MINISTRY OF EDUCATION AND RESEARCH
TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST
DOCTORAL SCHOOL

RESEARCH ON THE IMPROVEMENT OF THE ENERGY EFFICIENCY OF DISTRICT HEATING SYSTEMS. MODERN SUSTAINABLE SOLUTIONS. THE APPLICABILITY OF THE NEW LOW TEMPERATURE DISTRICT HEATING CONCEPT

- ABSTRACT OF DOCTORAL THESIS -

PhD Supervisor
Prof. IORDACHE FLORIN, PhD

PhD candidate
Ing. SECARĂ (STĂNIŞTEANU) CRISTINA ALICE

June 2020

Contents

I Forward

The EU Directive (2010/31/EU) on the energy performance of buildings states that "the rate of building renovation needs to increase as the building sector is the sector with the greatest potential for energy savings", while the EU Directive on energy efficiency (2012/27/EU) mentions that "buildings account for 40% of total energy consumption in the European Union".

I.1 The „low temperature district heating" concept

Thermal rehabilitation of buildings aims to reduce heat loss through building elements, resulting in a significant reduction in heat demand for heating the building. Feeding these consumers with a heat carrier at the same temperature as they had been previously fed leads to a decrease in the efficiency of the district heating systems by increasing energy losses. In order to increase the efficiency of district heating systems, it is possible to move further into the energy chain by supplying a low temperature heat carrier, reducing heat losses in thermal networks without any investment for their rehabilitation. As the number of low energy buildings will grow more and more, the new (LTDH) system will lead to significant energy savings and improve the energy performance of district heating systems.

I.1.3 Use of renewable energy sources

Using low temperature heat carriers in the district heating systems has opened the way for using a multitude of heat sources, previously considered inappropriate for this purpose:

- low temperature residual heat from energy or industrial processes;
- heat recovered from various processes, from data centers etc.;
- renewable energy sources:
  - solar thermal panels
  - geothermal energy
  - heat pumps
  - heat resulted from the conversion of excess power produced by photovoltaic panels or wind turbines
  - cogeneration using biomass or biogas

I.1.4 The „smart thermal grids" concept

Directive 2010/31/EU provides that the energy performance of new buildings will be even higher than the current one, i.e. new buildings will have nearly zero energy consumption. But even this small energy consumption will have to be covered with renewable energy. The new buildings will have to be equipped with renewable energy technologies (heat pumps, photovoltaic panels, solar thermal panels or wind turbines). These buildings will be consumers and producers of thermal energy, at the same time. In some periods, the amount of thermal energy produced will be higher than the one consumed, and excess heat will be used by other buildings. Distributed power sources with different temperature levels will be present in the network. On the other hand, some consumers will supply thermal energy into the system - unidirectional network must turn to a bidirectional network. The heat should be produced when it is available, but the system must always cover the demand, so the network must be fitted with heat storage technologies. In order for this complex system to work, and to operate with maximum efficiency, it is necessary for the existing thermal grids to undergo major changes: to become "smart". This is how the concept of "smart thermal grids" was born.

Experts are already talking about the smart energy systems of the future, based on integrated electric-heat-gas solutions, consisting in the integration of electrical, thermal and gas smart grids, in order to ensure maximum energy efficiency and overall maximum efficiency of energy production, transport, distribution and use.

II National context: district heating systems

According to the first draft of the "Energy Strategy of Romania 2016-2030 with the perspective of 2050", submitted for public enquiry, "From a total of approximately 7.5 million permanently occupied dwellings, 1.25 million are heated by district heating systems. [90]

The new Energy Strategy states that reaching the targets for thermal rehabilitation of buildings in the cities heated by district heating systems will cause a considerable decrease of the heat demand. For this reason, the rehabilitation of the thermal grids and the sizing of the heat sources must be correlated with the evolution of the heat demand.

According to the Strategy for mobilizing investments for the renovation of residential and commercial buildings, both public and private, existing at national level, "energy consumption in the buildings sector (housing, tertiary sector, including public buildings) represents 45% of total energy consumption". [91] The 2014-2020 Regional Operational Program states that "the potential for savings in buildings is significant by deep renovations, of about 40-50% for public buildings, and of more than 40% for residential buildings, with differences from one climate zone to another". In this context, the subject of this paper goes further into the energy efficiency chain, aiming at improving the energy efficiency of district heating systems supplying renovated buildings by reducing the temperature of the heat carrier.

III Modeling of heat transfer processes and transport of heat carriers. Dynamic thermal behavior of consumers

III.1. Adjustment of heat supply

<u>III.1.1 Concept</u>

The adjustment of heat supply is the set of measures and operations aimed at modifying the amount of heat delivered to the consumers so that it is as close as possible to their actual needs. Heat supply adjustment is a complex process, involving measures that are taken in the heat generation plant (central, primary control), thermal substation (secomndary control) and consumer (tertiary, local) control.

In large district heating systems, the adjustment of heat supply is a complex multi-level process, since the multiple aspects to be considered can not be solved by a single adjustment process.

III.1.2 Methods of adjustment of heat supply

The adjustment of heat supply in district heating systems can be carried out in three ways: by temperature cotrol, by flow control or by mixed (flow and temperature) control.

The adjustment of heat supply by temperature control is performed by modifying the temperature of the heat carrier in the supply and return pipes, maintaining a constant flow of the heat carrier delivered into the system.

The adjustment of heat supply by flow control is based on maintaining a constant temperature on the supply pipe and modifying the flow of the heat carrier delivered to the system.

Mixed (flow and temperature) control of heat supply consists in the continuous or stepwise variation of both the flow rate and the temperature of the heat carrier. Mixed control is the most flexible solution for adjusting to any general and local variation in heat demand of buildings supplied by large district heating systems. [93]

III.1.3 Heat supply adjustment curves

Heat supply adjustment curves are established to determine the operating mode of the heat generation plant, thermal substations and heating systems in buildings. Constant flow operation curves represent the dependence to be achieved between the temperature of the heat carrier and the climatic parameters. [95]

A building is connected to a district heating system consisting of a heat source, a heat transportation network, thermal substations and heat distribution networks.

The heat demand for heating the building in design conditions is as follows

$$\dot{Q}_0 = H \cdot (t_{i0} - t_{e0}) \qquad \text{(III.1)}$$

In design conditions, the thermal balance of the central heating system is written in the form:

$$\dot{Q}_0 = G_0 \cdot \rho \cdot c \cdot \left(t_{t0} - t_{r0}\right) = k \cdot S \cdot \Delta t_{ml0} \quad \text{[96]} \qquad \text{(III.2)}$$

The logarithmic mean temperature difference between the heat carrier in the distribution system (circulated through the radiators) and the indoor air in the heated rooms is calculated using the formula:

$$\Delta t_{ml0} = t_{ml0} - t_{i0} = \frac{\Delta t_M - \Delta t_m}{\ln \frac{\Delta t_M}{\Delta t_m}} = \frac{\left(t_t - t_{i0}\right) - \left(t_r - t_{i0}\right)}{\ln \frac{t_t - t_{i0}}{t_r - t_{i0}}} = \frac{t_t - t_r}{\ln \frac{t_t - t_{i0}}{t_r - t_{i0}}} \qquad \text{(III.3)}$$

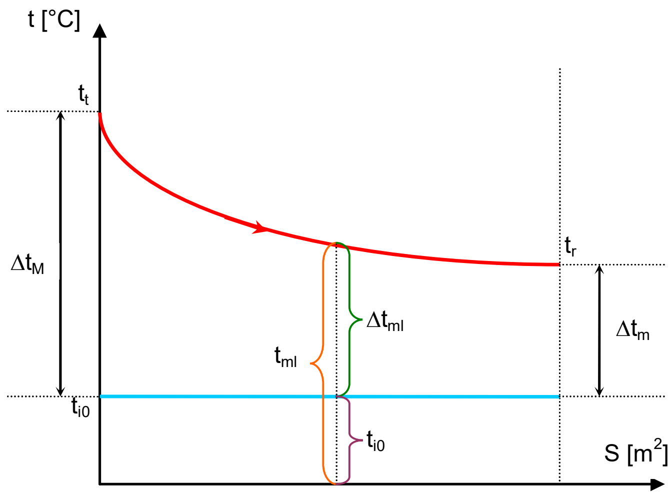


Figure III.1 The heat exchange in the radiators (between the heat carrier and the indoor air)

Relationships (II.2) and (II.3) result in:

$$NTU = \frac{k \cdot S}{G_0 \cdot \rho \cdot c} = \ln \frac{t_t - t_{i0}}{t_r - t_{i0}} \tag{III.4}$$

We note with E:

$$E = \exp(-NTU) = \frac{t_r - t_{i0}}{t_t - t_{i0}} \tag{III.5}$$

Thus, the relationship between the temperature of the heat carrier in the flow pipe and temperature of the heat carrier in the return pipe of the distribution system becomes:

$$t_r = E \cdot t_t + (1 - E) \cdot t_{i0} \tag{III.6}$$

Replacing (III.6) in (III.2), we get:

$$\dot{Q}_0 = G_0 \cdot \rho \cdot c \cdot (t_t - t_r) = G_0 \cdot \rho \cdot c \cdot (1 - E) \cdot (t_t - t_{i0}) \tag{III.7}$$

From (III.1) and (III.7) we obtain the formulas for the temperature variation of the heat carrier in the supply and return pipes of the distribution network in the case of constant flow operation (temperature control heat adjustment):

$$t_t = \left[1 + \frac{H}{G_0 \cdot (1 - E) \cdot \rho \cdot c}\right] \cdot t_{i0} - \frac{H}{G_0 \cdot (1 - E) \cdot \rho \cdot c} \cdot t_e \tag{III.8}$$

$$t_r = \left[1 + \frac{E \cdot H}{G_0 \cdot (1 - E) \cdot \rho \cdot c}\right] \cdot t_{i0} - \frac{E \cdot H}{G_0 \cdot (1 - E) \cdot \rho \cdot c} \cdot t_e \tag{III.9}$$

The outdoor calculation temperature t_{e0}, corresponding to the design conditions, correlates with the design (maximum) temperature of the heat carrier on the supply pipe t_{t0}. For design conditions, formulas (III.1) and (III.7) result in:

$$G_0 \cdot \rho \cdot c \cdot (1 - E) \cdot (t_{t0} - t_{i0}) = H \cdot (t_{i0} - t_{e0}) \tag{III.10}$$

Therefore:

$$\frac{H}{G_0 \cdot \rho \cdot c \cdot (1-E)} = \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \tag{III.11}$$

By introducing (III.11) in relations (III.8) and (III.9), we get the formulas for the variation of the temperature in the flow and return pipes of the distribution network (t_{t0} and t_{r0}) as a function of the indoor temperature t_{i0} and the outdoor calculation temperature t_{e0}, in the case of constant flow operation (temperature control heat adjustment):

$$t_t = \left(1 + \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}}\right) \cdot t_{i0} - \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot t_e \tag{III.12}$$

$$t_r = \left(1 + \frac{t_{r0} - t_{i0}}{t_{i0} - t_{e0}}\right) \cdot t_{i0} - \frac{t_{r0} - t_{i0}}{t_{i0} - t_{e0}} \cdot t_e \tag{III.13}$$

In determining the relationships used to establish the temperature variation of the heat transfer agent on the flow and return pipes, we considered that the thermal module of the heating system E is constant and has a nominal value E_0. In reality, by definition, the thermal module of the heating system E depends on the number of heat transfer units (NTU):

$$E_0 = \exp(-NTU_0) = \exp\left(-\frac{k_0 \cdot S}{G_0 \cdot \rho \cdot c}\right) = \frac{t_{r0} - t_{i0}}{t_{t0} - t_{i0}} \tag{III.5'}$$

We considered it to be constant and equal to the nominal value NTU_0. NTU is defined as a function of k (global heat transfer coefficient), which was considered constant and equal to the nominal value k_0.

$$NTU_0 = \frac{k_0 \cdot S}{G_0 \cdot \rho \cdot c} = \ln \frac{t_{t0} - t_{i0}}{t_{r0} - t_{i0}} \tag{III.4'}$$

In fact, k is not constant and depends (by the convective heat transfer coefficient) on the logarithmic mean temperature of the heat carrier. Therefore, the formulas for calculating the temperature of the heat carrier in the supply and return pipes should be corrected to consider this aspect. This is done by iterative calculation, which involves re-calculating the temperature values, while updating the value of the global heat transfer coefficient k. The iterative calculation is rapidly converging, resulting in final values after only 3-4 iterations. [97]

In formulas (III.8) and (III.9) we multiply and divide both terms of the relation with (1-E_0):

$$t_t = \left[1 + \frac{H}{G_0 \cdot (1-E_0) \cdot \rho \cdot c} \cdot \frac{1-E_0}{1-E}\right] \cdot t_{i0} - \frac{H}{G_0 \cdot (1-E_0) \cdot \rho \cdot c} \cdot \frac{1-E_0}{1-E} \cdot t_e \tag{III.14}$$

$$t_r = \left[1 + \frac{E_0 \cdot H}{G_0 \cdot (1-E_0) \cdot \rho \cdot c} \cdot \frac{E}{E_0} \cdot \frac{1-E_0}{1-E}\right] \cdot t_{i0} - \frac{E_0 \cdot H}{G_0 \cdot (1-E_0) \cdot \rho \cdot c} \cdot \frac{E}{E_0} \cdot \frac{1-E_0}{1-E} \cdot t_e \tag{III.15}$$

Formula (III.11) becomes:

$$t_t = \left[1 + \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{1 - E_0}{1 - E}\right] \cdot t_{i0} - \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{1 - E_0}{1 - E} \cdot t_e \tag{III.16}$$

$$t_r = \left[1 + \frac{t_{r0} - t_{i0}}{\left(t_{i0} - t_{e0}\right)} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E}\right] \cdot t_{i0} - \frac{t_{r0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot t_e \tag{III.17}$$

For an outdoor temperature value t_e different from the design temperature t_{e0}, we calculate the temperatures of the heat carrier on the flow and return pipes, using the relationships determined above. Then we calculate the value of the logarithmic mean temperature difference Δt_{ml}.

