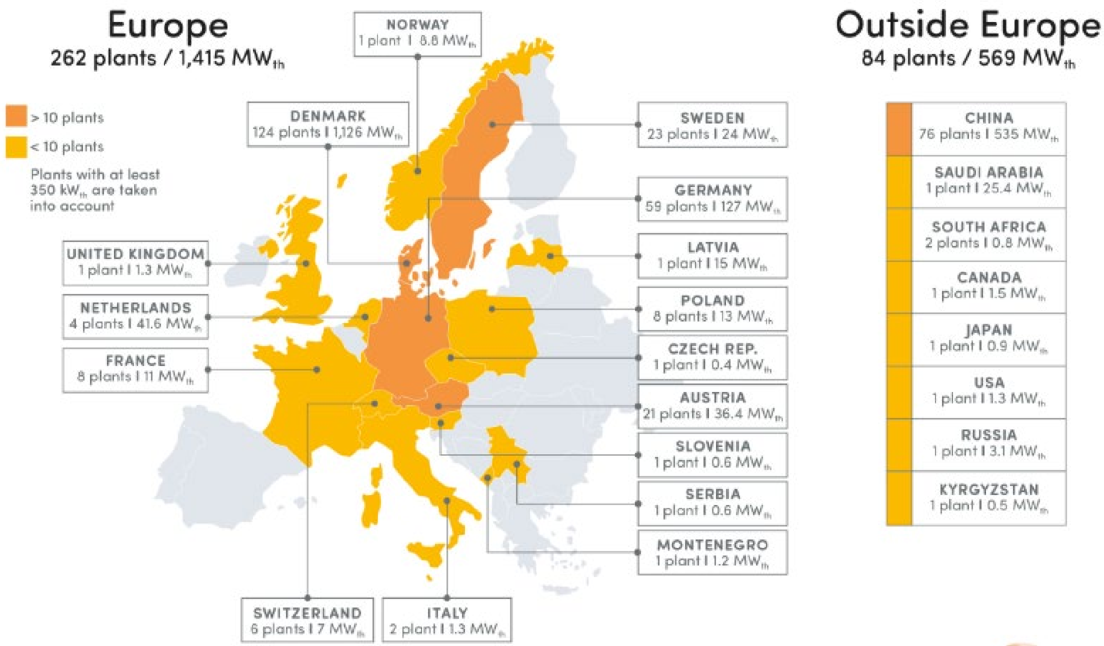

Figure 1. 346 towns and cities use solar district heating (end of year 2024).

Figure 2. Germany's largest thermal storage tank is 45 m high, 43 m in diameter, and has volume of 56,000 m^3 [5].

by up to 104,000 tonnes per year.

This project is unique in Germany [6].

Denmark plans to remain a global green leader in climate action, inspiring and encouraging the rest of the world. The country's ambitious goal is to reduce emissions by 70 % by 2030 and achieve climate neutrality by 2045. District heating is a key component of Denmark's future energy system [7].

For example, a unique project is being implemented in the city of Aarhus (Denmark), where the largest geothermal DH system in the EU is being developed [8].

Application of geothermal technologies at a thermal source (TS) with a maximum capacity of 110 MW, which corresponds to 20 % of Aarhus's DH demand [9], is planned for deep horizons down to 3,000 m. To extract heat from underground, it is first necessary to locate water in so-called geothermal reservoirs. If the porosity and permeability of the formation are sufficiently high, water can be pumped to the surface at a high rate. These reservoirs are located 1,000–3,000 meters below the Earth's surface — quite deep. To reach this depth, it is necessary to drill through several subsurface layers, including drinking water aquifers [10]. To protect drinking water, the well is lined with several "telescopic" steel casings and cement, and wells are regularly checked for leaks. In case a leak is detected, production is immediately stopped, and the well is repaired.

It is planned that the entire station will include 17 wells and 7 plants, as well as heat exchangers and heat pumps that will extract heat from geothermal water and transfer it to the DH network. This project started in 2022 after detailed geological and seismological studies. As of the end of 2024, the first plant has been implemented, and research on all calculated indicators is ongoing. During 2026–2029, the remaining plants are planned to be launched, and from 2030, full-scale operation of this unique station will begin. The expected operational lifetime is at least 30 years, with annual CO_2 emissions expected to be reduced by up to 165,000 tonnes.

A similar project is planned for Greater Copenhagen. An agreement has been signed between Denmark's largest waste-to-energy company Vestforbrжnding and the geothermal company Innargi to integrate geothermal energy into the Greater Copenhagen DH network. This will be combined with waste heat recovery and carbon capture technologies aimed at creating diversified and resilient heat supply [11]. This project will provide district heating for 39,000 households in seven municipalities, such as Ballerup, Herlev, and Lyngby-Taarbæk. All municipalities will benefit from an expanded DH network, which is expected to nearly double Vestforbrжnding's current heating capacity. When operated with renewable electricity, this process is CO_2-neutral and emits no harmful particulates.

