CONSTRUCTIVE SOLUTIONS FOR THERMAL ENERGY TRANSPORT AND DISTRIBUTION

SOLUȚII CONSTRUCTIVE PRIVIND TRANSPORTUL ȘI DISTRIBUȚIA ENERGIEI TERMICE

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Abstract: *District heating networks are essential components of urban energy infrastructure; however, in many Eastern European cities they face high energy losses caused by pipeline aging and outdated construction solutions. Reducing these losses is crucial for improving energy efficiency, lowering emissions, and ensuring the sustainability of heating systems. This paper analyzes modern solutions for reducing heat losses, focusing on next-generation pre-insulated pipes and advanced insulation materials, through a techno-economic assessment applied to the CT Vest district heating network in Chișinău. The results indicate significant reductions in thermal energy losses, operating costs, and CO_2 emissions, demonstrating that systematic modernization represents a viable and necessary direction for district heating systems in the Republic of Moldova and other regions with similar infrastructure.*

Keywords: thermal energy losses, district heating networks, energy efficiency, structural solutions.

Rezumat: *Rețelele de termoficare sunt esențiale pentru infrastructura energetică urbană, însă în multe orașe din Europa de Est se confruntă cu pierderi ridicate de energie, generate de uzura conductelor și soluții constructive depășite. Reducerea acestor pierderi este necesară pentru creșterea eficienței energetice, diminuarea emisiilor și asigurarea*

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sustenabilității sistemelor. Lucrarea analizează soluții moderne pentru reducerea pierderilor de căldură, cu accent pe conducte preizolate de nouă generație și materiale izolante avansate, printr-o evaluare tehnico-economică aplicată rețelei Centralei Termice Vest din Chișinău. Rezultatele indică reduceri semnificative ale pierderilor, costurilor de exploatare și emisiilor de CO_2, demonstrând că modernizarea sistematică reprezintă o direcție viabilă pentru sistemele de termoficare din Republica Moldova și regiuni similare.

Cuvinte cheie: pierderi de energie termică, rețele termice, eficiență energetică, soluții constructive.

1. Introduction

District heating systems play a key role in ensuring urban thermal comfort and improving the efficient use of energy resources, particularly in areas with high population density. At the European level, district heating networks are considered an effective solution for integrating renewable energy sources and reducing greenhouse gas emissions, in line with the decarbonization objectives established through the energy policies of the European Union [1-3].

However, in many cities in Central and Eastern Europe, including the Republic of Moldova, the infrastructure of district heating networks is characterized by an advanced level of deterioration. Most pipelines installed before the 2000s exhibit significant thermal energy losses caused by insulation degradation, water infiltration, and outdated construction solutions. Under such conditions, total network losses frequently exceed 18–20%, negatively affecting both the economic efficiency and operational reliability of district heating systems [4].

Official data from the 2024 report of the National Agency for Energy Regulation of the Republic of Moldova confirm the persistence of this problem: actual losses in district heating networks reached approximately 19.3% of the delivered thermal energy, representing about 348–352 GWh_{th}, despite the decrease in the total volume of heat production over the past decade. These values significantly exceed modern reference levels (typically 10–12%) and reflect the physical deterioration of district heating networks, particularly in large urban areas such as Chișinău [5].

It should also be noted that several studies addressing the current situation and development perspectives of district heating systems in the Republic of Moldova, as well as the justification of the structure and parameters of energy sources within urban district heating systems, are presented in the literature [6–15].

The modernization of district heating networks involves the adoption of modern engineering solutions, such as next-generation pre-insulated pipes, high-performance insulation materials, and rehabilitation technologies with reduced urban impact. These solutions enable the reduction of heat losses, extension of infrastructure service life, and decrease in operational costs.

The aim of this paper is to analyze the efficiency of modern engineering solutions applied to district heating networks through a case study conducted on the network associated with the Central Thermal Plant Vest (CT Vest) in Chișinău. The analysis considers both energy and economic aspects, as well as environmental impacts, providing an evaluation framework for modernization decisions in district heating systems.

2. Methodology

The methodology used in this study is based on a comparative techno-economic analysis of several engineering solutions applicable to district heating networks. The analysis aims to evaluate their efficiency in terms of reducing thermal energy losses, investment costs (CAPEX), operating costs (OPEX), and environmental impact.

The data used in this analysis were obtained from the technical documentation and operational records of the district heating network associated with the CT Vest thermal plant in Chișinău. The analyzed network includes pipelines with different diameters and service ages, representative of the district heating infrastructure installed during the period 1970–1990.

The evaluation of the engineering solutions was carried out based on the following criteria:

- specific thermal energy losses per unit length of pipeline;
- investment and operating costs;
- estimated service life of the analyzed solutions;
- environmental impact, expressed through the reduction of CO_2 emissions associated with energy losses.

The comparison of the solutions was carried out by analyzing several modernization scenarios relative to the existing state of the network, which was considered the baseline scenario. The obtained results allow the identification of optimal solutions from both energy and economic perspectives.

3. Innovative solutions in thermal energy transport and distribution

3.1. Thermal and structural properties of polyurethane foam

In recent decades, rigid polyurethane foam (PUR) has become the standard insulation material for district heating pipelines in Europe due to its low thermal conductivity, low weight, dimensional stability, and resistance to moisture. Compared to older mineral or bituminous insulation materials, the use of PUR in pre-insulated pipes has reduced heat losses by more than 50% and extended the service life of district heating networks to 30–40 years [16–22].

European standards establish strict requirements regarding foam density, thermal conductivity coefficient, adhesion to the steel service pipe, and mechanical performance during operation. Manufacturers have developed modern generations of PUR with thermal conductivity values (λ) between 0.022 and 0.028 W/mK, significantly lower than those of traditional insulation materials such as mineral wool, bitumen–perlite insulation, and similar solutions.