In the formula of the thermal module E (5), we multiply and divide by k_0 and we get:

$$E = \exp\left(-NTU\right) = \exp\left(-\frac{k \cdot S}{G_0 \cdot \rho \cdot c}\right) = \exp\left(-\frac{k_0 \cdot S}{G_0 \cdot \rho \cdot c} \cdot \frac{k}{k_0}\right) = E_0^{\frac{k}{k_0}} \tag{III.18}$$

According to an experimentally established relationship:

$$\frac{k}{k_0} = \left(\frac{\Delta t_{ml}}{\Delta t_{ml0}}\right)^{0,3} \tag{III.19}$$

In this way we determine the value of E, which we use to resume the calculation. We get new values for the return and return pipe temperatures tt and t_r and for the logarithmic mean temperature difference Δt_{ml}. The calculation is resumed until close or identical values for t_t and t_r are obtained

IV Thermal rehabilitation of buildings - energy consequences

IV.1 The effectul of thermal rehabilitation of buildings

The setting of the heat supply control curves is based on the premise underlying that the values of the heat transfer coefficients of the building elements are considered to be, in the current conditions, unchanged from the design values. This means that the heat supply adjustment graphs that are currently used in the operation of district heating systems were drawn up taking into account the heat demand of the buildings at the time they were built. Considering that, in recent years, a part of the buildings supplied by the district heating systems have been renovated, the values of the heat transfer coefficients through the building elements are significantly different, compared to the moment when these buildings were designed.

If high-energy buildings would be supplied from district heating systems by separate branches from low energy buildings, the heat supply adjustment graphs should be corrected to take account of the reduction in the heat demand of these consumers. Assuming that the previous relationships were determined based on the nominal value of the global thermal insulation coefficient of the building (H_0), and the actual value of this coefficient in the case of renovated buildings is H, relations (III.14) and (III. 15) can be written as:

$$t_t = \left[1 + \frac{H_0}{G_0 \cdot \left(1 - E_0\right) \cdot \rho \cdot c} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0}\right] \cdot t_{i0} - \frac{H_0}{G_0 \cdot \left(1 - E_0\right) \cdot \rho \cdot c} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0} \cdot t_e \tag{IV.1}$$

$$t_r = \left[1 + \frac{E_0 \cdot H_0}{G_0 \cdot (1 - E_0) \cdot \rho \cdot c} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0}\right] \cdot t_{i0} - \frac{E \cdot H_0}{G_0 \cdot (1 - E_0) \cdot \rho \cdot c} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0} \cdot t_e \quad \text{(IV.2)}$$

From (III.11) we get:

$$t_t = \left[1 + \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0}\right] \cdot t_{i0} - \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0} \cdot t_e \quad \text{(IV.3)}$$

$$t_r = \left[1 + \frac{t_{r0} - t_{i0}}{(t_{i0} - t_{e0})} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0}\right] \cdot t_{i0} - \frac{t_{r0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0} \cdot t_e \quad \text{(IV.4)}$$

If the building has not been renovated, the H/H_0 ratio is equal to 1, the values of the temperature of the heat carrier on the flow and return pipes are those presented in Table IV.1 and the heat supply adjustment curve is that shown in Figure IV.1.

If the building has been renovated, the values of the temperature of the heat carrier on the flow and return pipes must be recalculated using formulas (IV.3) and (IV.4) and the heat supply adjustment curves should be corrected according to the new temperature values.

IV.2 Functional and energy analysis

In this paper, the case of a building with a rated heat load of 1 MW located in the climatic zone 2 (outdoor design temperature -15°C) was considered. Several degrees of building renovation have been studied (H/H_0=0,8; H/H_0=0,6; H/H_0=0,4).

Using the formulas presented above, the heat flow transmitted by the heating system to the heated space were calculated, assuming that it is equal to the heat losses from the heated space to the outdoor environment. For this purpose, the temperatures of the heat carrier and the indoor temperature in the heated space were determined.

The reduction of annual energy consumption was analyzed as a result of the two types of measures presented above, namely:

- thermal rehabilitation of buildings (by reducing the global thermal insulation coefficient of the building, H)
- adjustment of the temperature of the primary and secondary heat carriers to the new heat demand of the renovated building, depending on the degree of rehabilitation.

The first case analysed was that of the building before renovation; the temperature of the heat carrier is in accordance with the heat supply diagram established at the design stage.

The second case was that of the renovated building supplied with a heat carrier having a temperature corresponding to the unrenovated building (the current situation of all renovated buildings supplied by DHS in Romania).

The third analised case was that of the low-energy building supplied with a heat carrier having the temperature adjusted to the new heat demand, in order to maintain a standard indoor temperature of 20°C in the building. A new heat supply graph was developed based on the newly determined supply and return temperatures of the heat carrier. To this end, the flow and return temperatures of the heat carrier that ensure this indoor temperature were determined and a new heat supply curve was established for the renovated building (the corrected heat supply graph), depending on the degree of thermal rehabilitation.

For a building with a rated heat load of 1 MW, the thermal rehabilitation of the building, coupled with low temperature heat supply, leads to significant energy consumption reductions, of about 20% for H/H_0 = 0.8, 40% for H/H_0 = 0.6 and 60% for H/H_0 = 0.4. These benefits can be obtained with minimal investment effort. For a better emphasis of the reduction of energy consumption, the graphs representing the energy consumption of the building in the three analyzed situations were developed, for three degrees of thermal rehabilitation: H/H_0 = 0,4, H/H_0 = 0, 6 and H/H_0 = 0.8 (Figure IV.11).

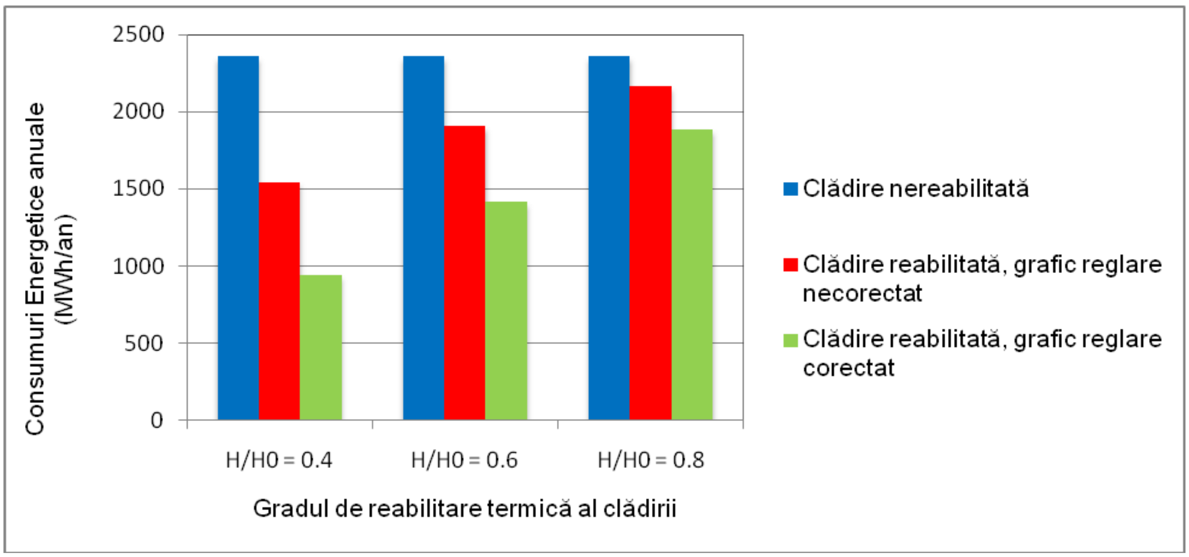


Figure IV.11 Annual heat consumption for heating in the three analized cases [100]

Figure IV.11 shows the reduction of annual heating energy consumption for heating in a building with a rated heat load of 1 MW in the case of the thermal rehabilitation of the building and in the case of the thermal rehabilitation of the building accompanied by the correction of the heat supply adjustment graph. Different degrees of thermal renovation (H/H_0 = 0.4, H/H_0 = 0.6 and H/H_0 = 0.8) were presented distinctly in the chart.

Figure IV.12 illustrates the annual heat savings for heating of the building in a building with a rated heat load of 1 MW in the case of the thermal rehabilitation of the building and in the case of the thermal rehabilitation of the building accompanied by the correction of the heat supply adjustment graph. Different degrees of thermal renovation (H/H_0 = 0.4, H/H_0 = 0.6 and H/H_0 = 0.8) were presented distinctly in the chart.

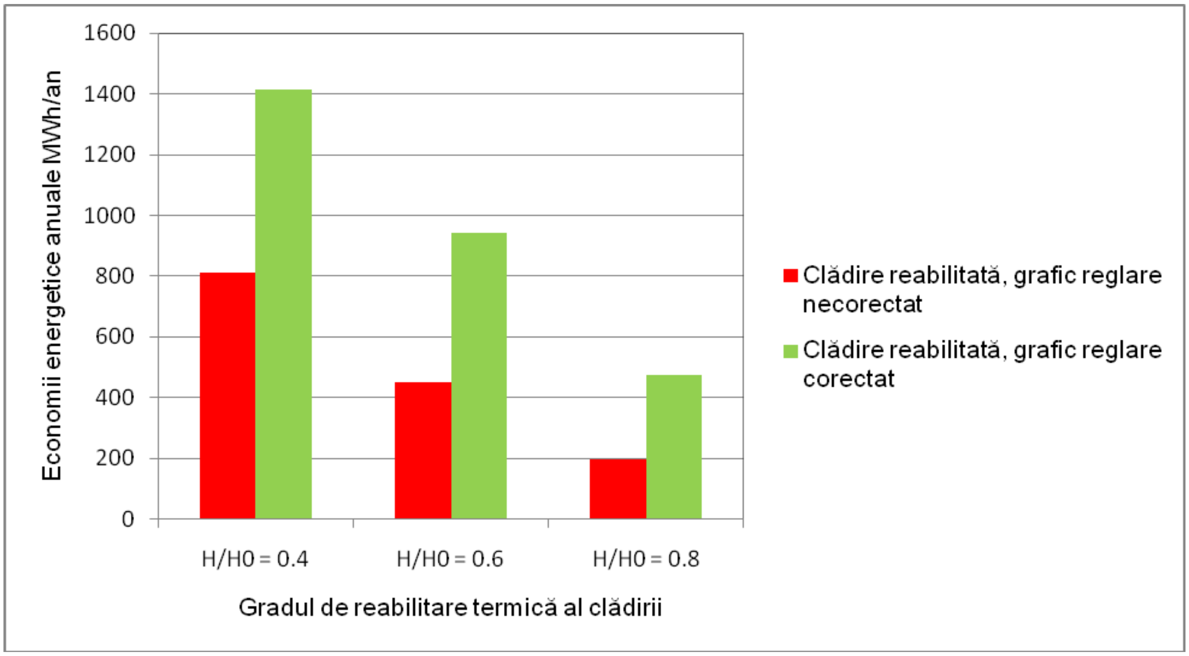


Figure IV.12 Annual heat savings for heating of the building in the three analized cases [100]

V The influence of the heat carrier temperature on the energy performance of district heating systems

An analysis on the influence of reducing the temperatures of the heat carrier on the efficiency of district heating systems has been carried out in this paper,

The following formulas were used in order to evaluate the efficiency of a centralized heating system [102]:

$$\eta = \frac{Q_C}{Q_{sursa}} = \frac{E_R \cdot (1 - E_C)}{1 - E_R{}^2 \cdot E_C} \tag{V.1}$$

$$E_R = \exp\left(-\frac{1}{\rho \cdot c} \cdot \frac{L}{R \cdot G}\right) \tag{V.2}$$

$$E_C = \exp\left(-\frac{1}{\rho \cdot c} \cdot \frac{k \cdot S}{G}\right) \tag{V.3}$$

$$E_C = \frac{t_r - t_i}{t_t - t_i} \tag{V.4}$$

$$E'_C = \frac{t_R - t_r}{t_T - t_t} \tag{V.5}$$

Table V.2 and Figure V.1 show the values of the efficiency of a distribution system for different values of the design temperatures of the heat carrier:

Table V.2 The efficiency of a distribution system for different values of the design temperatures of the heat carrier

t_t [°C]	t_r [°C]	t_i [°C]	E_C [-]	E_R [-]	η_{SD} [-]
90,0	70,0	20	0,714	0,98	0,89
80,0	60,0	20	0,667	0,98	0,91
70,0	50,0	20	0,600	0,98	0,93
60,0	40,0	20	0,500	0,98	0,94
50,0	30,0	20	0,333	0,98	0,96

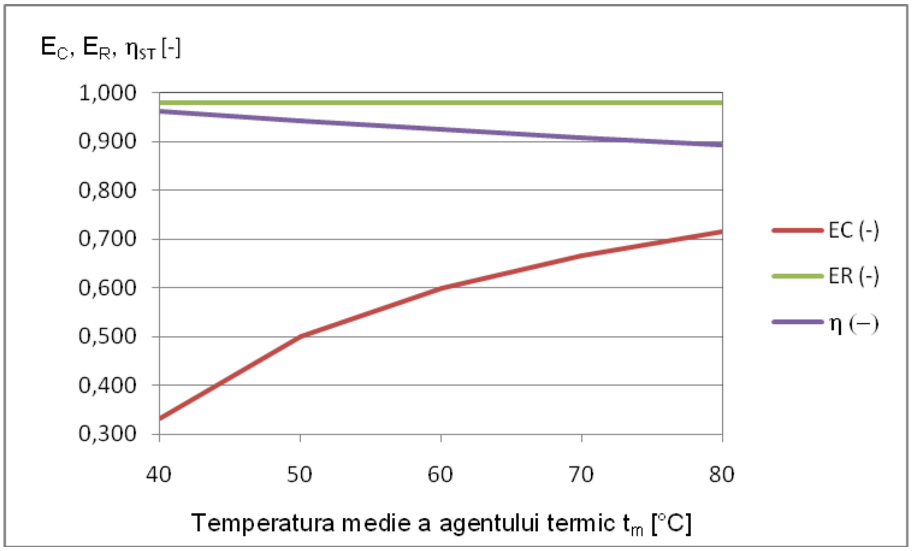


Figure V.1 The variation of the thermal module of the heating system and of the heating network and the efficiency of the distribution system, depending on the design temperatures of the heat carrier

Table V.2 shows that the efficiency of a distribution system is the higher the nominal temperatures of the heat carrier are lower.

Another analysis is aimed at determining the efficiency of heating systems when a temperature difference other than the 20°C (at which the existing systems are designed) is adopted for the heat carrier between flow and return pipes in the distribution system. This study was carried out considering that a temperature difference of 30°C could facilitate the introduction of the low temperature solution in some district heating systems.

Table V.3 The efficiency of a heat distribution system for different values of the design temperature of the heat carrier, for a temperature range of 30°C

t_t [°C]	t_r [°C]	t_i [°C]	E_C [-]	E_R [-]	η_{SD} [-]
90,0	60,0	20	0,571	0,97	0,90
80,0	50,0	20	0,500	0,97	0,92
70,0	40,0	20	0,400	0,97	0,93
60,0	30,0	20	0,250	0,97	0,95
50,0	20,0	20	0,000	0,97	0,97

The efficiency of the distribution system is better in case of a higher temperature difference, irrespective of the design temperature of the heat carrier on the supply pipe.