In Bremen (Germany), a flexible combined heat and power (CHP) plant has been implemented, allowing for a gradual phase-out of coal [12]. The gas engine CHP offers heat and flexible baseload during winter while eliminating peak demand in summer, providing significant economic benefits. Due to its modular design, the plant operates with exceptional efficiency at any load, both in CHP mode and in electricity-only mode. The plant's electrical capacity is 105 MW, with a thermal capacity of 93 MW, and it is planned to reduce CO_2 emissions by 75 %.

Large solar collector fields are very popular in Denmark's DH system, even though solar radiation conditions at high latitudes are less favorable than in many other regions. Achieving the target of 100 % decarbonization of Danish DH systems by 2030 requires continuous integration of renewable energy sources such as solar and wind, using large heat pumps and geothermal heating [13]; large-scale and seasonal heat storage, as well as increased utilization of industrial waste heat.

In recent years, the capacity of solar collectors in Danish DH systems has increased. Currently, near the city of Silkeborg, Denmark hosts the world's largest solar thermal collector field supplying a DH system. Opened in 2016, this heat-generating plant consists of 157,000 square meters of solar collectors with a capacity of 110 MW.

The capacity of heat pumps in Denmark's DH systems has also increased in recent years, and experts expect this trend to continue as gas and coal networks are gradually phased out [14]. As of 2020, over 1.6 million square meters of solar collectors supply heat to around 120 small and medium-sized DH systems in Denmark, with a total installed capacity of 1,100 MW. The annual heat production is about 700 GWh, which represents almost 2 % of the total heat supply to Danish district heating networks.

In 2023, a large heat pump (70 MW) was installed in Esbjerg, Denmark. This heat pump uses carbon dioxide as a refrigerant. It is called the world's largest seawater-based CO_2 heat pump and is expected to supply approximately 280 GWh of climate-neutral heat annually, covering the heating needs of 25,000 households. To meet future heating demand, a 60 MW biomass boiler will be built to operate in parallel with the heat pump. Thus, fossil fuels (coal), which were previously used in this city for heat supply, will be completely replaced. Moreover, the flexibility of the heat pump technology allows for full utilization of the connection to the electrical grid, providing electricity balancing services in a very short time by increasing or decreasing electricity consumption.

The above EU country projects meet strategic decarbonization requirements in accordance with the Energy Efficiency Directive (EU) 2023/1791 [15], implementing various measures aimed at accelerating improvements in energy efficiency, including the application of the "energy efficiency first" principle in both energy and non-energy policies. Compliance with this Directive is mandatory for all EU member states.

As European integration is one of Ukraine's priority directions in foreign policy, Ukraine must also align with the requirements of the member states in the DH sector. The main strategic documents for achieving this are the Association Agreement between Ukraine and the EU and the Treaty establishing the Energy Community.

The Association Agreement was ratified in 2014 by the Verkhovna Rada and the European Parliament [16]. The Agreement aims to strengthen relations between Ukraine and the EU and regulates tasks related to the development of the economy, politics, transport, energy, and agriculture.

The main objectives of the Energy Community are:

– creating a stable legal and commercial framework conducive to investment to ensure stable and continuous energy supply;

– creating a single regulatory space for energy exchange within the network;

– enhancing supply security in this sector and developing relations with neighboring countries;

— increasing energy efficiency and environmental protection related to network energy, as well as developing renewable energy sources;

— strengthening competition in network energy markets.

In addition, on December 15, 2022, the Energy Community Ministerial Council adopted new ambitious joint energy and climate targets for 2030 for all Contracting Parties [17]:

— improve energy efficiency:

— reduce final energy consumption to 79.06 million toe;

— reduce primary energy consumption to 129.88 million toe;

— achieve 31 % renewable energy in gross final energy consumption;

— reduce greenhouse gas emissions by 60.9 % compared to 1990 (< 427.64 million tonnes CO_2 equivalent).

Considering the above factors, Ukraine also faces ambitious targets according to its National Emission Reduction Plan [18], which require a comprehensive approach to reducing energy consumption and replacing fossil fuels with renewable energy sources. Unfortunately, at present, there is no methodology for the transformation of outdated DH systems. For European countries, this is not as crucial as for Ukraine, which, in addition to transformation, also needs measures to restore the energy sector under conditions of limited funding and constant attacks on energy facilities by Russia. Therefore, the authors believe that this research is extremely relevant at this time.

Methodology and materials

The methodology of this study is based on the general theory of change, analysis of the current state of DH systems, and comparative techno-economic analysis of the process of replacing traditional energy sources with known technologies for producing thermal and electrical energy from renewable energy sources, waste heat, and combined heat and power units.

The main components of the theory of change include: analysis of the current situation, identification of problems and their causes, prioritization of causes, identification of stakeholders, listing tasks, actions and measures, determination of necessary resources, monitoring and evaluation of results [19].

The methodological approach to analyzing the current state of DH systems was presented in study [20], which showed that problems in this area are interrelated and often create closed loops of cause-and-effect relationships. Therefore, it is very important to identify key problems and focus on solving them.

Based on the analysis of data on the current state of DH systems in Ukrainian settlements, it can be concluded that the key problems are the low energy efficiency of DH systems and the high dependence on a single type of fuel — natural gas. This creates a closed loop of cause-and-effect relationships (Figure 3).