Single pre-insulated pipes, widely used since the 1980s, consist of a steel service pipe, a layer of PUR thermal insulation, and an outer casing made of high-density polyethylene (PE-HD), aluminum, or stainless steel, which provides mechanical protection and corrosion resistance.

Pre-insulated pipes in a twin configuration (Twin Pipe) represent a modern solution in which the supply and return pipes are integrated within a single common PE-HD outer casing. The configuration includes two service pipes simultaneously insulated with PUR foam, providing reduced heat losses, improved mechanical stability, and the possibility of integrating leak detection cables in modern monitoring systems

3.2 Use of advanced **vacuum insulation panels**

Vacuum insulation panels (VIP) operate based on the removal of the gaseous medium from a porous core, typically composed of amorphous silica or glass fiber, which is subsequently encapsulated in a multilayer metallized envelope ensuring complete airtightness. The vacuum created inside almost completely eliminates heat transfer by convection, while the microporous structure of the core significantly limits thermal conduction.

A VIP panel consists of three main components:

- the insulating core, made of fumed silica, glass fiber, or ceramic microparticles;

• the multilayer envelope, composed of successive layers of aluminum and polyethylene, ensuring gas tightness;

• the internal vacuum, which reduces the density of the medium and limits the free movement of air molecules [23].

A newly manufactured VIP panel typically has an internal pressure of approximately 1–3 mbar. At a pressure of 1 mbar, the thermal conductivity reaches values of about 0.005–0.006 W/(m·K). As the pressure increases, the thermal conductivity rises to approximately 0.008–0.009 W/(m·K) at 100 mbar and to 0.020–0.021 W/(m·K) at 1000 mbar, corresponding to atmospheric pressure.

In cylindrical configurations, the insulation efficiency increases progressively as the analyzed region approaches the axis of the pipe, a phenomenon determined by the specific characteristics of radial heat transfer. This physical aspect has led to the development of hybrid insulation solutions in which materials such as vacuum insulation panels are placed in the immediate vicinity of the service pipe, while the outer layers are made of conventional rigid polyurethane foam (Fig. 1).

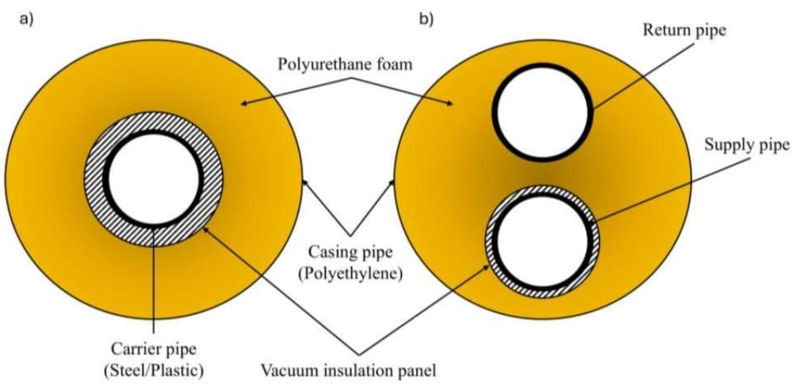

Figure 1. Schematic concept of hybrid insulation:
a) single-pipe configuration, b) twin-pipe configuration

For the district heating system of Chișinău, VIP panels are particularly suitable for secondary distribution networks and building connections, where pipeline sections are relatively short and specific heat losses are high. The main advantage lies in the reduction of thermal losses and the external diameter of the pipeline, facilitating installation under sidewalks or within existing utility ducts. Moreover, maintaining a higher temperature at the end of the branch connection allows the optimization of system operation and reduces the need for overheating the heat carrier at the source.

3.3. Aerogel-based insulation materials technology

Aerogel is one of the most advanced thermal insulation materials developed in recent decades. It is obtained through the supercritical drying of a gel, usually silica-based, a process in which the liquid is replaced by air without collapsing the porous structure. The result is an extremely lightweight material with a porosity exceeding 90–95%, a density of 100–200 kg/m³, and a very low thermal conductivity (0.013–0.018 W/m·K).

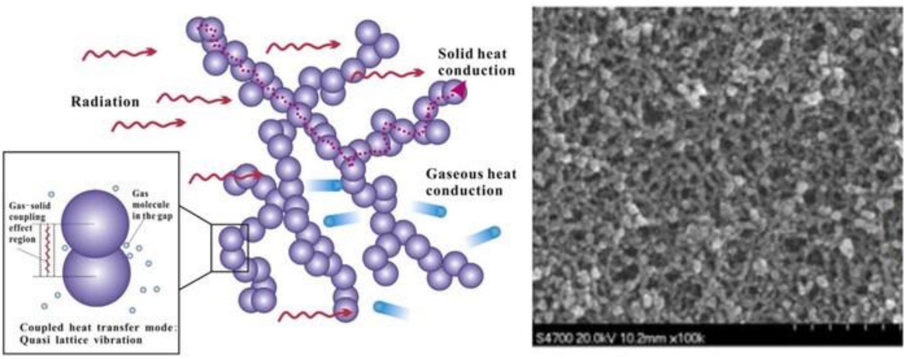

Figure 2. Typical structure of nanoporous insulation materials: SEM image of silica aerogel

Its structure consists of a three-dimensional network of nanometric silica particles, which generates the Knudsen effect: the movement of air molecules is restricted within the pores, almost completely eliminating convection and making heat transfer through the gas phase negligible [24].

3.4. Pipeline rehabilitation using trenchless technologies

Urban district heating networks in the Republic of Moldova, particularly in Chișinău, exhibit an advanced level of aging and degradation [25]. Traditional rehabilitation methods involve full excavation of the pipeline route and complete pipe replacement. Although effective, this approach is costly, time-consuming, and has significant urban impact, including traffic disruption, damage to existing infrastructure, and generation of construction waste.

In this context, increasing attention during the last decade has been directed toward trenchless rehabilitation technologies. These methods allow interventions from inside the pipeline through cleaning, video inspection, and the installation of internal liners or composite tubes, without the need for extensive excavation of the pipeline route [26].