VI Experimental research within district heating systems. Calibration and validation of theoretical models of simulation of behavior in operation of district heating systems

The experimental part of this paper aimed to evaluate the thermal module of an existing distribution system on an experimental basis. The purpose was to calibrate and validate the theoretical model used to determine the equivalent thermal module of a distribution system (formula VI.1):

$$E_{ech} = \frac{t_m - t_s}{t_0 - t_s} \tag{VI.1}$$

where

- t_m is the average temperature of the heat carrier at the consumers supplied;
- t_0 is the temperature of the heat carrier leaving the thermal substation;
- t_s is the ambient temperature in the duct where the pipes are installed or the soil temperature for the preinsulated pipes installed directly in the ground.

This analysis was performed for the flow pipe of the distribution system.

In the present paper, an experimental procedure for the thermal insulation of the existing thermal network was identified. Determining the quality of the thermal insulation is useful in assessing the energy performance of the pipeline network. The analysis was carried out by the theoretical and experimental evaluation of the thermal module of a distribution network whose layout and geometry is known. The analysis is aimed at the validation of the theoretical model of the system behavior in the current operating regime. Knowing the real degree of thermal insulation of the studied network, it was possible to compare and validate the theoretical model. To this end, the modeling of some particular branches of the distribution systems of two thermal substations in Bucharest has been carried out.

VI.1 Case study

The branch of the distribution system feeds 3 apartment buildings: building A having 7 entrances, block B having 6 entrances, and block C having 5 entrances. The heat distribution system that supplies the three buildimgs consists of pre-insulated pipes buried directly in the ground. The connection to each building is fitted with a heat meter. but the distribution pipes in the buildings are installed in the basement of each building. Only the distribution network outside the building was included in the analysis.

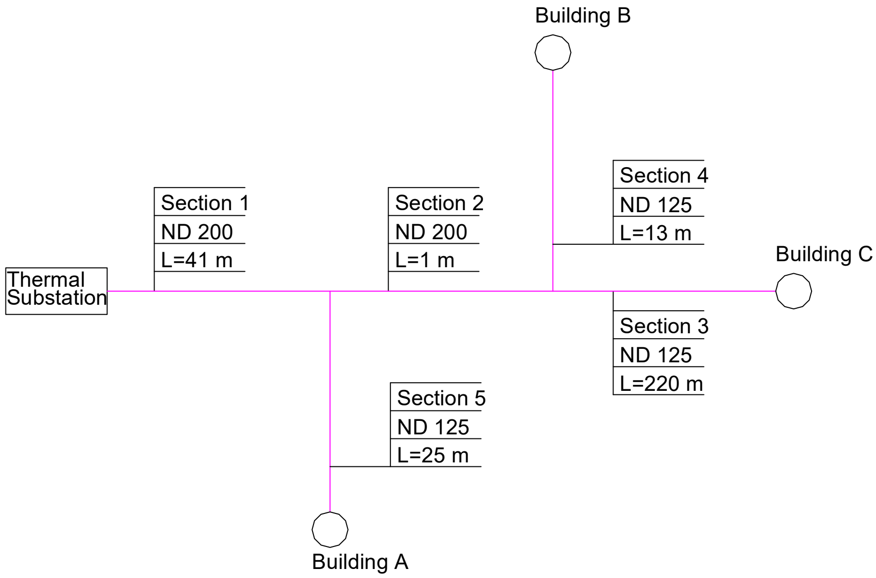


Figure VI.1 The branch of the distribution network analysed theoretically and experimentally (case I)

Firstly, the heat supply of the consumer has been analyzed theoretically. The data provided by the system operator was then included in the calculation, the comparison was made and the conclusions were drawn.

The physical and thermal characteristics of the pipe sections belonging to the studied branch of the distribution system are presented in Table VI.1.

The thermal resistances of the sections were calculated with formula (VI.2) [104].

$$R = \frac{1}{\pi \cdot D_i \cdot \alpha_i} + \frac{1}{2 \cdot \pi \cdot \lambda_t} \cdot \ln \frac{D_e}{D_i} + \frac{1}{2 \cdot \pi \cdot \lambda_{iz}} \cdot \ln \frac{D_{iz}}{D_e}$$

(VI.2)

The measured flow rates of the three consumers were used in the calculation; the theoretical thermal resistances and the thermal modules of the pipe sections were determined.

Then the theoretical temperature of the heat carrier was calculated for the three consumers supplied from the branch (buildings A, B and C), assuming that the temperature of the heat carrier leaving the thermal substation is 60 ° C (design temperature).

The following formulas were used to determine the temperature of the heat carrier entering the three buildings [105]:

$$t_C = E_1 \cdot E_2 \cdot E_3 \cdot t_0 + (1 - E_1 \cdot E_2 \cdot E_3) \cdot t_S \qquad \text{(VI.3)}$$

$$t_B = E_1 \cdot E_2 \cdot E_4 \cdot t_0 + (1 - E_1 \cdot E_2 \cdot E_4) \cdot t_S \qquad \text{(VI.4)}$$

$$t_A = E_1 \cdot E_5 \cdot t_0 + (1 - E_1 \cdot E_5) \cdot t_S \qquad \text{(VI.5)}$$

Further, the heat supply of the furthest consumer from the source (building C) was analyzed; the pipeline consists of sections 1, 2 and 3. Theoretical values of the respective thermal resistances of the analyzed sections were checked with the following formula [106]:

$$\begin{pmatrix} \frac{1}{R_1} \\ \frac{1}{R_2} \\ \frac{1}{R_3} \end{pmatrix} = \begin{pmatrix} \frac{1}{\rho c}\cdot\frac{L_1}{G_{11}} & \frac{1}{\rho c}\cdot\frac{L_2}{G_{21}} & \frac{1}{\rho c}\cdot\frac{L_3}{G_{31}} \\ \frac{1}{\rho c}\cdot\frac{L_1}{G_{12}} & \frac{1}{\rho c}\cdot\frac{L_2}{G_{22}} & \frac{1}{\rho c}\cdot\frac{L_3}{G_{32}} \\ \frac{1}{\rho c}\cdot\frac{L_1}{G_{13}} & \frac{1}{\rho c}\cdot\frac{L_2}{G_{23}} & \frac{1}{\rho c}\cdot\frac{L\ 3}{G_{33}} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \ln\frac{t_{01}-t_{S1}}{t_{31}-t_{S1}} \\ \ln\frac{t_{02}-t_{C2}}{t_{32}-t_{C2}} \\ \ln\frac{t_{03}-t_{S3}}{t_{33}-t_{S3}} \end{pmatrix} \qquad \text{(VI.6)}$$

where the significance of the two flow indices is the following: the first index is related to the section and the second index is related to the experiment.

The calculation resulted in the following values of the thermal resistances of the three sections:

R1=	1,9287	mK/W
R2=	1,9287	mK/W
R3=	2,5323	mK/W

The calculation resulted in the same values of thermal resistance as those calculated based on the physical characteristics of the pipeline.

The equivalent thermal module of the distribution branch supplying the three consumers was determined based on formulas (VI.7) and (VI.8) [105]:

For parallel pipe sections: $$E_{ij}^{p} = \frac{G_i \cdot E_i + G_j \cdot E_j}{G_i + G_j} \qquad \text{(VI.7)}$$

For serial pipe sections: $$E_{ij}^{s} = E_i \cdot E_j \qquad \text{(VI.8)}$$

Table VI.3 The equivalent thermal module of the distribution branch în the three scenarios (case I)

	(1)	(2)	(3)
E34	0,998824	0,998597	0,998597
E234	0,998818	0,998589	0,998589
E2345	0,999201	0,999041	0,999037
E12345	0,999036	0,998842	0,998837

Based on the calculated temperatures of the heat carrier on the flow pipe at the entrance to the internal distribution system of the consumers (t_A, t_B and t_C), the average temperature t_m for each case and the equivalent thermal module of the analysed distribution network were determined, using formula (VI.1):

Table VI.4 Values of the thermal modules determined based on the calculated temperatues (case I)

t_C [°C]	t_B [°C]	t_A [°C]	t_m [°C]	Eech [-]
59,919742	59,986447	59,985460	59,9614	0,999036
59,905205	59,983621	59,982433	59,9537	0,998842
59,905416	59,983550	59,982291	59,9535	0,998837

By comparing the respective values, we see that the equivalent thermal module of the distribution network determined based on the average temperatures of the heat carrier entering the three buildings is equal to the equivalent thermal module of the distribution network determined by calculation, based on formulas (VI.7) and (VI.8).

Conclusion

For a thermal distribution network whose constructive characteristics are known, we can determine by calculation the design equivalent thermal module of the network and, by measuring the temperature of the heat carrier at the heat source and at the ends of the network (at the consumers), it is possible to determine the real (actual) equivalent thermal module of the thermal network. By comparing the two values, one can appreciate the degree of degradation of the insulation and the actual efficiency of the distribution network.

For this purpose, the same analysis was performed based on the actual flows and temperatures of the heat carrier, measured at the entrances of the buildings, and the actual thermal resistances and the actual thermal modules of the pipe sections were calculated.

From the data provided by the system operator, the flows and temperatures measured in three different cases were selected. They were registered in January 2017, when the temperature on the flow pipe of the distribution network at the outlet of the thermal substation had the same value: 58.9°C (January 20, January 30, January 31).

The values of the thermal modules calculated based on the actual measured and recorded temperatures are different from the theoretical ones and are presented in Table VI.6.

Tablel VI.6 The values of the thermal modules calculated based on the actual measured temperatures
(case I)

t_C [°C]	t_B [°C]	t_A [°C]	t_m [°C]	Eech [-]
57,2	56,3	56,4	56,67	0,942709
57,1	56,1	56,3	56,55	0,939675
57,2	56,2	56,3	56,62	0,941317

By comparing the corresponding value sets, it is noted that the distribution network formed by pipe sections 1, 2 and 3 has low thermal resistances, and there is significant heat loss between the thermal substation and the consumers.

Knowing the thermal module of the flow pipe of the network can lead to the determination of a number of thermal units associated with the flow pipe of the network and an average thermal resistance of the flow pipe of the network, which can lead to the determination of the general state of the flow pipe of the branch of the distribution network. These data are not, however, sufficient to determine the status of the thermal insulation of each network section. For this purpose, the relationship (VI.6) can be used to determine the actual thermal resistances of each pipe section that supplies building C. The actual values of the thermal resistance of the three sections are as follows:

R1=	0,0008	mK/W
R2=	0,0001	mK/W
R3=	0,0223	mK/W

It can be concluded that the actual values of the thermal resistances for all three sections are very low, which means that the insulation of the pipes is impregnated with water and no longer has the properties necessary to keep the heat losses at the standard values.

VII Energy savings achieved by thermal rehabilitation of the building envelope as a function of the degree of thermal rehabilitation

Thermal rehabilitation of buildings aims to reduce the heat loss through the building elements, resulting in a significant reduction in heat demand for heating the building. Using a heat carrier having the same temperature as before the renovation for these consumers leads to a decrease in the efficiency of the district heating system by increasing energy losses. This paper presents the assessment of energy savings as a result of applying the first two measures of increasing the efficiency of district heating systems (thermal rehabilitation of buildings and using low temperature heat carrier for low energy buildings). The two types of measures are not independent, as the delivery temperature of the heat carrier depends on the level of thermal rehabilitation.

In order to assess the energy consumption, the formulas associated with the heat supply curves for constant flow rates have been used: [97]

$$t_t = \left[1 + \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0}\right] \cdot t_{i0} - \frac{t_{t0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0} \cdot t_e \tag{VII.1}$$

$$t_r = \left[1 + \frac{t_{r0} - t_{i0}}{\left(t_{i0} - t_{e0}\right)} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0}\right] \cdot t_{i0} - \frac{t_{r0} - t_{i0}}{t_{i0} - t_{e0}} \cdot \frac{E}{E_0} \cdot \frac{1 - E_0}{1 - E} \cdot \frac{H}{H_0} \cdot t_e \tag{VII.2}$$

where:

$$E_0 = \exp\left(-NTU_0\right) = \exp\left(-\frac{k_0 \cdot S}{G_0 \cdot \rho \cdot c}\right) = \frac{t_{r0} - t_{i0}}{t_{t0} - t_{i0}} \tag{VII.3}$$

$$E = E_0^{\frac{k}{k_0}} \tag{VII.4}$$

$$\frac{k}{k_0} = \left(\frac{\Delta t_{ml}}{\Delta t_{ml0}} \right)^{0,3} \tag{VII.5}$$

$$\Delta t_{ml0} = \frac{t_t - t_r}{\ln \frac{t_t - t_{i0}}{t_r - t_{i0}}} \tag{VII.6}$$

Using the formulas above, the heat flows transmitted by the heating system to the heated space were calculated, assuming that they are equal to the heat losses from the heated space to the outdoor environment. The temperatures of the heat carrier and the indoor temperature have been determined.

The reduction of the annual heating energy consumption was analyzed as a result of the two types of measures presented above, namely:

- the implementation of energy efficiency measures in the building (by reducing the thermal coupling coefficient of the building envelope, H)
- the adjustment of the temperature of the heat carrier to the new heat demand of the building, according to the degree of renovation.

The first case analysed was that of the building before renovation; the temperature of the heat carrier is in accordance with the heat supply diagram established at the design stage. The typical design temperatures for the primary (transport) the secondary (distribution) networks were considered: t_{T0}/t_{R0} = 150/80°C, t_{T0}/t_{R0} = 90/70°C.

The second case was that of the renovated building supplied with a heat carrier having a temperature corresponding to the unrenovated building (according to the heat supply curves determined at the design stage) - heat carrier used for the heating of the other unrenovated buildings supplied by the same DHS (the current situation of all renovated buildings supplied by DHS in Romania). Several degrees of building renovation have been studied (H/H_0=0,8; H/H_0=0,6; H/H_0=0,4).

The third analised case was that of the low-energy building supplied with a heat carrier having the temperature adjusted to the new heat demand. In order to maintain a standard indoor temperature of 20°C in the building. A new heat supply graph was developed based on the newly determined supply and return temperatures of the heat carrier. To this end, the flow and return temperatures of the heat carrier that ensure this indoor temperature were determined and a new heat supply curve was established for the renovated building (the corrected heat supply graph), depending on the degree of thermal rehabilitation:

Figure 1 is a graphical representation of the energy savings of the building characterized by a rated heat load of 1 MW in the climatic zone 2. The energy consumption reductions due to the thermal rehabilitation of the building, the energy consumption reductions due to the use of a low temperature heat carrier , as well as the cumulative effect of both measures, were represented in the chart. In the figure below, the R**1 curve represents the percentage reduction in energy consumption due to building renovation**, R2 represents the percentage reduction in energy consumption due to adjusting the temperature of the heat carrier to the new heat demand of the rehabilitated building, and R12 represents the percentage reduction in energy consumption due to the cumulative effect of both the thermal rehabilitation and the use of a low temperature heat carrier. The energy consumption reductions were plotted according to the degrees of building renovation.