The presented diagram indicates that, on the one hand, the state's compensation of heat energy

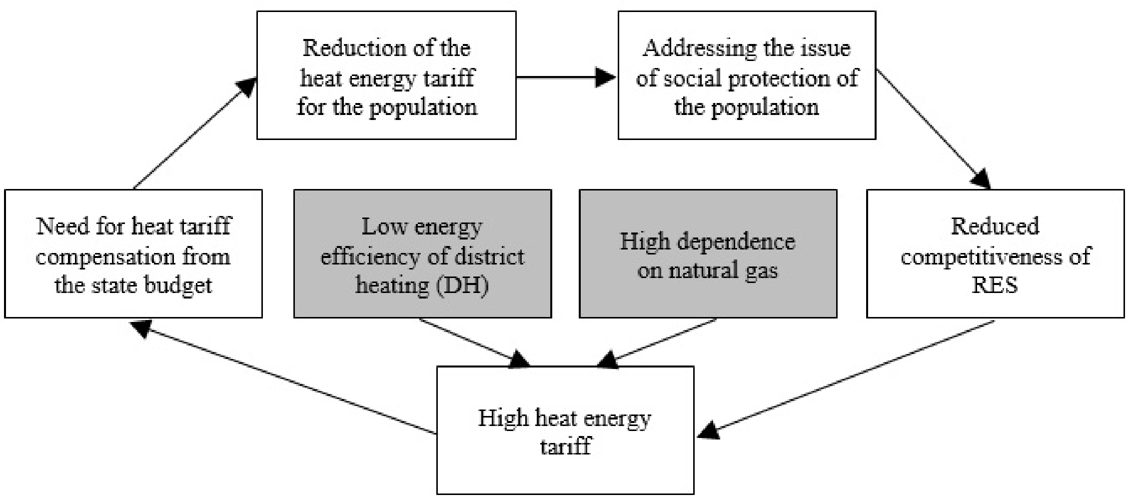

Figure 3. Closed loop of cause-and-effect relationships in DH systems of Ukrainian settlements.

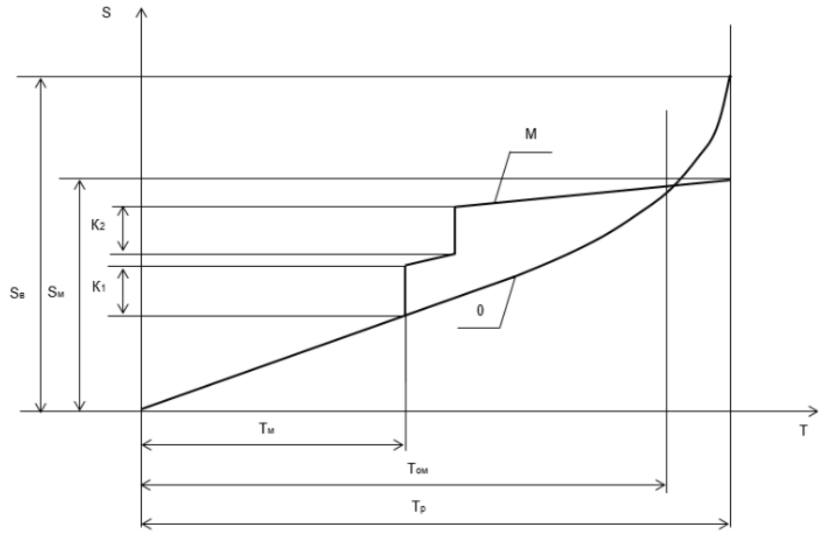

Figure 4. Change in total costs over time without (scenario 0) and with modernization of DH (scenario M).

tariffs for the population helps to address the issue of social protection under conditions of high DH tariffs. On the other hand, it hinders the implementation of projects aimed at replacing natural gas with renewable energy sources, thus creating a closed loop of energy inefficiency in DH systems.

Obviously, a reasonable path forward is the gradual implementation of projects to replace natural gas with renewable energy sources (RES) and waste heat, as well as improving the efficiency of natural gas use through energy-saving measures, including CHP generation. In this approach, natural gas and existing boilers should be considered as balancing tools during the transition period, enabling an increase in the share of variable RES-based vaste energy generation.

In this study, a holistic approach was applied to thermal sources, heat networks, and the connected heat consumers. All these components are united under the concept of a thermo-hydraulic cluster. A thermo-hydraulic cluster is defined as a set of one or more continuously operating, interconnected thermal sources, heat networks, and heat supply entry points in buildings connected to the heat networks.

Research results

The analysis of the temporal changes in DH energy production costs and the determination of the critical point for initiating DH system transformation are illustrated in Figure 4, where are: T — time; T_p — planning period; T_m — start time of modernization; T_{0m} — start time of the period when the total costs of scenario 0 become lower than those of scenario M; S — total costs (capital and operational); S_0 — total costs of scenario 0 at the end of the planning period; S_m — total costs of scenario M at the end of the planning period; K_1 — capital expenditures for the first stage of DH modernization under scenario M; K_2 — capital expenditures for the second stage of DH modernization under scenario M.

Figure 4 conditionally illustrates two stages of DH modernization. In practice, there may be more stages.