Rehabilitation by pipe insertion

This method consists of inserting a new pipe inside the existing one. The main variants include:

- Sliplining - where the new pipe is inserted without deformation
- Swagelining or U-liner - where the pipe is temporarily compressed and later restored to its original shape through heating.

These methods are suitable for small and medium pipe diameters (DN ≤ 200 mm), typically used in secondary district heating networks with heat carrier temperatures below 100 °C.

Rehabilitation by controlled replacement

This category includes pipe bursting and horizontal directional drilling (HDD).

- Pipe bursting fractures the old pipeline while simultaneously installing a new pipe, typically made of PE-HD or composite materials.
- HDD allows the installation of a new pipeline without removing the existing one and is particularly useful in areas with heavy traffic or when crossing infrastructure obstacles.

These methods are suitable for large diameters (DN > 200 mm), long pipeline sections, or installations at significant depths..

Internal rehabilitation (composite lining)

The most representative method is CIPP (Cured-In-Place Pipe), which uses a textile liner impregnated with resin that is expanded and cured thermally or by UV radiation, forming a continuous and sealed internal layer.

High-temperature variants (CIPP-HT) can withstand temperatures of up to 130°C. The selection of the appropriate method depends on pipeline condition, material, operating temperature, and installation environment. For main pipelines (DN > 400 mm), controlled replacement methods are generally preferred, whereas for secondary branches and service connections (DN 80–150 mm), insertion or lining solutions tend to be more efficient from a techno-economic perspective [27].

4. Implementation of solutions in the CT Vest district heating networks

The Central Thermal Plant Vest (CT Vest), part of the district heating system of Chișinău, supplies the western area of the city and was selected as a case study based on technical and economic criteria, being representative for the analysis of heat loss reduction in urban district heating networks.

The associated networks have a mixed structure, including both older pipeline sections with traditional insulation and modernized segments, allowing a comparative evaluation of the proposed solutions under real operating conditions. The significant level of thermal energy losses confirms the relevance of this analysis.

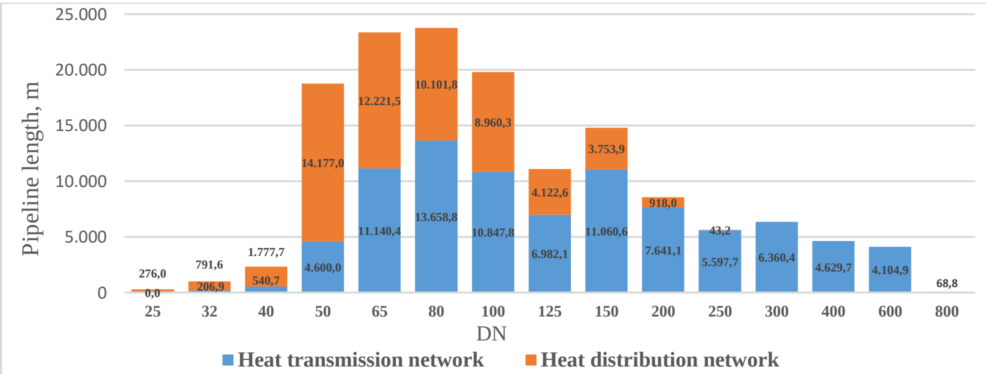

Figure 3. Length of supply and return pipelines by diameter in the district heating networks associated with CT Vest, study year 2024

The need to modernize the CT Vest networks is primarily determined by the fact that a large portion of the pipelines were installed before the year 2000, according to technical standards that are outdated compared to current requirements for efficiency, reliability, and durability.

The insulation materials used at that time exhibit higher thermal conductivity and lower resistance to moisture and thermal cycles, which over time has led to degradation and increased energy losses. Even after local repairs, the energy performance remains inferior compared to modern insulation solutions. Moreover, these pipelines were not designed for current operating regimes characterized by frequent load variations and increased control requirements, which results in a higher risk of failures and heat carrier losses.

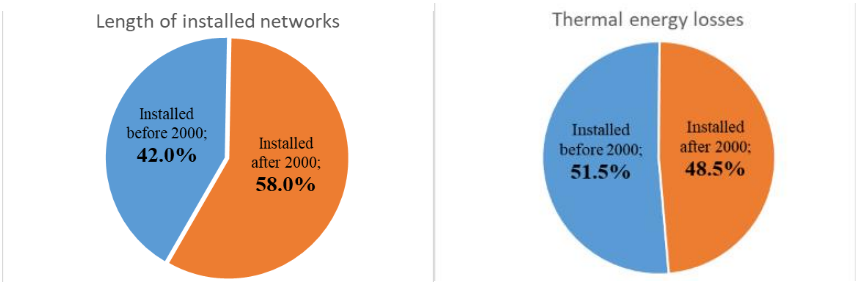

Figure 4. Ratio of pipeline lengths and heat losses for networks installed before and after the year 2000 in the CT Vest district heating system

The comparative analysis of losses (Fig. 4) shows that networks installed before 2000, although quantitatively smaller, account for the largest share of total losses – approximately 16003.8 MWh_{th} out of 31066.2 MWh_{th}.

This situation requires systematic modernization through the implementation of modern engineering solutions capable of ensuring a sustainable reduction of energy losses.

Therefore, prioritizing the pipelines installed before the year 2000 is essential for improving energy efficiency, reducing operating costs, and aligning the system with current sustainability requirements. At the same time, some of the pipelines installed after 2000 also require interventions, either through insulation replacement or, in some cases, through complete pipe replacement.

4.1. Implementation of solutions for reducing thermal energy losses

The analysis is structured according to the types of solutions considered: pre-insulated pipelines with polyurethane foam (**PUR**) in single and twin configurations (Twin Pipe), pipelines with vacuum insulation panels

(**VIP**) in single and twin configurations, **aerogel**-based insulation materials, and rehabilitation using **CIPP** technology.