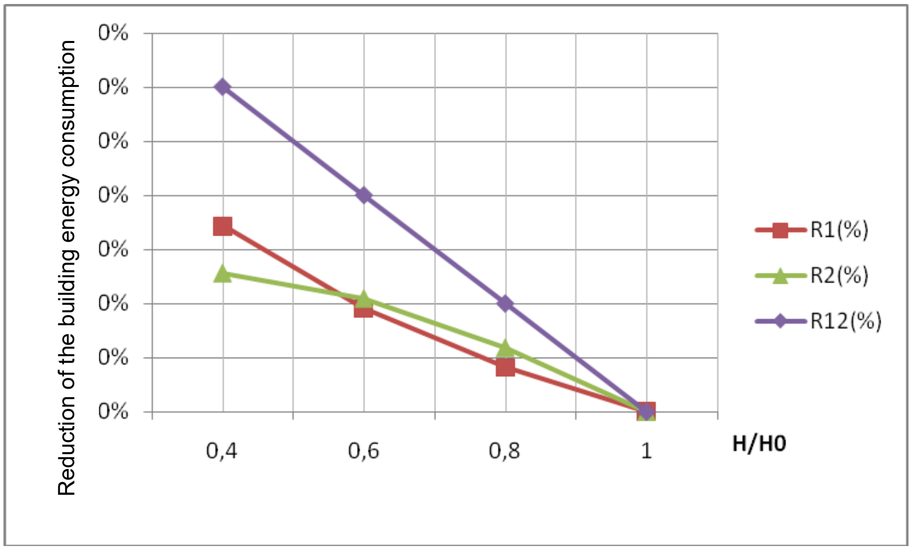


Figure VII.1 Reduction of the building energy consumption as a result of the thermal rehabilitation of the building and as a result of adjusting the temperature of the heat carrier to the new heat demand of the rehabilitated building, corresponding to the degree of building renovation

The chart illustrates that the reduction of energy consumption as a result of the thermal rehabilitation and the supply of a lower temperature heat carrier, corresponding to the degree of thermal renovation, lead to significant energy consumption reductions of about 20% for H/H0 = 0.8, about 40% for H/H0 = 0.6 and about 60% for H/H0 = 0.4.

Figure VII.1 shows that for a degree of building renovation H/H0>0.55, R2>R1, hence the adjustment of the heat supply curve has a more significant weight in the percentage reduction of the energy consumption than the thermal rehabilitation of the of the building, and for a degree of thermal renovation H/H0<0.55, R1> R2, hence the weight of the two components is reversed and the thermal rehabilitation of the building prevails.

VIII Energy savings due to the reduction of the temperature of the heat carrier in the distribution networks

In this chapter, an analysis has been carried out on the effect of the reduction of temperatures of heat carriers on the heat losses in distribution networks.

To this end, the modelling of a branch (part of a distribution system of a thermal substation) was carried out. The thermal substation and the assciated distribution network are part of the district heating system in Bucharest.

The same thermal substation in Berceni district as in chapter VI was selected for analysis and data provided by RADET Bucharest were used.

The measured flow rates on the supply line to each of the three consumers were used in the calculation.

The following formulas were used to assess the heat losses of the distribution network:

$$Q_p = \frac{1}{R} \cdot L \cdot \Delta t_{ml,sol} \tag{VIII.1}$$

$$R = \frac{1}{\pi \cdot D_i \cdot \alpha_i} + \frac{1}{2 \cdot \pi \cdot \lambda_t} \cdot \ln \frac{D_e}{D_i} + \frac{1}{2 \cdot \pi \cdot \lambda_{iz}} \cdot \ln \frac{D_{iz}}{D_e} \tag{VIII.2}$$

The theoretical heat losses of the sections of the distribution network were determined for two situations:

- feeding the consumers with a heat carrier having a temperature corresponding to the uncorrected heat supply curve (unrenovated buildings)
- feeding the consumers with a heat carrier having a temperature corresponding to the corrected heat supply curve (renovated buildings) (H/H_0=0,6 case).

It can be noticed that, during a heating season, the heat losses of the distribution network are reduced by 31.6% if the renovated buildings are fed with a heat carrier having a temperature corresponding to the corrected heat supply curve, compared to the situation when they are fed with a heat carrier having a temperature corresponding to the uncorrected heat supply curve.

Table VIII.2 Heat losses of the distribution network when consumers are supplied with a heat carrier having a temperature corresponding to the uncorrected heat supply curve (unrenovated buildings)

				Supply						Return							
No. of days	te (°C)	t_{tB} (°C)	tr_B (°C)	Qp1 (kW)	Qp2 (kW)	Qp3 (kW)	Qp4 (kW)	Qp5 (kW)	Qt (kW)	Qp1 (kW)	Qp2 (kW)	Qp3 (kW)	Qp4 (kW)	Qp5 (kW)	Qr (kW)	Qtot (kW)	Qp (MWh)
2	-15	90,0	70,0	1,49	0,04	6,07	0,36	0,69	8,65	1,06	0,03	4,35	0,26	0,49	6,19	14,84	0,7
11	-10	81,8	64,7	1,31	0,03	5,37	0,32	0,61	7,64	0,95	0,02	3,89	0,23	0,44	5,53	13,17	3,5
32	-5	73,4	59,1	1,14	0,03	4,63	0,27	0,53	6,60	0,83	0,02	3,41	0,20	0,39	4,84	11,44	8,8
60	0	64,6	53,2	0,95	0,02	3,87	0,23	0,44	5,52	0,71	0,02	2,89	0,17	0,33	4,11	9,63	13,9
53	5	55,5	46,9	0,75	0,02	3,08	0,18	0,35	4,38	0,57	0,01	2,34	0,14	0,27	3,33	7,71	9,8
24	10	45,7	39,9	0,55	0,01	2,23	0,13	0,25	3,17	0,42	0,01	1,74	0,10	0,20	2,47	5,64	3,2
									35,95						26,49	62,44	39,9

Table VIII.3 Heat losses of the distribution network when consumers are supplied with a heat carrier having a temperature corresponding to the corrected heat supply curve (renovated buildings)

				Supply						Return							
No. of days	te (°C)	t_{tB} (°C)	tr_B (°C)	Qp1 (kW)	Qp2 (kW)	Qp3 (kW)	Qp4 (kW)	Qp5 (kW)	Qt (kW)	Qp1 (kW)	Qp2 (kW)	Qp3 (kW)	Qp4 (kW)	Qp5 (kW)	Qr (kW)	Qtot (kW)	Qp (MWh)
2	-15	66,4	54,4	0,99	0,02	4,03	0,24	0,46	5,74	0,73	0,02	3,00	0,18	0,34	4,26	10,00	0,5
11	-10	61,0	50,7	0,87	0,02	3,56	0,21	0,40	5,07	0,65	0,02	2,68	0,16	0,30	3,81	8,88	2,3
32	-5	55,5	46,9	0,75	0,02	3,08	0,18	0,35	4,38	0,57	0,01	2,34	0,14	0,27	3,33	7,71	5,9
60	0	49,7	42,8	0,63	0,02	2,57	0,15	0,29	3,67	0,49	0,01	1,99	0,12	0,23	2,83	6,49	9,4
53	5	43,6	38,4	0,50	0,01	2,05	0,12	0,23	2,91	0,39	0,01	1,61	0,09	0,18	2,29	5,20	6,6
24	10	37,1	33,7	0,43	0,01	2,05	0,10	0,20	2,79	0,29	0,01	1,19	0,07	0,13	1,69	4,48	2,6
									24,56						18,21	42,77	27,3

IX Case study: Assessing the reduction of heat losses related to a consumer by lowering the temperature of the heat carrier

We analize the building studied in the previous chapters, a building located in the climatic zone 2, having a 1 MW hourly energy consumption at the outdoor design temperature of -15 ° C.

1) First we consider the unrenovated building.
2) We consider the current solution applied in Romania in building renovation projects: the application of 10 cm of polystyrene on the opaque parts of the building envelope and the complete replacement of wooden windows with airtight windows with thermo-insulating glass. From the calculation example in Chapter VII, these characteristics result in a H/H_0 ratio of 0.4.
3) We consider that the temperature of the heat carrier supplied to the consumer corresponds to the new heat demand resulted from the renovation of the building, as derived from the calculations made in Chapter IV.

We therefore analyze three distinct situations for that building; each of these situations corresponds to a certain heat consumption Q_C, a certain global thermal insulation coefficient of the building H, a certain pair of design temperature (supply-return values) of the heat adjustment graph t_t/t_r and a certain amount of thermal energy Q_{source} required to be supplied from the heat source (thermal substation) to ensure the energy consumption Qc.

	Q_C	H	t_t/t_r	Q_{source}
1. Unrenovated building	Q_{C0}	H_0	t_{t0}/t_{r0}	$Q_{source0}$
2. Renovated building + uncorrected heat adjustment curve	Q_{C2}	H	$t_{t0}/t_{r''}$	$Q_{source2}$
3. Renovated building + corrected heat adjustment curve	Q_{C3}	H	t_t/t_r	$Q_{source3}$

This calculation example aims at highlighting the reduction of the heat consumption Q_C and the power required to be delivered by the heat source Q_{source} in the three mentioned scenarios as a result of:

a) the renovation of the building envelope, i.e. the excess area of the radiators;
b) the reduction of the heat losses in heat distribution networks. For this purpose, the heat losses in the distribution networks associated with the renovated consumer were determined separately.

In order to determine the heat losses in the distribution networks, the formulas given in Chapter V have been used:

$$E_C = \frac{t_r - t_i}{t_t - t_i} \tag{V.4}$$

$$\eta_{SD} = \frac{Q_C}{Q_{sursa}} = \frac{E_R \cdot (1 - E_C)}{1 - E_R^{\ 2} \cdot E_C} \quad \text{(V.1)}$$

For the conventional design indoor temperature of 20°C**,** considering that the thermal module of distribution networks (E_R) is constant and equal to 0.98 (value corresponding to thermal networks in a state of average wear in an area with high linear heat density) and for different values of the design temperatures in the heat supply adjustment graph, the values of the efficiency of the distribution system are listed in the following table::

Table IX.1 The efficiency of the distribution system for different values of the design temperatures in the heat supply adjustment graph

t_{t0} (°C)	90	70	50	85	65	45
t_{r0} (°C)	70	50	30	75	55	35
E_R (-)	0,98	0,98	0,98	0,98	0,98	0,98
E_C (-)	0,71	0,60	0,33	0,85	0,78	0,60
η_{SD} (-)	0,89	0,93	0,96	0,80	0,86	0,93

But the efficiency of the district heatong system is also:

$$\eta = \frac{Q_C}{Q_{sursa}} \ \text{(V.1)} \qquad \text{therefore} \qquad Q_{sursa} = \frac{Q_C}{\eta}$$

For the building with an hourly energy consumption of 1 MW, at the outdoor design temperature of -15 °C and the analyzed renovation case (H/H_0 = 0,4), the following data rezult from calculation:

Table IX.2 The heat consumption and the thermal power delivered by the heat source for the considered building

H/H_0=0,4	Q_C (MWh)	t_t (°C)	t_r (°C)	t_i (°C)	E_R (-)	E_C (-)	η_{SD} (-)	Q_{source} (MWh)	Q_p (MWh)
1	2.356	90	70	20	0,98	0,71	0,89	2.642	286
2	1.546	90	77,2	41,1	0,98	0,74	0,88	1.753	208
3	942	53,6	45,6	20	0,98	0,76	0,87	1.083	141

In Table IX.2, Q_p represents the heat losses in the thermal network corresponding to the renovated building.

Table IX.3 presents (as a percentage) the power consumed at the building level, respectively the heat losses in the network, compared to the power delivered by the heat source prior to building renovation, for each of the analyzed scenarios.

Table IX.3 The power consumed at the building level and the heat losses in the network, in relation to the power delivered by the source prior to building renovation

	Putere consumată (%)	Pierderi reţea (%)
1	0,89	0,11
2	0,59	0,08
3	0,36	0,05

Representing graphically the reduction of the consumed thermal power Q_C and the power required to be delivered by the heat source $Q_{sursă}$ in the three mentioned situations, we get:

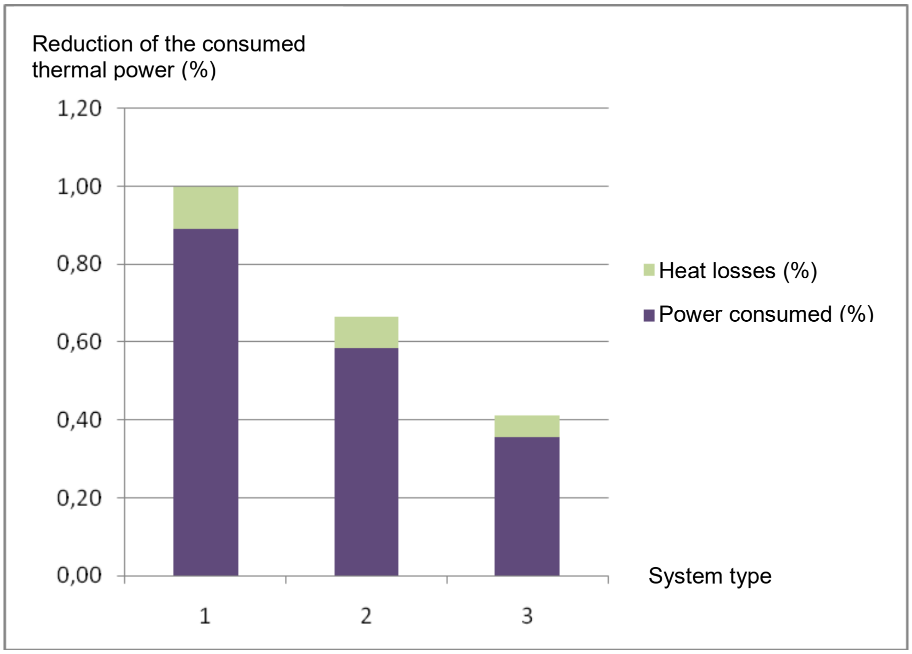


Figure IX.1 The consumed thermal power and the heat losses in the distribution network associated with the building, in the three analyzed scenarios

In the figure above, the system types are those specified above, respectively:

1. Unrenovated building
2. Renovated building + uncorrected heat adjustment curve
3. Renovated building + corrected heat adjustment curve