As shown in Figure 4 above, in the absence of modernization of the DH system (scenario 0), the operating costs of such a system increase significantly over time due to the need to eliminate breakdowns and repair aging equipment, as well as increased losses in heat production and transportation. This trend requires modernization at a certain point in time, T_m. The point T_m is characterized by a noticeable change in the linear character of the total cost curve, where the ratio $\Delta S / \Delta T$ and operating costs start to increase more and more nonlinearly. Modernization can be carried out in several stages (two stages are shown in Figure 4), requiring certain capital investments at each stage (K_1 and K_2 in Figure 4). The implementation of modernization changes the nature of the total cost curve (line M in Figure 4) so that, after a certain point in time T_{om}, the total costs of scenario M become lower than those of scenario 0 and eventually $S_m < S_0$, which is the ultimate goal of DH system modernization. The point T_{om} should be considered as the payback period for the capital investment $K = K_1 + K_2$. It should be noted that failure to modernize the system (scenario 0) will ultimately lead to reduced resilience, reliability issues in heat supply, and loss of operational capability of the DH system.

Current state of DH systems

An important component of the transformation plan for outdated DH systems is the assessment of the scale of existing systems, their current condition, necessary changes, required financial resources, and the rational sequence for implementing the transformation.

In terms of installed capacity, Ukraine's DH systems are among the largest in Europe. They operate in more than one hundred settlements and supply heat to almost 100,000 buildings with a total area of about 300 million m^2. There are more than 4,000 boiler houses in Ukraine's DH systems, with over 12,200 boilers and a total installed capacity of 52.6 GW. The total length of DH networks (measured in two-pipe equivalent) is about 21,000 km, but 56 % of these DH networks require replacement. Transforming such a large outdated system requires significant financial resources, which cannot be allocated all at once but only in separate tranches over a long period. The total amount of necessary financial resources has not yet been precisely determined, but preliminary estimates suggest that replacing only the outdated sections of DH networks will require about USD 2.6 billion. Therefore, it is important to define priorities and funding volumes according to planned tasks.

Key features of DH systems in Ukrainian settlements include.

1. Heat energy is produced at a large number of boiler houses with installed capacities ranging from < 1 MW to 100 MW and more, but most of the heat is produced at a relatively small number of large boiler houses (≥ 20 MW). These boiler houses should serve as starting points for transforming outdated DH systems. However, 83 % of the boilers in these facilities have been in operation for over 15 years. About 75 % of the DH networks connected to these boiler houses are more than 15 years old. Thus, the powerful boiler houses and their connected DH networks, which form the backbone of Ukraine's DH system, are outdated and require modernization.

2. The main fuel used in Ukraine's DH systems is natural gas (86 %). The consumption of other fuels, including peat and coal, is about 13 %. The share of heat production from biofuels does not exceed 1 % (2023). There is virtually no use of solar energy, ambient energy, or waste heat. The installed capacity of small CHP units at boiler houses is minimal, so electricity for DH internal needs is mainly supplied from local grids.

3. Gas boiler houses lack backup fuel sources, posing a threat to stable heat supply in case of potential gas supply interruptions.

4. The total number of buildings connected to DH is about 100,000, but only a small portion of them have undergone thermal modernization and meet modern energy efficiency requirements. This introduces uncertainty regarding the required installed capacity of DH systems during energy efficiency transformations.

5. Most heat sources and DH networks are owned by municipal heat supply companies, which are also the operators of the heat networks. This must be considered when ensuring third-party access to the heat networks, which is an important tool for transforming outdated gas-based DH systems.

All these features should be taken into account when developing the transformation plan for outdated DH systems.

The transformation targets should include not only boiler houses but entire thermo-hydraulic clusters of high-capacity boiler plants, with the priority for transformation determined according to the following criteria:

– heat load density and linear heat density;
– condition of DH networks;
– availability of centralized domestic hot water supply systems, which increase the investment attractiveness of certain thermo-hydraulic clusters;
– potential for replacing natural gas with RES, waste energy potential, and CHP.

Table 1. Limit values of heat load density (HLD) and linear heat density indicators (LHDI)

Indicator value	Existing DH zone	Existing individual (autonomous) heating zone	Planned high-rise development zone
HLD ≥ 50 MW/km^2	DH	CBA	DH
HLD = 30–50 MW/km^2	CBA	CBA	CBA
HLD ≤ 30 MW/km^2	CBA	IH/AH	IH/AH
LHDI ≥ 3 MWh/m	DH	CBA	DH
LHDI = 1–3 MWh/m	CBA	CBA	CBA
LHDI ≤ 1 MWh/m	CBA	IH/AH	IH/AH

Heat load density is defined as the ratio of connected and/or projected heat loads for space heating, ventilation, and domestic hot water preparation to the area of residential and public development where existing and/or future consumers are located. Linear heat density is defined as the ratio of annual heat supplied to consumers to the length of the DH networks used for its transportation.

The quantitative values of heat load density and linear heat density indicators are discussed in detail in [21, 22].

In Table 1, abbreviations are interpreted as follows: CBA — cost-benefit analysis recommended; DH — district heating recommended; IH/AH — individual or autonomous heating recommended.