For each solution, the technical description, calculation parameters, estimated thermal energy losses after implementation, and the reduction achieved compared to the baseline scenario were determined.

Table 1. **Percentage distribution of modernization works in the district heating networks**

DN	Complete renovation of pipelines installed **before the year 2000**											Partial renovation of pipelines and insulation installed **after the year 2000**				
	Underground (without quick access)						**Above-ground** (with quick access)									
	PUR	**PUR Twin**	**VIP**	**VIP Twin**	**CIPP**	**Total**	**PUR**	**PUR Twin**	**VIP**	**Aerogel** (insulation only)	**Total**	**PUR**	**PUR Twin**	**VIP**	**Aerogel** (insulation only)	**Total**
25	30%	40%		30%		100%	40%	50%		10%	100%					
32	30%	40%		30%		100%	40%	50%		10%	100%					
40	30%	40%	20%	10%		100%	30%	40%	20%	10%	100%		20%	20%	10%	50%
50	20%	50%	30%			100%	30%	40%	20%	10%	100%		20%	20%	10%	50%
70	30%	50%	20%			100%	30%	40%	10%	20%	100%		30%		20%	50%
80	30%	50%	20%			100%	30%	30%	10%	30%	100%		30%		20%	50%
100	40%	30%	10%		20%	100%	30%	30%	10%	30%	100%	10%	20%		20%	50%
125	70%	10%			20%	100%	40%	30%		30%	100%	20%			30%	50%
150	70%	10%			20%	100%	50%	20%		30%	100%	20%			30%	50%
200	80%				20%	100%	70%			30%	100%	20%			30%	50%
250	80%				20%	100%	70%			30%	100%	20%			30%	50%
300	80%				20%	100%	70%			30%	100%	20%			30%	50%
400	80%				20%	100%	70%			30%	100%	20%			30%	50%
500	100%					100%	80%			20%	100%	20%			30%	50%
600	100%					100%	80%			20%	100%	20%			10%	30%

Table 1 presents the percentage distribution of modernization solutions for the district heating networks associated with CT Vest, depending on the nominal diameter of the pipelines, their installation period, and installation conditions (underground or above ground). The distribution of solutions was determined based on technical analysis, taking into account the energy performance of each technology, its optimal application range, and the construction constraints specific to each type of network.

For pipelines installed before 2000, which are predominantly underground and have degraded insulation, the main modernization solution is complete replacement with PUR or PUR Twin pre-insulated pipes, especially for small and medium diameters (DN 25–DN 100 mm), ensuring reduced heat losses and improved reliability. For larger diameters, where replacement costs become significant, the share of CIPP solutions increases, being used for the rehabilitation of existing pipelines.

In the case of above-ground pipelines, PUR and PUR Twin pre-insulated pipes are generally preferred, complemented selectively with aerogel-based insulation for connections and areas with limited installation space, reducing heat losses without major structural interventions.

To determine the feasibility of the proposed solutions, it is necessary to calculate the specific heat losses before and after intervention, as well as to estimate the costs associated with replacement or rehabilitation using both conventional methods and trenchless technologies.

Pre-insulated pipes with **polyurethane foam – single system**

Knowing the values of thermal energy losses and the lengths of the pipelines before renovation, it is possible to determine the heat losses per meter of pipeline length per heating season. This makes it possible to compare the losses and to determine the advantages of implementing the district heating network rehabilitation solution through the installation of PUR pre-insulated pipelines.

The obtained results (Fig. 5) indicate a significant reduction in linear thermal energy losses compared with the existing situation, particularly in the case of network sections with severely degraded insulation, typically those installed before the year 2000. Depending on the pipeline diameter, the implementation of PUR pre-insulated pipes in a single configuration leads to a reduction in linear heat losses of approximately 50–60% compared with the existing situation.

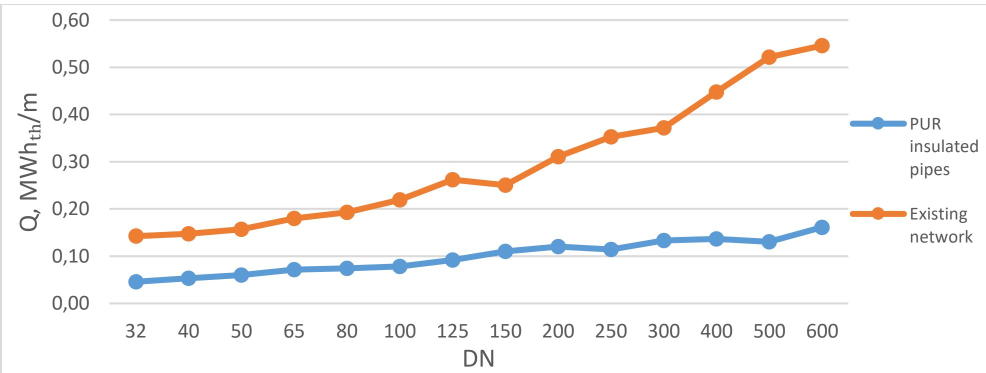

Figure 5. Thermal energy losses per meter of pipeline length installed directly in the ground, before and after rehabilitation, per heating season (PUR)

On an annual basis, the total thermal energy losses associated with rehabilitated pipelines or pipelines replaced with PUR pre-insulated pipes are considerably reduced, which results in an improvement in the energy efficiency of the district heating networks associated with the CT Vest thermal plant.

Pre-insulated pipes with **polyurethane foam – twin pipe system**

Based on the technical parameters specific to the Twin Pipe system and the operating regime of the district heating networks associated with the CT Vest thermal plant, the linear thermal energy losses were determined for each analyzed nominal diameter.