X Analysis of the consumer connection schemes in order to supply low temperature heat carrier to renovated buildings

Since district heating systems in Romania supply both renovated and unrenovated buildings, these systems must continue to operate by the current heat supply adjustment curves (corresponding to the unrenovated buildings). In order to supply low energy buildings with a low-temperature heat carrier, we propose a connection scheme whereby the heat supply of energy-efficient buildings is carried out mainly from the return pipe of the system, and only if the temperature of the heat carrier on the return pipe is insufficient, the required flow will be taken over from the supply pipe. The adjustment will be made by means of a three-way, electrically driven mixing control valve, adjusting the temperature of the heat carrier supplied to the renovated building according to the heat supply curve corrected for the energy-efficient buildings. The proposed configuration is based on that presented in „*Low temperature networks: Concept, demonstration and guideline*” presentation at DHC+ 2nd International Research Conference, 5-6 november 2013 [16]

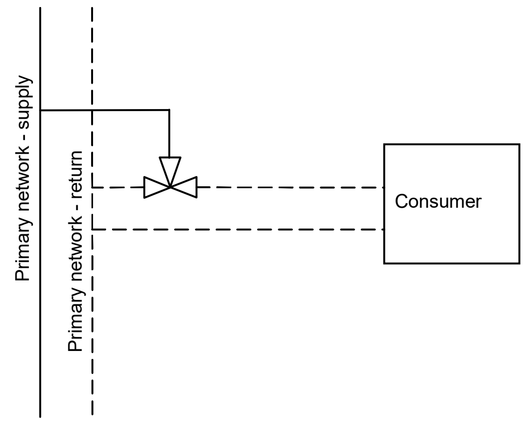


Figure 3 Connection scheme for energy-efficient buildings

This paper explores the possibility of connecting low-energy buildings to existing district heating systems in several scenarios, covering all the possibilities that may arise in practice today and in the future. Three possible scenarios have been identified:

a. **The thermal substation supplies only energy efficient buildings**
b. **A branch of the thermal substation supplies only energy efficient buildings**
c. **The thermal substation supplies both low and high energy buildings.**

The solutions corresponding to each of the scenarios are analyzed below.

a. Scenario (a): The thermal substation supplies only energy efficient buildings

This scenario analyses the way thermal substations feeding only low-energy buildings can supply low-temperature heat carrier to consumers. Low-energy buildings include both renovated buildings and new buildings, built in accordance with the new regulations for energy-efficiency in buildings.

In order to supply consumers with a low temperature heat carrier, according to the corrected heat supply adjustment curve, the most convenient solution would be to use the scheme shown in Figure 3 at the point of connection of the thermal substation to the heat transportation system (primary network), in order to supply the thermal substation with a primary heat carrier in compliance with the corrected heat adjustment curve for renovated buildings. This would make it possible to additionally increase the efficiency of the district heating system by reducing the heat losses in the transportation network representing the connection to that thermal substation. However, this solution has not been proposed in this paper for several reasons:

- the connection point is a point on the route where there is at most one connection chamber; the installation of the control valve requires space, as well as power supply. Transmitting information from the controller in the thermal substation or from another controller to the control valve can be done by wire, internet or GSM, all requiring equipment and materials, which are additional costs. On the other hand, in the thermal substation there is space, power supply, and it is necessary only to reprogram the controller by entering the data corresponding to the new heat supply adjustment curve.

- feeding the thermal substation with a heat carrier of a temperature different from the one it was designed for requires a thorough analysis of the capacity of heat exchangers to produce domestic hot water at the temperature provided by the norms (60°C). This analysis should be performed at the level of the whole district heating system, so that, when all the buildings supplied by the thermal substation will be energy-efficient, it can operate with low temperature heat carrier.

In the first scenario (a), several connection schemes of thermal substations to district heating systems were analyzed, and the most common were selected for analysis below.

- Indirect connection of the heating systems and the preparation of domestic hot water in two stages, in series with the heating system. Both situations occuring in the operation of the district heating systems were analyzed: constant flow operation (temperature control) and variable flow operation (mixed control).
- Indirect connection of the heating system and domestic hot water preparation in one stage in parallel with the heating system. Both situations occuring in the operation of the district heating systems were analyzed: constant flow operation (temperature control) and variable flow operation (mixed control).
- Indirect connection of the heating system and domestric hot water preparation in one stage in series with the heating system, with flow injection and storage system. Both situations occuring in the operation of the district heating systems were analyzed: constant flow operation (temperature control) and variable flow operation (mixed control).

In the case of constant flow operation, no additional equipment is required. The solution consists in reprogramming the existing electronic controller to enter the temperatures of the corrected heat supply adjustment curve. The existing three-way control valve will continue to operate in the same way: only the flow required to prepare the heat carrier at the set temperature for the energy efficient buildings will be circulated through the heat exchanger from the high-temperature primary network, depending on the outdoor temperature. The electronic controller compares the temperature in the corrected heat supply curve corresponding to the outdoor temperature to the temperature on the flow (supply) pipe of the distribution system. If the temperature of the heat carrier is higher than the one provided in the corrected heat supply curve, the controller commands the reduction of the flow through the heat exchanger and the increase of the flow on the bypass pipe to the return pipe of the primary network. If the temperature of the heat carrier is lower than that provided in the corrected heat supply curve, the controller commands the increase of the flow through the heat exchanger and the reduction of the flow on the bypass pipe to the return pipe of the transportation network.

The introduction of new equipment is also not required for variable flow operation. The solution is the same: reprogramming the existing electronic controller by introducing the corrected heat supply adjustment curve. The two-way control valve will have the same function, allowing the circulation through the heat exchanger of the exact flow required to prepare the heat carrier at the set temperature for the energy efficient buildings, depending on the outdoor temperature. The electronic controller compares the temperature in the corrected heat supply curve corresponding to the outdoor temperature to the temperature on the flow (supply) pipe of the distribution system. If the temperature of the heat carrier is higher than the one provided in the corrected heat supply curve, the controller commands the reduction of the flow through the heat exchanger. If the temperature of the heat carrier is lower than that provided in the corrected heat supply curve, the controller commands the increase of the flow through the heat exchanger.

It can be concluded that the proposed solutions do not require new investments in equipment and materials, the only necessary costs being related to the development of studies to establish the new heat supply adjustment charts, depending on the degree of thermal rehabilitation of the buildings, and the reprogramming of the electronic controller for entering the appropriate data.

It is obvious that the degree of rehabilitation of the buildings is different and it is possible that the heat demand of the buildings supplied from the same thermal substation could not be ensured with heat carriers of the same temperature. In this situation, it is necessary for the operator of the district heating system to carry out certain studies to determine in each case the temperature of the heat carrier that can meet the heat demand of the consumers. For maximum efficiency of the system operation, but also to ensure the optimum indoor temperature in each room, fitting the radiators with thermostatic valves is essential.

b. Scenario (b): A branch of the thermal substation supplies only energy efficient buildings

- For this scenario, the acquisition of a three-way valve that works as a mixing valve is necessary. It will be installed on the branch that supplies energy efficient buildings, at the output of the heating manifold. It is also necessary to purchase a temperature transducer to be installed on the branch supplying low-energy buildings. The three-way valve will mix part of the flow from the return pipe with the exact flow from the supply pipe in order to ensure the required thermal comfort (Figure X.14).

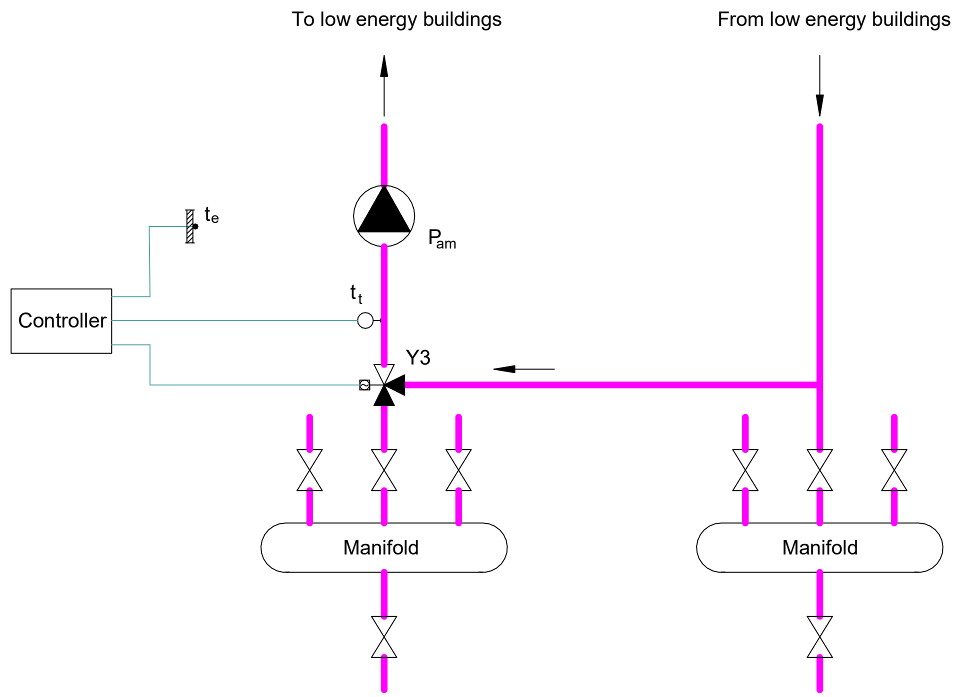


Figure X.14 Supplying low-temperature heat carrier to energy-efficient buildings in the case when they are supplied from the same branch of the distribution system - case 1

The heat supply adjustment curves for the high energy buildings needs to be determined and entered into the electronic controller. The controller compares the temperature in the adjustment chart corresponding to the outdoor temperature to the temperature of the heat carrier suppling the low energy buildings. If the temperature of the heat carrier is higher than the one provided in the adjustment chart, the flow from the supply pipe is reduced and the flow from the return pipe is increased. If the temperature of the heat carrier is lower than the one provided in the adjustment chart, the flow from the return pipe is reduced and the flow from the supply pipe is increased.

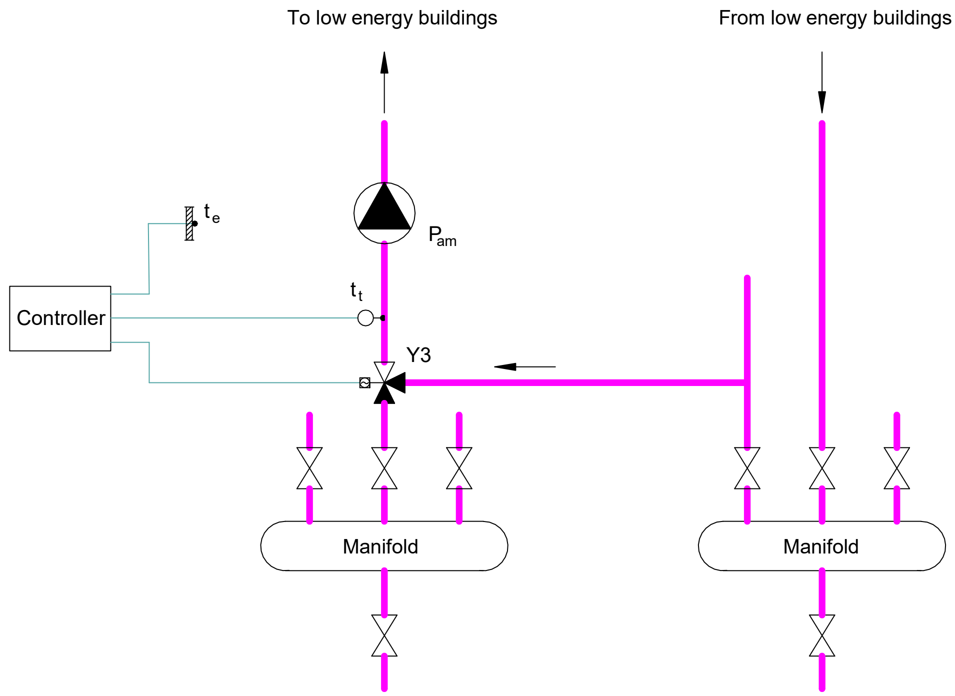


Figure X.15 Supplying low-temperature heat carrier to energy-efficient buildings in the case when they are supplied from the same branch of the distribution system - case 2

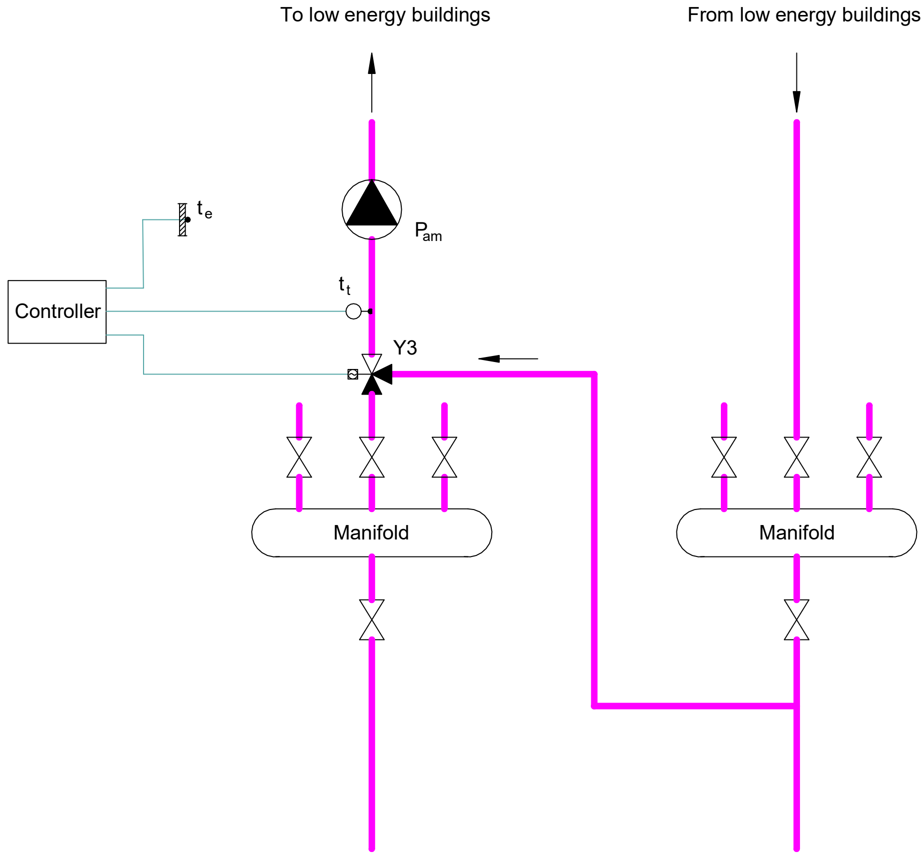


Figure X.16 Supplying low-temperature heat carrier to energy-efficient buildings in the case when they are supplied from the same branch of the distribution system - case 3

c. Scenario (c): The thermal substation supplies both low and high energy buildings

This situation is also the most difficult to solve in practice since the flow control should be performed at the point of connection of the consumer or even at the consumer, which is difficult to achieve because the flow control involves the existence or the installation of a controller. If the connection to an electronic controller in the neighborhood can be achieved, the scheme in Figure X.17.