According to the data in Table 1, priority transformation objects are thermo-hydraulic clusters with HLD ≥ 50 MW/km^2 and LHDI ≥ 3 MWh/m.

The selection of the most suitable technologies for replacing existing gas boilers

It is carried out by performing a comparative techno-economic analysis and constructing a ranked list of known technologies (Figure 5). As a comparison criterion, it is appropriate to consider the levelized cost of energy (LCOE). To compare technologies, it is sufficient to consider the LCOE indicator at a zero discount rate.

Various known energy production technologies can be considered, including a baseline technology for comparison. The baseline should be the existing energy production technology used at the boiler plant under consideration, which is usually outdated gas boilers with low efficiency. For example, in Figure 5, the baseline technology is technology 6. Technologies 1–5 have a lower LCOE than LCOE$_6$, therefore their implementation is considered economically feasible. Technologies 7–10 have a higher LCOE than LCOE$_6$, and thus their implementation is considered economically infeasible. The alternative technologies which shoud to be considered include high-efficiency gas boilers, heat recovery systems for gas boilers (including condensing economizers), cogeneration units operating on natural gas and biomass, heat pumps utilizing low-grade waste heat, ambient air, natural water bodies, and wastewater, electric boilers, solar thermal plants, and combined energy sources using the aforementioned sources. It is also advisable to consider combining energy sources with energy storage systems: daily and seasonal thermal storage, as well as electricity storage systems.

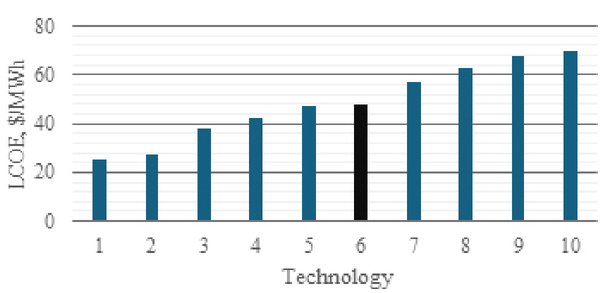

Figure 5. Example of a comparative analysis of the techno-economic efficiency of heat production technologies in DH.

Hybrid DH system with local solar domestic hot water systems

A systemic drawback of traditional DH systems is the reduction in energy efficiency during the non-heating season due to high specific heat losses in pipelines connecting the heat source and domestic hot water (DHW) consumers. Reference [23] examines a conceptual scheme of hybrid district heating systems (HDHS), where space heating is provided centrally, while DHW is supplied by a local heat source. A mathematical model was developed to perform a comparative techno-economic analysis of two modernization scenarios for the heating system: replacing boilers, heat networks, and pumps while maintaining the traditional DHW scheme and replacing these elements combined with installing a local DHW heat source that supplies consumers via a local heat network, which is significantly shorter than the existing one. As local heat sources, electric boilers and solar collectors with electric backup heating were considered. The advantages of HDHS schemes were demonstrated for a 10-year planning horizon. A calculation-based analysis was conducted to evaluate the influence of different factors on the benefits of the HDHS scheme. The developed model can be used for preparing techno-economic feasibility studies for energy-efficient modernization projects of DH systems.

Solar district heating plants integrated with gas boiler houses

One of the most promising and environmentally friendly directions for replacing natural gas with

RES in existing DH boiler houses is the use of solar energy. This can be implemented by constructing solar district heating plants (SDHP) with STES. If there are suitable free areas on or near the existing gas boiler house site to accommodate SDHP and STES, these possibilities should be thoroughly investigated.

For conducting such studies and preliminary assessments, a techno-economic model has been developed for replacing natural gas-derived thermal energy at a boiler house that operates during the heating season. The potential investment project consists of replacing a share of thermal energy produced from natural gas with solar thermal energy generated by SDHP and accumulated in STES throughout the year, primarily during the non-heating period when solar irradiation is at its maximum. The model enables determination of the dependence of capital expenditures and payback period of SDHP and STES on the share of thermal energy to be replaced by solar energy, as well as other influencing factors.

Data on actually constructed STES systems presented in [24] indicate that the specific cost of STES decreases significantly with increasing storage volume, which can be represented by an exponential relationship (Figure 6).

Using the example of a gas boiler house with an installed capacity of 10 MW, numerical modeling was performed to assess the impact of the share of natural gas substitution by solar energy on the main parameters that determine the feasibility and economic viability of implementing a project for the installation of SDHP and STES on the territory of or near the gas boiler house. The main input data for the simulation are presented in Table 2, and the main simulation results are presented in Figure 7.

The simulation results show that the project of integrated application of SDHP and STES has a long payback period and specific energy cost, which is explained by the large capital costs for STES, which make up 55–70 % of the total cost of the project. With an increase in the share of natural gas replacement by solar energy, the T and LCOE indicators improve, which is explained by the decrease in the specific cost of STES with an increase in its volume (Figure 6).

As the price of natural gas increases, the economic feasibility of implementing a comprehensive project of SDHP and STES increases but will remain low. Figure 8 illustrates the impact of the price of natural gas on the T and LCOE of the project, as well as the normalized cost of energy for a gas boiler LCOE(b) for comparison.