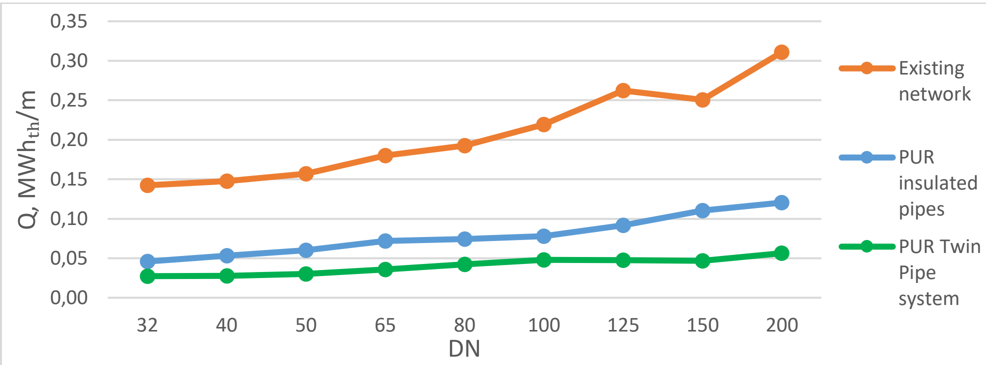

Figure 6. Thermal energy losses per meter of pipeline length installed directly in the ground, before and after rehabilitation, per heating season (PUR Twin).

The comparative analysis (Fig. 6) shows that Twin Pipe systems reduce linear heat losses by **70–80%** compared with existing networks with degraded insulation and by an additional **30–40%** compared with single PUR pre-insulated pipes.

These advantages result from:

- a reduced external heat dissipation surface (common outer casing);
- a lower average temperature difference relative to the ambient environment.

The Twin Pipe solution is particularly efficient in secondary networks, areas with a high density of pipelines and consumer connections, contributing to increased energy efficiency, reduced fuel consumption, and improved sustainability of the district heating system.

Pipelines with advanced **VIP insulation – single** and **twin systems**

Vacuum insulation panels (VIP) can be used in district heating networks both in a single configuration (one pipeline) and in a twin system (double). The difference lies in the geometry of the assembly and the thermal interaction between the pipes; however, the principle remains the same: reducing thermal conductivity and the heat dissipation surface.

For the evaluation, prefabricated flexible pipelines Uponor Ecoflex VIP Thermo were selected, which are frequently used in district heating networks in Northern Europe. Uponor, headquartered in Helsinki, is a major manufacturer of flexible pre-insulated systems, with representatives in most EU countries, including Romania.

Based on the technical parameters of the VIP and VIP Twin systems, correlated with the operating regime of the CT Vest district heating networks, the specific linear heat losses were determined for each nominal diameter.

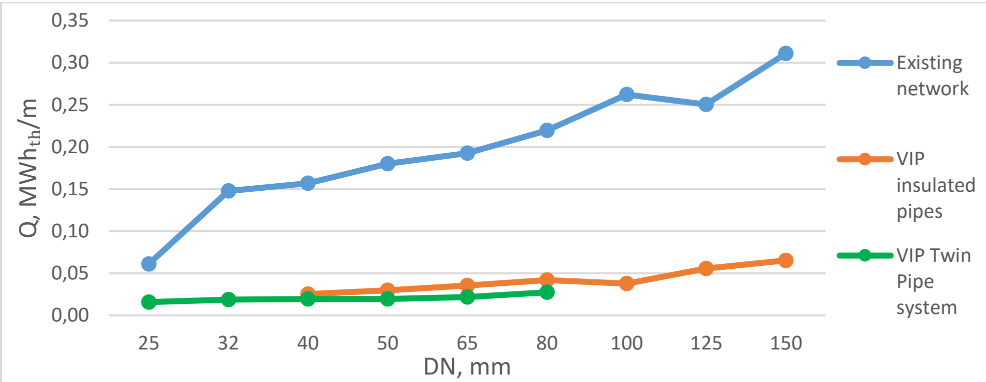

Figure 7. Thermal energy losses per meter of pipeline length installed directly in the ground, before and after rehabilitation, per heating season (VIP).

Pipelines insulated with VIP panels achieve substantial reductions in thermal losses: 60–80% compared with existing networks (with degraded insulation), while the VIP Twin configuration provides an additional gain of 10–15% compared with the single VIP solution.

Due to their exceptional thermal performance, VIP solutions are ideal for:

- short pipeline sections and secondary networks;
- areas with limited installation space;
- applications where maximum loss reduction is a priority.

The main limitations are the high cost of the materials and the need for strict mechanical protection, which requires selective application.

Thus, VIP systems (especially Twin) represent advanced solutions for the energy optimization of the CT Vest district heating networks, recommended as a targeted complement to conventional solutions rather than as a general replacement.

Insulation of pipelines with **aerogel-based materials**

Aerogel is used in the form of flexible blankets or thin panels applied directly on existing pipelines without replacement. It is ideal for rehabilitation in confined spaces or areas where conventional interventions are difficult, providing minimally invasive modernization and effective reduction of thermal energy losses.

For the techno-economic analysis of thermal network insulation rehabilitation, Pyrogel XTE/XTF (10 mm thickness) produced by Aspen Aerogels, one of the global leaders in aerogel-based materials headquartered in the United States, was selected.

In the context of the district heating networks associated with CT Vest, the aerogel solution is analyzed as a selective measure, primarily recommended for:

1. rehabilitation of existing pipelines with degraded insulation (without replacement);
2. insulation of connections, elbows, valves, and valve chambers;
3. short pipeline sections in areas with limited space;
4. sensitive urban areas where excavation works are difficult.

This approach reduces thermal losses in critical points and for large diameters where PUR or VIP solutions are less practical. Aerogel insulation does not replace conventional solutions but complements them in a targeted manner depending on construction and economic conditions.

Figura 8. Installation of Pyrogel blankets on district heating pipelines

Pyrogel blankets are installed by wrapping them in multiple layers directly around the existing pipeline (Fig. 8). The number of layers is determined depending on:

- the pipeline diameter;
- the thickness of each layer (typically 10 mm);
- the desired level of thermal loss reduction;
- spatial constraints at the installation site.