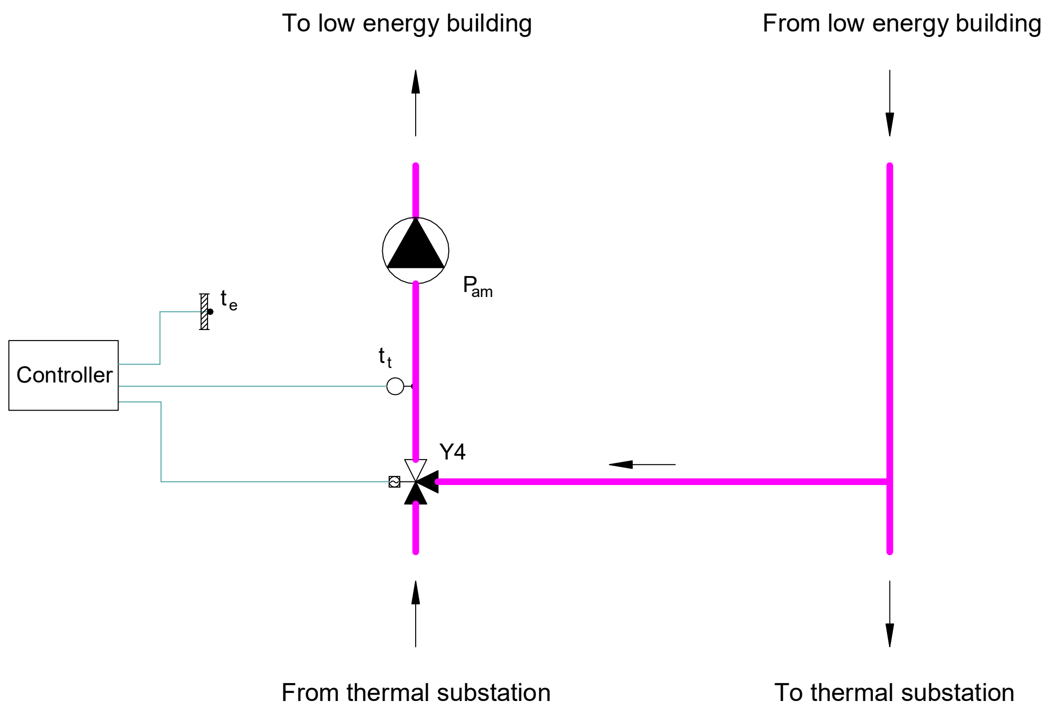


Figure X.17 Supplying low-temperature heat carrier to one or more low-energy buildings in the case they are supplied from the same branch as high-energy buildings

Another solution, which requires a higher investment cost, is to fit the energy efficient building with its own thermal substation. The equipment will be sized for low-temperature system operation. The solution requires a new connection to the heat transportation (primary) system and a thermal substation to prepare both the heat carrier andthe domestic hot water, or a connection to the heat distribution (secondary) system and a thermal substation to prepare only the heat carrier at the temperature required by the energy efficient buildings. This solution can also be adopted for a group of two or more renovated buildings located at a short distance from each other. On a case-by-case basis, a technical-economic analysis will be carried out, which will analyze several possible solutions and choose the most efficient one.

If the low-energy building is already connected to the district heating system by its own thermal susbtation, one of the solutions described in Scenario (a) will be applied, depending on the connection scheme and the type of operation (constant flow, variable flow).

XI Low temperature district heating. Increasing the heating surface. Energy and economic justification

Another solution of supplying consumers with low temperature heat carriers is increasing the heating surface. Considering that the use of a low temperature heat carrier leads to the reduction of heat losses in the distribution networks, but implies an investment cost related to the increase of the heating surface, an analysis was carried out to determine to what extent the reduction of the temperature of the heat carrier in district heating systems is cost effective. [107]

Figure XI.1 shows graphically the dependence of R_t (the ratio of the design temperature differences) on the design temperature of the heat carrier entering the heating system. The lower the average design temperature of the heat carrier, the larger the heating surface has to be, in order to deliver the required heat flow to the heated space.

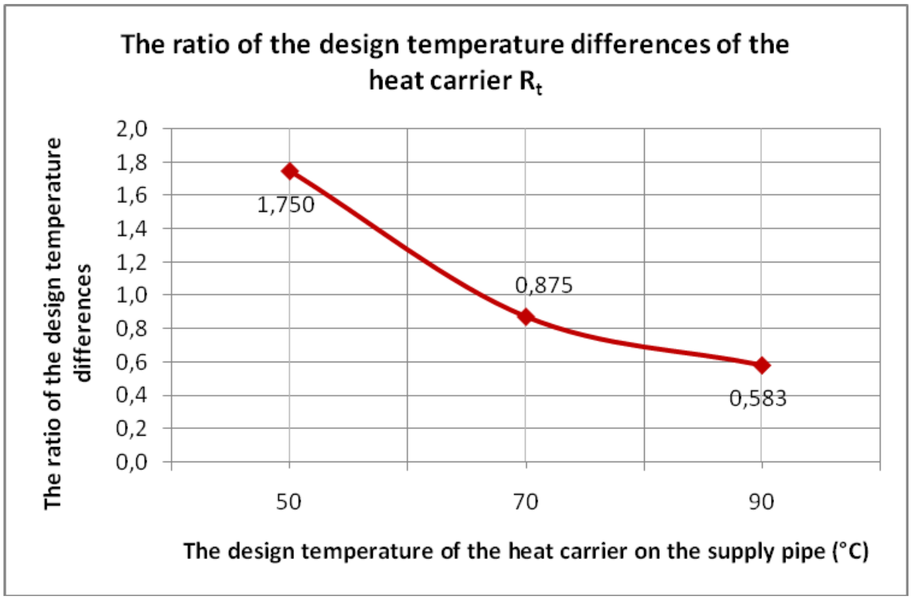


Figure XI.1 Dependence of R_t (the ratio of the design temperature differences) on the design temperature of the heat carrier entering the heating system

Three scenarios were considered for the sizing the heating surface at the consumer (90/70 – 1st scenario; 70/50 – 2nd scenario; 50/30 – 3rd scenario).

The efficiency of the district heating system is:

$$\eta = \frac{\Phi_C}{\Phi_F} = \frac{\Phi_C}{\Phi_C + \Phi_P} = \frac{E_R \cdot (1 - E_C)}{1 - E_R^2 \cdot E_C} \tag{XI.4}$$

The share of heat losses of the distribution network is the ratio between the thermal losses of the distribution network (Φ_P) and the output thermal power delivered to the consumer by the heating system (Φ_C):

$$\xi = \frac{\Phi_P}{\Phi_C} = \left(\frac{1}{\eta} - 1\right) = \frac{(1 - E_R) \cdot (1 + E_R \cdot E_C)}{E_R \cdot (1 - E_C)} \tag{XI.5}$$

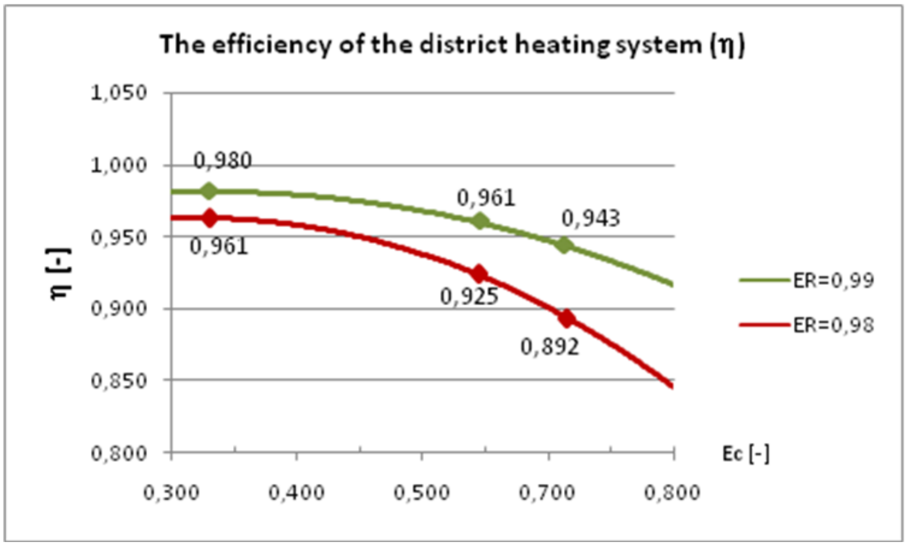


Figure XI.2 The efficiency of the district heating system (η) as a function of the thermal module of the consumer's heating system (E_C) and the thermal module of the heat distribution system (E_R)

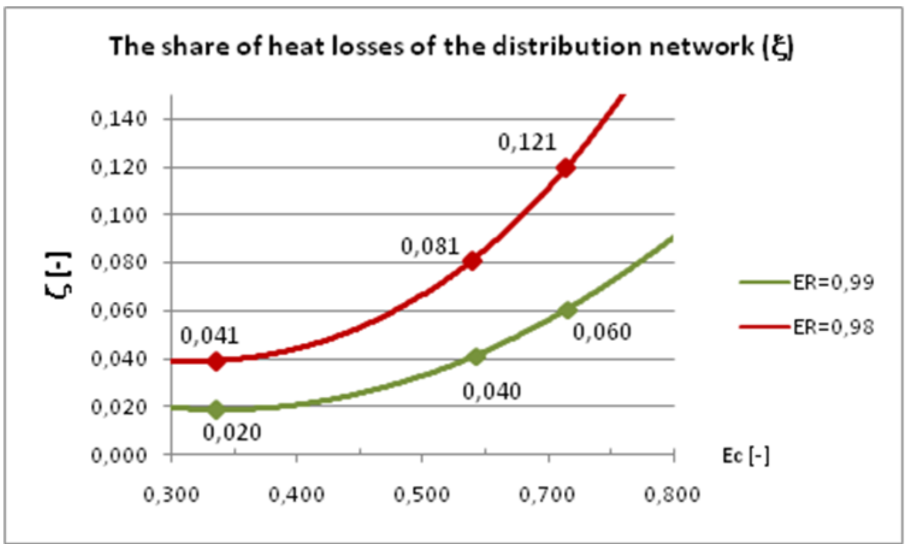


Figure XI.3 The share of heat losses of the distribution network (ξ) as a function of the thermal module of the consumer's heating system (E_C) and the thermal module of the heat distribution system (E_R)

If the sizing of the central heating system of the consumer is done for the design temperatures of the heat carrier of 90/70 °C, the efficiency of the district heating system is about 89%, and the heat losses of the heat distribution system are about 12%, If the sizing of the central heating system of the consumer is done for design temperatures of the heat carrier of 50/30 °C, the efficiency of the district heating system is about 96%, and the share of thermal losses related to the heat distribution system is 4%. These results are based on a heat distribution network with a thermal module E_R = 0.98.

The heat flow representing the losses of the heat distribution system in the three scenarios is:

$$\begin{aligned}\Phi_{P1} &= \xi_1 \cdot \Phi_C \\ \Phi_{P2} &= \xi_2 \cdot \Phi_C \\ \Phi_{P3} &= \xi_3 \cdot \Phi_C\end{aligned} \tag{XI.8}$$

The energy savings throughout the cold season are:

$$\begin{aligned}\Delta Q_{P12} &= \int \Delta\Phi_{P12} \cdot d\tau = (\xi_1 - \xi_2) \cdot H \cdot \int (t_{i0} - t_e) \cdot d\tau \\ \Delta Q_{P13} &= \int \Delta\Phi_{P13} \cdot d\tau = (\xi_1 - \xi_3) \cdot H \cdot \int (t_{i0} - t_e) \cdot d\tau\end{aligned} \tag{XI.10}$$

Considering a consumer characterized by H = 1 W/K and a heating season characterized by the values in the table below, the following savings are achieved:

Table XI.2 Savings achieved by reducing the design temperature of the heat carrier

ti	te	Days	Q	Qp1	Qp2	Qp3	Qp1-Qp2	Econ(1-2)	Qp1-Qp3	Econ(1-3)
(°C)	(°C)	-	(kWh)	(kWh)	(kWh)	Qp3	(kWh)	(Euro)	(kWh)	(Euro)
20	-15	2	1,68							
20	-10	11	7,92							
20	-5	32	19,2							
20	0	60	28,8							
20	5	53	19,08							
20	10	24	5,76							
			82,44	10,0	6,7	3,3	3,3	0,33	6,7	0,67

Considering a cost of thermal energy of 0,1 euro/kWh, it results in saving 3,3 kWh/year in the 2nd scenario, which means savings of 0.33 euro/year, and saving 6,7 kWh/an in the 3rd scenario, ceea which means savings of 0.67 euro/year. The installed heating surface was 0.042 m^2 larger in the 2nd scenario compared to the 1st scenario, and 0.167 m^2 larger in the 3rd scenario compared to the 1st scenario. Considering that 1 of installed heating surface costs about 30 euro/m^2, that means that the diiference of installed heating surface of 0,042 m^2 would cost about 1,25 euro. In this case, the additional investment is recovered in 1,25/0,33 = 3,8 years in the 2nd scenario and in 5/0,66 = 7,5 years in the 3rd scenario.

Table XI.3 Duration of investment recovery in the three scenarios

Scenario	Duration of investment recovery (years)
90/70	0.0
70/50	3.8
50/30	7.5

From an energy point of view, a very good option for sizing the central heating systems is selecting t_{T0}/t_{R0} = 70/50^{o}C as design temperatures for the heat carrier. The investment in the additional surface of the heating system will be recovered quite quickly, in about 3.5-4.0 years. We consider that the further reduction of the design temperatures of the heat carrier can continue down to t_{T0}/t_{R0} =

60/40 ^{o}C. Below these temperature values, the low temperature floor heating or ceiling heating apply.