The performed calculation study shows that the replacement of gas thermal generation using gas boilers for the energy complex of SDHP and STES can be economically justified with a significant increase in the price of natural gas, the use of powerful STES with a volume of more than 20 thousand m^3, a decrease in the specific cost of STES and state financial support for the implementation of projects of this type.

Ensuring third-party access

Most DH companies in Ukraine are municipally owned. These companies typically include both basic energy sources (BES), primarily gas boiler houses, and thermal networks (TN). The operators of the TN are mainly these same municipal enterprises. The installed capacity of the BES at these companies usually exceeds the connected thermal load by several times, which can cause a conflict of interest when ensuring third-party access to the thermal networks. However, according to [26], DH system operators are obliged to connect suppliers of renewable energy and excess heat based on non-discriminatory criteria.

An important technical

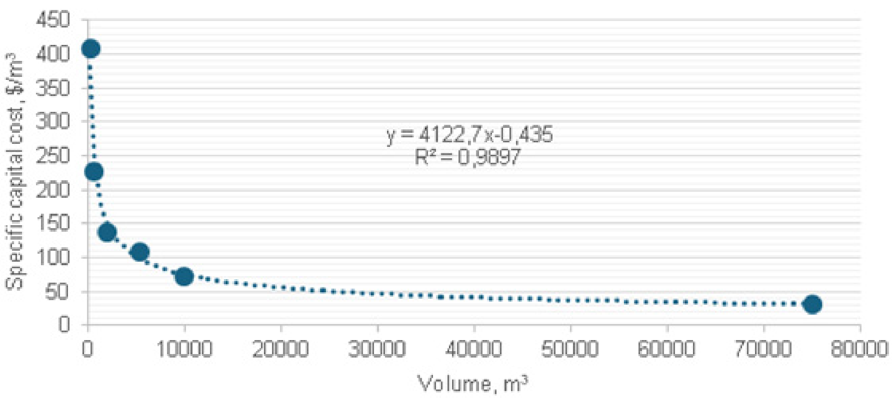

Figure 6. Dependence of the specific cost of a seasonal thermal storage tank on its volume.

Table 2. Key input data for numerical modeling

Name of parameter	Unit	Value
Installed thermal capacity of the boiler house	MW	10.0
Average thermal load of the boiler house during the heating season	MW	5.25
Share of natural gas substitution by solar energy	%	5–40
Average annual solar irradiation level	kWh/m^2·day	3.03
Efficiency of the solar collector		0.6
Specific cost of SDHP	\$/m^2	300
The price of natural gas	UAH/m^3 (\$/m^3)	25 (0.6)

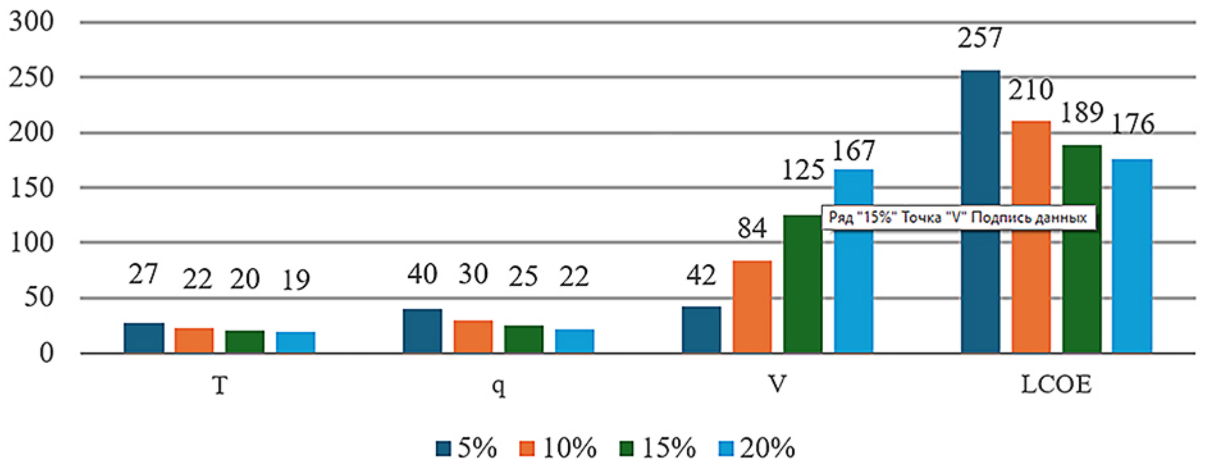

Figure 7. The impact of the natural gas substitution share (5, 10, 15, 20 %) on a 10 MW boiler house on the payback period of capital costs (T, years), specific capital costs for a seasonal thermal accumulator (q, \$/m^3) and its volume (V, thousand m^3), as well as the life cycle cost (LCOE, \$/MWh). The LCOE calculation was performed at a zero-discount rate.