The total insulation thickness is selected as an optimal compromise between thermal performance, available space, and cost. For the same thermal effect, the required thickness using Pyrogel is approximately half that of PUR pre-insulated insulation. To avoid thermal bridges, the joints are installed in a staggered arrangement (both longitudinally and circumferentially), and each layer is fixed using metal bands or dedicated fastening systems. This method allows easy adaptation to complex geometries (elbows, connections, valves), while maintaining high thermal insulation performance.

Based on the Pyrogel parameters and the operating regime of the CT Vest thermal plant, the specific linear heat losses were calculated for each nominal diameter of above-ground pipelines (Fig. 9).

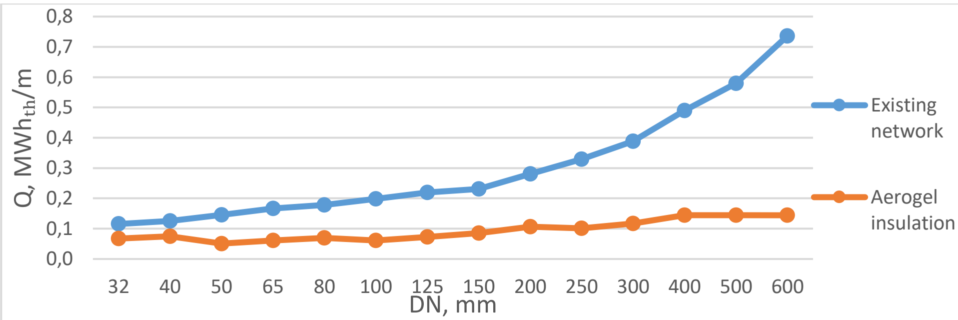

Figure 9. Thermal energy losses per meter of above-ground pipeline length, before and after rehabilitation, per heating season

Rehabilitation of district heating pipelines using **CIPP** technology

Although CIPP (Cured-In-Place Pipe) technology is primarily used for structural rehabilitation and sealing, the polymer liner with epoxy resin also provides an additional thermal benefit. The continuous layer adds its own thermal resistance, which is combined with that of the pipe wall and the existing insulation (typically mineral wool), increasing the total thermal resistance and reducing heat losses to the surrounding environment.

In the calculation model, the thermal resistance of the CIPP layer was included, determined based on the sleeve thickness and the thermal conductivity of the polymerized epoxy resin.

This approach allows the evaluation of the real contribution of CIPP to the reduction of linear heat losses, particularly in pipelines with degraded insulation, without requiring the complete replacement of the existing system.

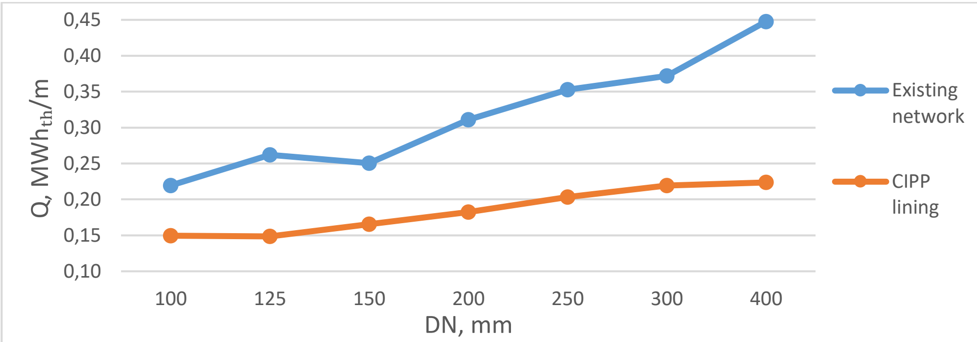

Figura 10. Thermal energy losses per meter of pipeline length installed directly in the ground, before and after rehabilitation, per heating season (CIPP).

CIPP technology is applied in the calculation model for underground pipelines insulated with mineral wool, assuming degradation of the existing insulation expressed as a <u>50% reduction in the initial thermal resistance</u>, resulting from aging and operating conditions. The results of the calculation of linear thermal energy losses for pipelines rehabilitated using CIPP technology are presented in Figure 10.

Results of implementation

Following the technical analysis of the implementation of the proposed solutions and the reduction of thermal energy losses in the district heating networks associated with CT Vest, the result was a total loss reduction of **11511.63 MWh$_{th}$** for each heating season (estimated at 4000 hours).

The annual reductions in thermal energy losses are distributed as follows:

- **-6672.72 MWh$_{th}$** – complete rehabilitation of underground pipelines installed before 2000;
- **-3584.40 MWh$_{th}$** – complete rehabilitation of above-ground pipelines installed before 2000;

- **-1254.51 MWh_{th}** – partial rehabilitation of above-ground pipelines installed after 2000.

The obtained results confirm that the largest thermal energy savings are achieved through the rehabilitation of pipelines installed before the year 2000, especially those located underground, where insulation degradation and initial heat losses are the most significant.

Knowing the total thermal energy delivered to the network in 2024, 166860.2 MWh_{th}, and the total network losses of 31066.2 MWh_{th}, the following estimates can be made:

1. Thermal energy losses in the network were reduced by **37.1%**, from 31066.2 MWh_{th} to 19555.5 MWh_{th};
2. The share of thermal energy losses in the network relative to the total thermal energy delivered decreased from **18.6%** to **11.7%**.

The obtained value of thermal energy losses in the network, 11.7%, falls within the reference range of 10–12%, which is considered representative for modern and efficient district heating networks in the European Union. This result confirms that the implementation of the proposed solutions makes it possible to bring the district heating networks associated with CT Vest to an energy performance level comparable to European best practices.