XII Conclusions

1. The heated spaces in the renovated buildings are overheated if they are supplied with a heat carrier having the same temperature as that supplied to unrenovated buildings. Supplying a high temperature heat carrier to low energy buildings is economically inefficient. Inefficiency refers to several aspects of system operation, namely:
   - the heat losses in the transportation and distribution systems are higher than they would be if energy efficient buildings would be supplied with a low temperature heat carrier
   - if the pumps in the distribution system are not fitted with variable speed drives, the closing of the thermostatic valves by the consumer results in increasing the temperature on the return pipe of the distribution system, an important drawback in cogeneration systems
   - operating the system at temperatures higher than necessary leads to greater stress in the pipelines and other components of the systems, which lead to high maintenance expenses and faster pipe wear processes.
2. Building renovation associated with low temperature district heating is economically efficient: the efficiency of energy use increases by about 40% for a building with a rated heat load of 1 MW located in the climatic zone 2 whose degree of thermal renovation is H/H_0 = 0.6. These benefits can be achieved with minimal investment effort.
3. The lower the design temperatures of the heat carrier, the higher the efficiency of the heat distribution system. The efficiency of the distribution system is even higher in the case of a higher temperature difference between the supply and return pipes.
4. For a thermal distribution network whose constructive characteristics are known, the equivalent thermal module of the network can be determined by calculation. By measuring the temperature at the heat source and at the ends of the grid (consumers), the actual equivalent thermal module of the thermal network can be determined. By comparing the two values, the quality and efficiency of the insulation and the actual efficiency of the distribution network can be assesed, as compared to the design network.
5. The measures for energy conservation in buildings associated with low-temperature district heating, corresponding to the degree of renovation, lead to significant energy consumption reductions, of about 20% for H/H0 = 0.8, about 40% for H/H0 = 0.6 and about 60% for H/H0 = 0.4. For a degree of building renovation H/H0>0.55, the adjustment of the heat supply curve has a more significant weight in the percentage reduction of the energy consumption than the thermal rehabilitation of the of the building, and for a degree of thermal renovation H/H0<0.55, the weight of the two components is reversed and the thermal rehabilitation of the building prevails.

6. During the heating season, the heat losses of the distribution network are reduced significantly if energy efficient buildings are supplied with a heat carrier having a temperature corresponding to the uncorrected heat supply curve. An analysis performed for a branch of a distribution system supplying three apartment buildings in Bucharest shows that, during a heating season, the heat losses of the distribution network are reduced by 31.6% if the renovated buildings are fed with a heat carrier having a temperature corresponding to the corrected heat supply curve, compared to the situation when they are fed with a heat carrier having a temperature corresponding to the uncorrected heat supply curve.

7. To supply low-temperature heat carrier to low-energy buildings, the solution will be chosen based on a case-by-case analysis. Simple solutions can be proposed, that do not require new investments in equipment and materials.

8. In order to use low temperature district heating in unrenovated buildings, a technical-economic analysis can be carried out for each case in order to increase the heating surface. The cost-benefit analysis will be done by comparing the benefits obtained by reducing the heat losses in the distribution system with the costs represented by the additional investment required to increase the heating surface. Energy and economic analysis performed on a district heating system that supplies building heating systems sized for the temperatures of the heat carrier of t_{t0} / t_{r0} = 90/70 °C, t_{t0} / t_{r0} = 70/50 °C, t_{t0} / t_{r0} = 50 / 30 °C leads to the conclusion that the additional investments related to the additional heating surface in the latter 2 scenarios compared to the 1st scenario are recovered in about 4 years and about 8 years, respectively, significantly shorter than the lifespan of the district heating systems.

XIII Personal contributions and possibilities for further research

The author's personal contribution to the analysis of the ways of increasing the efficiency of the district heating systems resides in the following aspects:

- Assessment and breakdown of the energy benefits achieved exclusively by the building renovation, exclusively by the correction of the heat supply adjustment curve for low energy buildings, respectively by the combined application of both measures;
- Experimental identification of the thermal module of the network branches of the district heating systems, a useful parameter in the energy assessments related to the thermal distribution networks;
- Assessment and analysis regarding the effect of reducing the temperature of the heat carrier on the heat losses in the distribution networks;
- Analysis regarding the influence of the temperature of the heat carrier on the efficiency of the district heating system;
- Analysis of the existing constructive and functional heat supply schemes of renovated buildings in order to supply a heat carrier having a temperature adjusted to the new heat demand;
- Solutions proposed for supplying low temperature heat carrier to renovated buildings connected to the existing distribution network, which feeds both high and low energy buildings.

The research can be continued by:

- expanding the analysis regarding the increasing of the efficiency of the district heating systems to the heat transportation system (primary network);
- expanding the analysis by determining the reduction of heat losses in the heat transportation system (primary network);
- analysis of the overall efficiency of district heating systems, before and after building renovation, with and without the use of low temperature district heating;
- expanding the analysis to district heating systems located in other climatic zones (zones 1, 3, 4 or 5);
- performing a cost-benefit analysis, determining the indicators that demonstrate the economic efficiency of using low temperature district heating.

XIV Symbols and abbreviations

$\dot{Q}_0$	=	energy needs for heating (design conditions) [W]
H	=	global thermal insulation coefficient of the building [W/K]
H_0	=	global thermal insulation coefficient of the building for the unrenovated building [W/K]
t_{i0}	=	conventional design indoor temperature, determined according to SR 1907/2-2014 [°C]
t_e	=	outdoor temperature [°C]
t_{e0}	=	conventional design outdoor temperature, determined for each climatic zone, according to SR 1907/1-2014 [°C]
t_t	=	flow (supply) temperature of the heat distribution system (secondary network) [°C]
t_{t0}	=	flow (supply) temperature of the heat distribution system (secondary network) corresponding to the conventional design outdoor temperature (design conditions) [°C]
t_r	=	return temperature of the heat distribution system (secondary network) [°C]
t_{r0}	=	return temperature of the heat distribution system (secondary network) corresponding to the conventional design outdoor temperature (design conditions) [°C]
t_{ml}	=	logarithmic average temperature of the heat carrier [°C]
Δt_{ml}	=	logarithmic average temperature difference between the fluids involved in the heat transfer [°C]
Δt_{ml0}	=	logarithmic average temperature difference between the fluids involved in the heat transfer (design conditions) [°C]
k	=	global heat transfer coefficient [W/m^2K]
k_0	=	global heat transfer coefficient (design conditions) [W/m^2K]
G	=	flow of the heat carrier [m^3/s]
G_0	=	flow of the heat carrier (design conditions) [m^3/s]
ρ	=	density of the heat carrier [kg/m^3]
c	=	specific heat capacity of the water [W·s/kg·K]
S	=	heat transfer area [m^2]
NTU	=	number of thermal units [-] (dimensionless)
NTU_0	=	number of thermal units – design conditions [-] (dimensionless)
E	=	thermal module of the heating system [-] (dimensionless)
E_0	=	thermal module of the heating system (design conditions) [-] (dimensionless)
E_C	=	thermal module of the consumer's heating system [-] (dimensionless)
E'_C	=	thermal module of the heat exchanger preparing the heat carrier [-] (dimensionless)
E_R	=	thermal module of the heat distribution system (secondary network) [-] (dimensionless)
E'_R	=	thermal module of the transportation system (primary network) [-] (dimensionless)
t_T	=	flow (supply) temperature of the heat transportation system (primary network) [°C]
t_{T0}	=	flow (supply) temperature of the heat transportation system (primary network) corresponding to the conventional design outdoor temperature (design conditions) [°C]
t_R	=	return temperature of the heat transportation system (primary network) [°C]

t_{R0} = return temperature of the heat transportation system (primary network) corresponding to the conventional design outdoor temperature (design conditions) [°C]

P = heat load of the building [MW]

P_0 = rated heat load of the building [MW]

Q_C = thermal power used by the consumer [W]

$Q_{sursă}$ = thermal power delivered by the heat source [W]

Q_p = heat losses of the heat distribution network [W]

η = efficiency of the district heating system [-] (adimensional)

η_{SD} = efficiency of the heat distribution system [-] (dimensionless)

η_{ST} = efficiency of the heat transportation system [-] (dimensionless)

R = average linear thermal resistance of the heat distribution network [m·K/W]

$\lambda_ţ$ = thermal conductivity of the pipe wall [W/mK]

λ_{iz} = thermal conductivity of the pipe insulation [W/mK]

λ_s = thermal conductivity of the ground [W/mK]

L = length of pipeline sections of the heat distribution network [m]

$\Delta t_{ml,\ sol}$ = logarithmic average temperature difference between the heat carrier and the ground where the pipe is buried [K]

E_{sch} = equivalent thermal module of a thermal network [-] (adimensional)

t_m = average temperature of the heat carrier at the consumers supplied [°C]

t_0 = temperature of the heat carrier leaving the thermal substation [°C]

t_s = ambient temperature in the duct where the pipes are installed or the soil temperature for the preinsulated pipes installed directly in the ground [°C]

Di = inside diameter of the pipe [m]

De = outside diameter of the pipe [m]

$\delta ţ$ = thickness of the pipe wall [m]

δiz = thickness of the insulation layer [m]

Diz = diameter of the pipe over the insulation layer [m]

αi = convective heat transfer coefficient [W/m²K]

RPTS = ratio of the specific thermal powers [-] (adimensional)

G = global thermal insulation coefficient of the building [W/m³·K]

V = volume of the building [m³]

S = area of the surface of the thermal envelope [m²]

R_m = average thermal resistance of building envelope [m²·K/W]

n_a = average number of air changes per hour [h⁻¹]

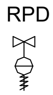
SACET = district heating system

Heat transportation pipe (primary network)

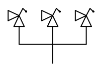
Heat distribution pipe (heating network)

Domestic cold water pipe

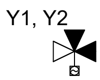
Domestic hot water pipe



Differrential pressure regulator



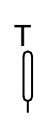
Safety valves



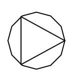
Electrically driven, mixing or separating three-way control valve

Electrically driven, two-way control valve

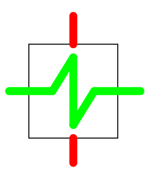
Manometer



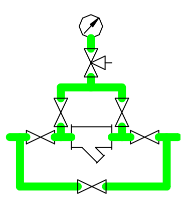
Thermometer



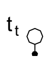
Pump



Heat exchanger



Strainer



Temperature transducer

XV References

[1] Bahar Saeb-Gilani, Barbara Giorgi, Max Bachmann and Martin Kriegel, Potential analysis of heat sharing at different temperature levels in a district, CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3. Aalborg: Aalborg University, Department of Civil Engineering
http://vbn.aau.dk/files/233716906/paper_320.pdf

[2] European Commission - Energy Research Knowledge Centre, Smart District Heating and Cooling, 2014
https://setis.ec.europa.eu/energy-research/sites/default/files/library/ERKC_%20TRS_Smart_District_HC.pdf

[3] Henrik Lund, Sven Werner, Robin Wiltshire, Svend Svendsen, Jan Eric Thorsen, Frede Hvelplund, Brian Vad Mathiesen, 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems, Energy, Volume 68, 15 April 2014, Pages 1-11, ISSN 0360-5442,
http://dx.doi.org/10.1016/j.energy.2014.02.089.
http://www.sciencedirect.com/science/article/pii/S0360544214002369

[4] Frost and Sullivan, Energy and Power Systems, Smart Thermal Grids, 2016 http://www.frost.com/sublib/display-report.do?id=D961-00-05-00-00

[5] Ralf-Roman Schmidt, Nicolas Fevrier, Philippe DUMAS, Key to Innovation Integrated Solution. Smart Thermal Grids, November, 2013, Version 2: - Smart Cities Stakeholder Platform https://eu-smartcities.eu/sites/all/files/Smart%20Thermal%20Grids%20-%20Smart%20Cities%20Stakeholder%20Platform.pdf

[6] R.R. Schmidt, O. Pol, D. Basciotti, J. Page, Smart thermal networks for smart cities – Introduction of concepts and measures, EPJ Web of Conferences 33 04002 (2012), EDP Sciences, 2012 http://www.epj-conferences.org http://dx.doi.org/10.1051/epjconf/20123304002

[7] Cristina Stănişteanu, "Smart Thermal Grids – A Review", De Gruyter Open, 2016, DOI: 10.1515/SBEEF-2016-0030
https://www.degruyter.com/downloadpdf/j/sbeef.ahead-of-print/sbeef-2016-0030/sbeef-2016-0030.pdf

[8] Ralf-Roman Schmidt, The role of thermal grids in the Smart City – presentation at IEA CHP/DHC Collaborative & Clean Energy, Ministerial CHP/DHC Working Group Joint Strategic Workshop, 27-28 May 2014
https://www.iea.org/media/workshops/2014/chpdhcmayworkshop/VIII_SMARTCITIES_EHP_270514CHPDHC.pdf

[9] E.H.A. Van Vliet, Flexibility in heat demand at the TU Delft campus smart thermal grid with phase change materials, Master of Science Thesis, Process & Energy Department, Mechanical, Maritime and Materials Engineering, Delft University of Technology, 2013 http://repository.tudelft.nl/assets/uuid:727209bf-8f38-4914-a9d8-0dc68ee38acb/Thesis_Edwin_van_Vliet_2013_.pdf

[10] European Commission – Thematic research summary – Smart district heating and cooling, septembrie 2014, raport elaborat de Energy Research Knowledge Centre (ERKC) https://setis.ec.europa.eu/energy-research/sites/default/files/library/ERKC_%20TRS_Smart_District_HC.pdf

[11] IEA DHC/CHP Annex IX - District Heating for Energy Efficient Building Areas, Kari Sipilä presentation, 30.06.2011
http://www.districtenergy.org/assets/pdfs/2011Annual_Conf/Proceedings/B45-SIPILAEIDEA-2011-Kari-Sipilae-ConferenceTorontoIEA-Annex-IXVTT27-29062011.pdf

[12] IEA Annex X Final report - Toward 4th Generation District Heating: Experience and Potential of Low-Temperature District Heating, 2014 Authors: Alessandro Dalla Rosa, Hongwei Li, Svend Svendsen, Sven Werner, Urban Persson, Karin Ruehling, Clemens Felsmann, Martin Crane, Robert Burzynski, Ciro Bevilacqua
http://energia.fi/sites/default/files/iea_annex_x_final_report_2014_-_toward_4th_generation_district_heating.pdf

[13] IEA DHC-CHP - Transformation roadmap from high to low temperature district heating system http://www.iea-dhc.org/fileadmin/documents/Annex_X/IEA_DHC_2014_-_4th_gen._DH_presentation.ppt

[14] ECBCS Annex 49 Final Report - Low Exergy Systems for High-Performance Buildings and Communities, Detailed Exergy Assessment Guidebook for the Built Environment, Fraunhofer IBP 2011 http://www.annex49.info/download/Annex49_guidebook.pdf

[15] Hovedrapport Energistyrelsen - EFP 2007 Udvikling og demonstration af Lavenergi-fjernvarme til Lavenergibyggeri www.teknologisk.dk/_root/media/34221_EFP%202007.pdf