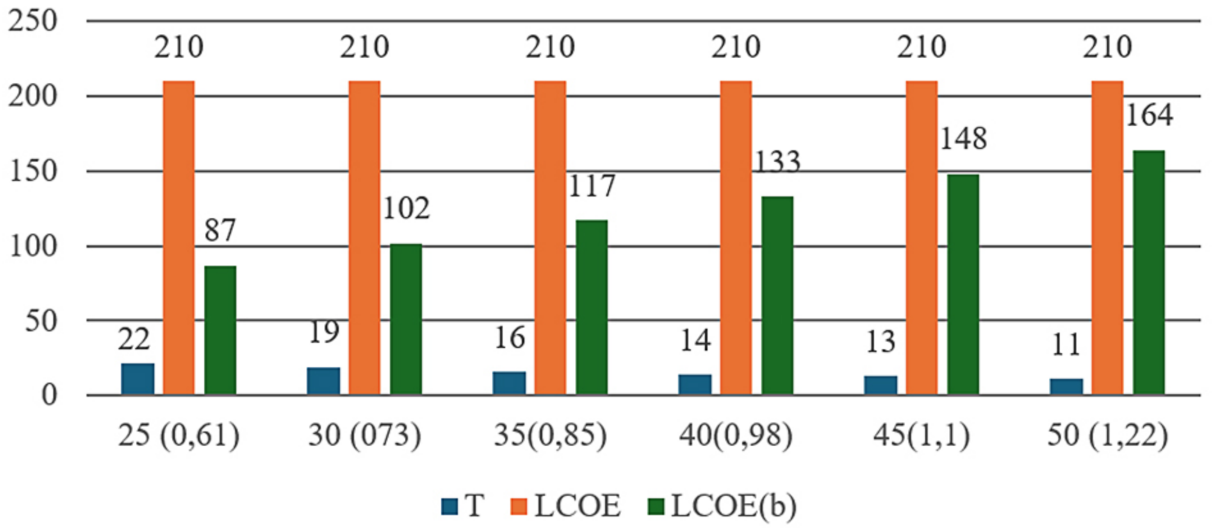

Figure 8. Dependence of T, LCOE and LCOE(b) on the price of natural gas, UAH/m^3 (\$/m^3).

issue in connecting third parties (TP) is the determination of access points (AP) to the thermal network. The solution to this issue largely depends on the configuration of the thermal network. Various types of TN configurations are known [27]. Let us consider possible APs for third parties to the TN using the example of a linear network with a single BES, which is the most typical situation for existing DH systems in Ukraine.

The diagram (Figure 9) shows the BES (on the left side of the diagram) and seven options for the location of APs to the thermal network (I–VII). These AP options differ in the length of the TN from the BES (I–V) and, accordingly, in the number of thermal consumers (shown as circles in the diagram) located before and after the AP. In addition, thermal storage at central heating substations (CHS, type VI), as well as at the boiler house of a neighboring thermo-hydraulic cluster (VII), which has already lost part of its thermal consumers (crossed-out circles), operates inefficiently, and

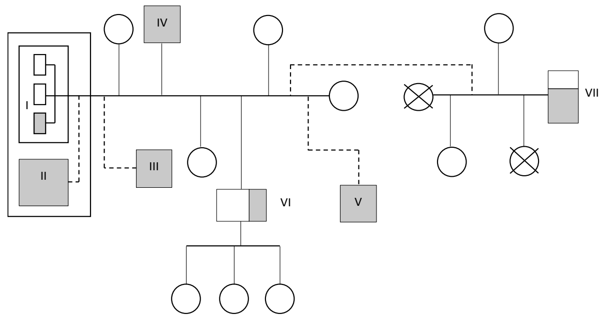

Figure 9. Options for placement of third-party access points.

has (or may have) a thermal connection with the considered thermo-hydraulic cluster, are also considered. The topology of the AP determines the zone of thermo-hydraulic influence of the third-party heat source on thermal consumers, as well as on the BES.Each option for providing an AP has its own specific features, which are discussed in Table 3.

Table 3. Characteristics of access point options

AP	Brief description of the option	Features and challenges	Positive aspects
I	Separate unit on the BES site	Use of the existing underloaded BES infrastructure. Parallel operation with BES units on the existing thermal network. No changes in thermal network operating parameters	Can only be used for third-party energy sources not tied to a specific location. Requires availability of decommissioned, outdated energy units at the BES
II	Separate production site on the BES territory	Parallel operation with BES units on the existing thermal network. No changes in thermal network operating parameters	Can only be used for third-party energy sources not tied to a specific location. Requires available space at the BES site for placement of third-party energy sources
III	Location near the BES	Similar to option II	Independence from the BES
IV	Location in the center of thermal loads	Significant changes in the thermo-hydraulic regime of the thermal network. Requires detailed analysis of the impact of the third-party access point on thermal consumers	
V	Location in the area of remote thermal consumers	Possibility to address issues of remote thermal consumers, especially in cases of long, worn-out thermal networks or consumers with complex terrain features	
VI	Location at the central heating substation (CHS)	Proximity to thermal consumers. Availability of the necessary infrastructure.	Thermal capacity of the third-party access point is approximately equal to that of the CHS. Choice between four-pipe or two-pipe system
VII	Location of a new third-party energy source on the territory of an outdated neighboring thermo-hydraulic cluster with an inefficient heat source	Optimization of the structure and renovation of outdated, inefficient clusters. Integration of thermal networks	Need to create (or use existing) thermal connections between neighboring thermo-hydraulic clusters

When determining the access points for third parties, it is necessary to ensure the efficient operation of the entire thermo-hydraulic cluster, including the basic energy sources, third-party energy sources, thermal networks, and thermal consumers. For this, it is essential to model the heat balance and thermo-hydraulic regimes of the TN, taking into account third-party energy sources under different operating conditions.