4.2. Techno-economic analysis and environmental impact assessment

<u>Determination of material costs</u>

The evaluation of the techno-economic feasibility of modernizing the district heating networks associated with CT Vest begins with the precise determination of investment costs, which represent a major component of capital expenditures and a decisive factor for the payback period, net present value, and overall economic sustainability.

Material costs were calculated for the following construction solutions: PUR pre-insulated pipelines (single and Twin), pipelines with VIP insulation (single and Twin), additional aerogel-based insulation (Pyrogel), and rehabilitation using CIPP technology.

Unit costs (MDL per linear meter) were determined in a differentiated manner depending on the nominal diameter of the pipelines, the type of construction solution, and the specific field of application (underground/above-ground, full or partial rehabilitation, trenchless methods).

To ensure a high level of realism, the unit material costs were obtained from current commercial offers, manufacturers' price lists, and specialized sources, adapted to the local implementation conditions in the CT Vest district heating networks:

1. **PUR** and **PUR Twin** – Price offer dated 10.12.2025, S.C. ISOPLUS ROMÂNIA S.R.L., Oradea.
2. **VIP** and **VIP Twin** – Uponor Ecoflex price offer dated 18.11.2025, Uponor Romania, Bucharest.
3. **Pyrogel XTE/XTF** blankets (10 mm) – Average price, manufacturer Aspen Aerogels, USA.
4. **CIPP** technology – Rehabilitation contract.

The costs are expressed in MDL per linear meter of pipeline (or per unit for accessories/equipment) and serve as the basis for calculating total investment costs.

Determination of construction costs

The determination of the construction costs for the modernization of the district heating networks associated with CT Vest was carried out by estimating the unit execution costs (MDL/m), differentiated according to the installation method of the pipelines (underground/above-ground) and the intervention method used.

Cost savings compared to conventional excavation and installation works::

- Controlled pipe bursting – 35%;
- Horizontal directional drilling (HDD) – 40%;
- Twin pipe installation – 30%.

In the analysis, the total renovation cost was considered as the sum of material costs (pipelines/insulation), auxiliary costs (components and consumables), transportation expenses, and the direct costs of installation works.

Installation works represent the dominant cost component: 60% (single system) and 42% (twin system) for conventional excavation. Trenchless methods (pipe bursting and horizontal directional drilling) reduce their share to 25–39%, highlighting their economic and technical advantages in densely populated urban areas.

Table 2. **Percentage distribution of total costs for underground installation of PUR pipelines**

Method	Pipe cost	Other components	Transport	Installation works	
				Single system	Twin system
Excavation (standard)	30%	5%	5%	60%	42%
Controlled pipe bursting	30%	5%	5%	39%	27%
Horizontal directional drilling	30%	5%	5%	36%	25%

Table 3 presents the percentage distribution of underground rehabilitation methods differentiated by nominal diameters. Costs increase significantly with the increase in pipeline diameter due to the larger volume of materials and the greater complexity of execution. VIP and VIP Twin solutions have the highest total costs, determined by the price of advanced insulation and the complexity of installation. In contrast, single PUR and PUR Twin solutions provide a balanced cost–performance ratio for most of the analyzed diameters. CIPP technology is particularly competitive for medium and large diameters, where complete pipeline replacement is not technically or economically justified.

Table 3. **Percentage distribution of underground rehabilitation methods**

DN, mm			25	32	40	50	65	80	100	125	150	200	250	300	400	500	600
Pipeline length		m	144	386	962	9541	7843	7619	6105	2598	4019	2952	1268	2873	1713	4540	557
Rehabilitation method	Excavation	%	100%	100%	100%	100%	100%	70%	50%	50%	50%	50%	30%	30%	30%	70%	70%
	Pipe Bursting	%						30%	30%	30%	30%	30%	30%	30%	20%		
	Horizontal directional drilling	%											20%	20%	30%	30%	30%
	CIPP	%							20%	20%	20%	20%	20%	20%	20%		

These differences highlight the importance of a targeted selection of solutions, adapted to the pipeline diameter, the level of specific heat losses, and the actual budgetary constraints of the CT Vest district heating networks.

Table 4 presents the percentage structure of total costs related to the rehabilitation of above-ground pipelines for two distinct scenarios: complete pipeline replacement and insulation replacement.

Table 4. **Percentage distribution of total costs for above-ground installation of pipelines**

Measure	Pipe / insulation cost	Other components	Transport	Installation works	
				Single system	Twin system
Pipeline replacement	55%	5%	5%	35%	25%
Insulation replacement	60%	5%	5%	30%	-

Table 5. **Percentage distribution of above-ground rehabilitation methods**

DN, mm		32	40	50	65	80	100	125	150	200	250	300	400	500	600
Pipeline length	m	65	829	5361	6478	6316	5494	2021	3377	1923	1068	2175	816	5169	836
Pipeline replacement	%	90%	90%	90%	80%	78%	77%	70%	70%	70%	70%	70%	70%	75%	90%
Insulation replacement	%	10%	10%	10%	20%	22%	23%	30%	30%	30%	30%	30%	30%	25%	10%

Table 5 presents the total renovation costs for above-ground pipelines, including both the scenarios of complete pipeline replacement and rehabilitation through insulation replacement.

Following the economic analysis of the implementation of thermal energy loss reduction solutions in the district heating networks associated with CT Vest, the required total investment was estimated at 365.86 million MDL.

The economic analysis of the modernization project of the district heating networks associated with CT Vest aims to evaluate the long-term feasibility of the investment by comparing the total implementation costs with the economic benefits generated by the reduction of thermal energy losses. The evaluation was carried out using a calculation model developed in Microsoft Excel, based on the technical and economic data determined previously.

For the economic analysis of the modernization of the district heating networks associated with CT Vest, prudent and representative assumptions for district heating infrastructure investments were adopted:

- Study period: 25 years (*service life of the analyzed solutions: PUR/PUR Twin and CIPP – 30–40 years; VIP/VIP Twin and aerogel – 25–30 years*).
- Implementation period: 5 years, with a uniform distribution of annual investments.

- Total investment: 365.86 million MDL → equivalent average annual investment: 73.17 million MDL.
- Discount rate: 5% per year.
- Annual degradation rate of savings: 0.5% per year.
- Annual growth rate of thermal energy price: 0.9% per year.
- Reference tariff for thermal energy: 2151 MDL/MWh_{th}.
- Annual reduction of losses: 11511.6 MWh_{th}/year.

The distribution of the investment over 5 years was treated by using the average annual investment as an equivalent initial value in the financial cash-flow calculations, ensuring a realistic and conservative evaluation of the economic indicators.

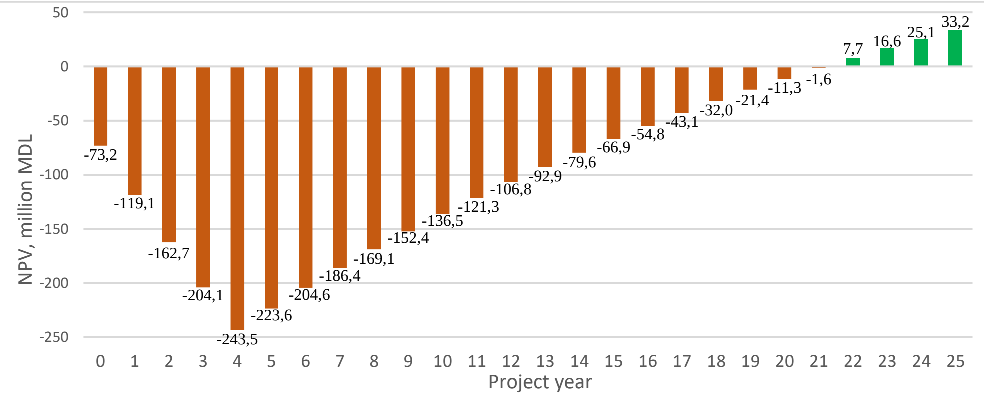

Figure 11. Evolution of the NPV depending on the project year

The positive value of the Net Present Value (NPV) confirms the long-term economic feasibility of the project under the adopted assumptions. Although the investment payback period is relatively long, approximately 22 years, this behavior is typical for district heating infrastructure modernization projects, where the main objectives are improving energy efficiency, reducing heat losses, and ensuring system reliability.

The economic analysis of the modernization of the CT Vest district heating networks shows that the investment is feasible in the long term under the adopted prudent assumptions. The positive Net Present Value confirms that the savings obtained through the reduction of heat losses exceed the total discounted costs.

The gradual recovery of the investment, with the break-even point reached around year 21, is typical for infrastructure projects, where the main objective is long-term efficiency and reliability rather than rapid profit. The analysis does not include important indirect benefits such as reduced maintenance costs, fewer failures and heat carrier losses, increased operational safety, and reduced greenhouse gas emissions.

Environmental impact assessment

The modernization of thermal energy transport and distribution networks brings important environmental benefits: reduced energy losses, limited invasive interventions in the urban environment, and decreased greenhouse gas emissions.

Modern insulation systems. The use of next-generation polyurethane foam, aerogel-based materials, and VIP panels significantly reduces thermal conductivity compared with degraded insulation, thereby decreasing linear heat losses. As a result, the required heat production in natural gas-fired plants decreases, reducing fuel consumption and emissions. At the same time, the service life of pipelines increases to 30–50 years, reducing the consumption of raw materials and the volume of waste in line with the principles of the circular economy.

Trenchless technologies. Rehabilitation through CIPP, sliplining, pipe bursting, or horizontal directional drilling reduces the impact compared with open excavation: less soil excavation, lower indirect emissions, reduced noise, and protection of green spaces and existing infrastructure.

The reduction of CO_2 emissions results directly from the decrease in thermal energy losses in the network. Initial losses, estimated at 31066.2 MWh_{th} (18.6%), are reduced after modernization to 19555.5 MWh_{th} (11.7%). The difference equivalent to 11519 MWh_{th}/year, represents the annual energy savings.

Considering an average heat production efficiency of $\eta = 0.92$, the avoided fuel energy amounts to approximately 12521 MWh of natural gas per year. Applying an emission factor of 0.202 t CO_2/MWh, the estimated annual reduction is about 2529 tonnes of CO_2. The equivalent economic value (at 80 €/t CO_2) is approximately 202320 €/year, representing a potential benefit that is currently not monetized in the Republic of Moldova

5. Conclusion

District heating systems represent a strategic component of the urban infrastructure in the Republic of Moldova, essential for energy efficiency, security, and environmental protection. However, their performance is significantly affected by aging thermal networks characterized by high losses, frequent failures, and elevated operating costs.

The analysis of the CT Vest area shows that the highest losses occur in large-diameter pipelines with degraded insulation (installed before 2000), requiring targeted modernization prioritized according to energy and economic impact.

Modern solutions such as PUR pipelines (single and Twin), VIP systems (single and Twin), aerogel insulation, and CIPP technology significantly reduce linear heat losses, stabilize operating regimes, and increase system reliability. PUR Twin provides the best cost–benefit ratio for large-scale implementation, while VIP and aerogel perform best in selective applications (short sections, confined spaces), and CIPP is effective for rehabilitation without complete pipeline replacement.

The techno-economic analysis confirms the feasibility of the investments: reducing losses decreases fuel consumption, operating costs, and tariffs, with reasonable payback periods. Indirect benefits (fewer failures, reduced maintenance, improved operational safety) together with emission reductions (approximately 2529 t CO_2/year in the CT Vest area) further increase the value of the project.

The modernization of thermal energy transport and distribution systems is a priority for district heating systems in the Republic of Moldova. The targeted implementation of modern construction solutions, supported by technical and economic justification, can transform these systems into efficient, reliable, and sustainable infrastructures, reducing losses, emissions, and costs for the benefit of both consumers and the environment.

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