Providing TP access can achieve the following main positive outcomes: an increase in the share of renewable energy sources and excess heat, as well as highly efficient cogeneration. In addition, TP access can be used to improve the operation of the thermo-hydraulic cluster or its parts. Examples of improved cluster operation include: ensuring backup of installed thermal capacity; improving heat supply to consumers located far from the BES; reducing heat losses in TN; and reducing electricity consumption for heat energy transportation.

Discussion of results. Directions for further research

The results of the study confirm the relevance of the issue of developing a scientifically based methodology for the transformation and decarbonization of outdated gas-fired district heating systems. Despite the presence of many pilot projects implemented in this direction in the EU countries, the issue of ensuring the investment attractiveness of these projects and attracting commercial financial resources for their implementation remains unresolved. The study allows us to formulate the main principles of the methodology for the decarbonization of outdated powerful gas-fired district heating systems. Further improvement of the strategy can be achieved through a holistic approach to electricity supply, district heating, buildings connected to DH, and municipal infrastructure, the use of combined renewable energy sources using natural gas as a balancing fuel for the transition period, the development of tools and incentives to accelerate DH decarbonization processes, the identification of key decarbonization objects for large DH systems, the creation of a library of economic justifications for typical decarbonization projects, the provision of favorable conditions for third-party access to DH heating networks, and the development of effective transition plans based on the application of the theory of change. The investment attractiveness of decarbonization projects can be achieved through a comprehensive approach to solving environmental and other existing problems of outdated gas-fired district heating systems: the exhaustion of the operating resource of these systems, ensuring the stability of these systems in unforeseen circumstances, optimization of heat supply zones, uneven loading of DH systems throughout the year, using DH as a consumer-regulator for electricity supply systems. The distribution of centralized cooling services along with centralized hot water supply should be considered as a tool for ensuring the investment attractiveness of DH transformation. It is advisable to improve the methodology for comparative analysis of various options for transforming outdated systems, taking into account not only quantitative but also qualitative indicators, for example, using expert assessments.

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Трансформація застарілих систем централізованого теплопостачання

Анотація. Трансформація застарілих систем централізованого теплопостачання (ЦТ), які були побудовані переважно у попередньому сторіччі та розраховані на використання викопного палива, є актуальною темою для країн з розвинутими ЦТ. У цих системах одночасно необхідно вирішувати завдання заміни застарілого обладнання, підвищення ефективності використання викопного палива та його заміщення відновлюваними джерелами енергії і скидними енергетичними ресурсами. Ці завдання мають вирішуватися в умовах необхідності стабільного забезпеченням споживачів тепловою енергією. Вирішення такого складного комплексного завдання потребує розробки науково обґрунтованої стратегії. Темпи оновлення та декарбонізації ЦТ у різних країнах суттєво різняться. Для Україні, яка належить до числа країн з розвинутим, але застарілим ЦТ, трансформація та декарбонізація цієї важливої енергетичної інфраструктури вирішується на основі європейського досвіду з урахуванням національних особливостей. Досліджено методичні та техніко-економічні аспекти стратегії перехідного періоду декарбонізації великих застарілих систем ЦТ з використанням особливостей поточного стану цих систем в Україні. Розглянуто необхідність та зміст планів перехідного періоду, досвід трансформації застарілих систем ЦТ у країнах ЄС, важливі методичні аспекти планів перехідного періоду, включно з часовими змінами у системах ЦТ, особливостями поточного стану та структури існуючих ЦТ, наявністю потенціалу заміщення викопного палива відновлюваними джерелами енергії, критеріями порівняння різних напрямів декарбонізації, питаннями доступу третіх сторін до теплових мереж та напрямками подальших досліджень декарбонізації ЦТ. Основним видом палива в існуючих застарілих системах централізованого теплопостачання є природний газ, а основним джерелом теплової енергії — газові котли, що є базою для порівняння економічної ефективності альтернативних напрямків трансформації. Показано економічну доцільність заміни газових котлів на сонячні станції централізованого теплопостачання із сезонними тепловими акумуляторами. *Бібл. 29, Рис. 9, Табл. 3.*

Ключові слова: методологія трансформації застарілих газових систем централізованого теплопостачання, теплогідравлічні кластери, зміна витрат в системах централізованого теплопостачання у часі, граничні значення індикаторів щільності теплового навантаження та лінійної щільності теплоти, поточний стан централізованого теплопостачання в Україні, порівняння технологій заміщення природного газу, гібридні системи централізованого теплопостачання з локальними сонячними системами гарячого водопостачання, системи сонячного теплопостачання у комплексі з газовими котельнями, комплексний підхід до модернізації систем централізованого теплопостачання та будівель.

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