[16] Christian Holm Christiansen, Danish Technological Institute cnc@teknologisk.dk – „Low temperature networks: Concept, demonstration and guideline" presentation at DHC+ 2nd International Research Conference, 5-6 noiembrie 2013 http://www.lsta.lt/files/events/2013-11-05-06_EHP_Briuselis/2013-11-05_pranesimai/11_131105_3B_1600_1730+Christiansen.pdf

[17] Delrapport 3 Energistyrelsen - EUDP 2008-II "CO2-reductions in low-energy buildings and communities by implementation of low-temperature district heating systems. Demonstration cases in EnergyFlexHouse and Boligforeningen Ringgården." (2011) Journalnr. 63011-0152 https://setis.ec.europa.eu/energy-research/sites/default/files/project/docs/byg_r251.pdf

[18] Hovedrapport Energistyrelsen – EUDP 2010-II Journalnr. 64010-0479 „*Fuldskalademonstration af lavtemperatur-fjernvarme i eksisterende bebyggelser*" (Full-scale demonstration of low-temperature heating in existing buildings), iunie 2014 http://www.danskfjernvarme.dk/~/media/danskfjernvarme/gronenergi/projekter/eudp-lavtemperatur%20fjv/eudp%20lavtemp%20fjv%20-%20hovedrapport.pdf

[19] Guidelines for Low-Temperature District Heating deliverable of the project "Full-scale demonstration of low temperature district heating in existing buildings" (In Danish: "Fuldskala demonstration af lavtemperatur fjernvarme i eksisterende bebyggelser") financial supported by the Danish Energy Agency in the R&D programme EUDP (Energiteknologisk Udviklings- og Demonstrations Program), EUDP 2010-II project Journal No. 64010-0479, 2014 https://setis.ec.europa.eu/energy-research/sites/default/files/project/docs/Guidelines%20for%20LTDH-final_rev1.pdf

[20] http://www.4dh.dk/

[21] http://www.ecolife-project.eu/index.html

[22] René Verhoeven, Eric Willems, Virginie Harcouët-Menou, Eva De Boever, Louis Hiddes, Peter Op't Veld, Elianne Demollin, Minewater 2.0 Project in Heerlen the Netherlands: Transformation of a Geothermal Mine Water Pilot Project into a Full Scale Hybrid Sustainable Energy Infrastructure for Heating and Cooling, Energy Procedia, Volume 46, 2014, Pages 58-67, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2014.01.158 http://www.sciencedirect.com/science/article/pii/S187661021400174X

[23] Dutch Smart Thermal Grid, Towards a sustainable heat supply (2016) www.marcovermeulen.eu/files/?file=/files/1505...SmartThermalGrid_EN...pdf

[24] Jonna Zwetsloot - The Hague's Heat Initiative, Towards a smart thermal grid, a dissertation submitted in partial fulfilment of the requirements for the degree of Professional Doctorate of Engineering, 2016, ISBN: 978-90-444-144-0 https://pure.tue.nl/ws/files/19399560/2016_02_12_SEBC_Zwetsloot_J.pdf

[25] Robin Wiltshire, BRE - International Energy Agency (IEA) research on district heating, presentation 2013 http://www.heatandthecity.org.uk/__data/assets/pdf_file/0003/102000/Wiltshire-IEA_Research_on_District_Heating.pdf

[26] Katharina Link, Roland Wyss, Matthias Kolb - Minimization of primary energy consumption and CO2 emissions by smart geothermal applications – examples from Switzerland (presentation at Central and South American Workshop on Geothermal Energy Cuernavaca, Mexico 18 - 19 April 2016) http://iea-gia.org/wp-content/uploads/2016/05/1-11-Link-Smart-Geothermal-Applications-%E2%80%93-Switzerland.pdf

[27] Matthias Kolb - Operational Experience with Low Temperature Networks in Zurich, Switzerland (presentation in Geneva, 30.10.2015) http://iea-gia.org/wp-content/uploads/2016/05/1-11-Link-Smart-Geothermal-Applications-%E2%80%93-Switzerland.pdf

[28] Soma Mohammadi, Department of Energy Technology, Aalborg University, Denmark PhD Thesis "Conversion of Existing District Heating Grids to Low-Temperature Operation and Extension to new Areas of Buildings", 06.10.2016.
http://www.en.aau.dk/digitalAssets/229/229173_soma-mohammadi.pdf
http://www.en.aau.dk/events/event/phd-defence-by-soma-mohammadi-on-conversion-of-existing-district-heating-grids-to-low-temperature-operation-and-extension-to-new-areas-of-buildings.cid279477
http://www.4dh.dk/images/projects/Conversion_of_existing_DH_systems/4dh_presentation_FV.pdf

[29] Hakan İbrahim Tol, Svend Svendsen, Effects of boosting the supply temperature on pipe dimensions of low-energy district heating networks: A case study in Gladsaxe, Denmark, Energy and Buildings, Volume 88, 1 February 2015, Pages 324-334, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2014.10.067

[30] Ivar Baldvinsson, Toshihiko Nakata, A feasibility and performance assessment of a low temperature district heating system – A North Japanese case study, Energy, Volume 95, 15 January 2016, Pages 155-174, ISSN 0360-5442
http://dx.doi.org/10.1016/j.energy.2015.11.057
http://www.sciencedirect.com/science/article/pii/S0360544215016205

[31] Wei Wu, Wenxing Shi, Xianting Li, Baolong Wang, Air source absorption heat pump in district heating: Applicability analysis and improvement options, Energy Conversion and Management, Volume 96, 15 May 2015, Pages 197-207, ISSN 0196-8904, http://dx.doi.org/10.1016/j.enconman.2015.02.068
http://www.sciencedirect.com/science/article/pii/S0196890415001892

[32] Poul Alberg Østergaard, Anders N. Andersen, Booster heat pumps and central heat pumps in district heating, Applied Energy, Available online 19 March 2016, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2016.02.144
http://www.sciencedirect.com/science/article/pii/S0306261916303105

[33] Qian Wang, Sture Holmberg, Combined Retrofitting with Low Temperature Heating and Ventilation Energy Savings, Energy Procedia, Volume 78, November 2015, Pages 1081-1086, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2015.11.055
http://www.sciencedirect.com/science/article/pii/S1876610215017877

[34] Herena Torío, Dietrich Schmidt, Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis, Energy and Buildings, Volume 42, Issue 10, October 2010, Pages 1601-1609, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2010.04.002
http://www.sciencedirect.com/science/article/pii/S0378778810001210

[35] A. Dalla Rosa, R. Boulter, K. Church, S. Svendsen, District heating (DH) network design and operation toward a system-wide methodology for optimizing renewable energy solutions (SMORES) in Canada: A case study, Energy, Volume 45, Issue 1, September 2012, Pages 960-974, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2012.06.062
http://www.sciencedirect.com/science/article/pii/S0360544212005142

[36] Eline Himpe, Arnold Janssens, Julio Efrain Vaillant Rebollar, Energy and Comfort Performance Assessment of Monitored Low Energy Buildings Connected to Low-temperature District Heating, Energy Procedia, Volume 78, November 2015, Pages 3465-3470, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2015.12.331
http://www.sciencedirect.com/science/article/pii/S1876610215030052

[37] Marek Brand, Alessandro Dalla Rosa, Svend Svendsen, Energy-efficient and cost-effective in-house substations bypass for improving thermal and DHW (domestic hot water) comfort in bathrooms in low-energy buildings supplied by low-temperature district heating, Energy, Volume 67, 1 April 2014, Pages 256-267, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2014.01.064

http://www.sciencedirect.com/science/article/pii/S0360544214000863

[38] Antonio Colmenar-Santos, Enrique Rosales-Asensio, David Borge-Diez, Eduardo Collado-Fernández, Evaluation of the cost of using power plant reject heat in low-temperature district heating and cooling networks, Applied Energy, Volume 162, 15 January 2016, Pages 892-907, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2015.10.161 http://www.sciencedirect.com/science/article/pii/S0306261915014038

[39] D. Connolly, H. Lund, B.V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P.A. Østergaard, S. Nielsen, Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system, Energy Policy, Volume 65, February 2014, Pages 475-489, ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2013.10.035 http://www.sciencedirect.com/science/article/pii/S0301421513010574

[40] Arefeh Hesaraki, Adnan Ploskic, Sture Holmberg, Integrating Low-temperature Heating Systems into Energy Efficient Buildings, Energy Procedia, Volume 78, November 2015, Pages 3043-3048, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2015.11.720 http://www.sciencedirect.com/science/article/pii/S1876610215024522

[41] Brian Elmegaard, Torben Schmidt Ommen, Michael Markussen, Johnny Iversen, Integration of space heating and hot water supply in low temperature district heating, Energy and Buildings, Volume 124, 15 July 2016, Pages 255-264, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2015.09.003 http://www.sciencedirect.com/science/article/pii/S0378778815302449

[42] Gudni Axelsson, Einar Gunnlaugsson, Thorgils Jónasson, Magnús Ólafsson, Low-temperature geothermal utilization in Iceland – Decades of experience, Geothermics, Volume 39, Issue 4, December 2010, Pages 329-338, ISSN 0375-6505, http://dx.doi.org/10.1016/j.geothermics.2010.09.002 http://www.sciencedirect.com/science/article/pii/S0375650510000416

[43] M. Köfinger, D. Basciotti, R.R. Schmidt, E. Meissner, C. Doczekal, A. Giovannini, Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies, Energy, Available online 15 January 2016, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2015.12.103 http://www.sciencedirect.com/science/article/pii/S036054421501748X

[44] Robin Wiltshire (Building Research Establishment BRE, United Kingdom) – Low temperature district heating systems – Urban Energy Conference, Debrecen, Hungary, 2011 http://www.energycity2013.eu/media/Documents%20Centre/WP2/mid-term%20conference/Conference%20papers/14_Wiltshire.pdf

[45] Michele Tunzi, Dorte Skaarup Østergaard, Svend Svendsen, Rabah Boukhanouf, Edward Cooper, Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings, Energy, Volume 113, 15 October 2016, Pages 413-421, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.07.033 http://www.sciencedirect.com/science/article/pii/S0360544216309574

[46] Nguyen Le Truong, Ambrose Dodoo, Leif Gustavsson, Renewable-based heat supply of multi-apartment buildings with varied heat demands, Energy, Volume 93, Part 1, 15 December 2015, Pages 1053-1062, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2015.09.087 http://www.sciencedirect.com/science/article/pii/S0360544215012979

[47] Marek Brand, Svend Svendsen, Renewable-based low-temperature district heating for existing buildings in various stages of refurbishment, Energy, Volume 62, 1 December 2013, Pages 311-319, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2013.09.027 http://www.sciencedirect.com/science/article/pii/S0360544213007780

[48] Dorte Skaarup Østergaard, Svend Svendsen, Replacing critical radiators to increase the potential to use low-temperature district heating – A case study of 4 Danish single-family houses from the 1930s, Energy, Available online 7 May 2016, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.03.140 http://www.sciencedirect.com/science/article/pii/S0360544216303930

[49] Lisa Brand, Alexandra Calvén, Jessica Englund, Henrik Landersjö, Patrick Lauenburg, Smart district heating networks – A simulation study of prosumers' impact on technical parameters in distribution networks, Applied Energy, Volume 129, 15 September 2014, Pages 39-48, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2014.04.079 http://www.sciencedirect.com/science/article/pii/S0306261914004425

[50] Rasmus Lund, Danica Djuric Ilic, Louise Trygg, Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark, Journal of Cleaner Production, Volume 139, 15 December 2016, Pages 219-229, ISSN 0959-6526, http://dx.doi.org/10.1016/j.jclepro.2016.07.135 http://www.sciencedirect.com/science/article/pii/S0959652616310277

[51] Maunu Kuosa, Kaisa Kontu, Tapio Mäkilä, Markku Lampinen, Risto Lahdelma, Static study of traditional and ring networks and the use of mass flow control in district heating applications, Applied Thermal Engineering, Volume 54, Issue 2, 30 May 2013, Pages 450-459, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2013.02.018 http://www.sciencedirect.com/science/article/pii/S1359431113001233

[52] Dorte Skaarup Østergaard, Svend Svendsen, Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s, Energy and Buildings, Volume 126, 15 August 2016, Pages 375-383, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2016.05.034 http://www.sciencedirect.com/science/article/pii/S0378778816304030

[53] Satu Paiho, Francesco Reda, Towards next generation district heating in Finland, Renewable and Sustainable Energy Reviews, Volume 65, November 2016, Pages 915-924, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2016.07.049 http://www.sciencedirect.com/science/article/pii/S1364032116303768

[54] Natasa Nord, Maren E. Ingebretsen, Ivar S. Tryggestad (Norwegian University of Science and Technology) - Possibilities for transition of existing residential buildings to low temperature district heating system in Norway. Conference: CLIMA 2016 - 12th REHVA World Congress, At Aalborg, Denmark, Volume: 3 https://www.researchgate.net/publication/306364685_Possibilities_for_Transition_of_Existing_Residential_Buildings_to_Low_Temperature_District_Heating_System_in_Norway

[55] Jacopo Vivian, Angelo Zarrella, Michele De Carli - Analysis of a wastewater based low temperature district heating system with booster heat pumps for new and existing residential buildings. Conference: CLIMA 2016 - 12th REHVA World Congress, At Aalborg, Denmark, Volume: 3 https://www.researchgate.net/publication/303672889_Analysis_of_a_wastewater_based_low_temperature_district_heating_system_with_booster_heat_pumps_for_new_and_existing_residential_buildings

[56] Mattias Gustafsson, Mats Rönnelid, Louise Trygg, Björn Karlsson, CO2 emission evaluation of energy conserving measures in buildings connected to a district heating system – Case study of a multi-dwelling building in Sweden, Energy, Volume 111, 15 September 2016, Pages 341-350, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.05.002 http://www.sciencedirect.com/science/article/pii/S0360544216305527

[57] Alessandro Dalla Rosa - The Development of a new District Heating Concept. Network Design and Optimization for Integrating Energy Conservation and Renewable Energy Use. PhD Thesis, Technical University of Denmark, 2012 http://www.byg.dtu.dk/-/media/Institutter/Byg/publikationer/PhD/byg_r269.ashx?la=da http://orbit.dtu.dk/files/51481483/Alessandro_Dalla_Rosa_PhD_Thesis.pdf

[58] Marek Brand - Heating and Domestic Hot Water Systems in Buildings Supplied by Low-Temperature District Heating, PhD Thesis, Technical University of Denmark, 2013, ISSN 1601 – 2917 www.byg.dtu.dk/-/media/Institutter/Byg/publikationer/PhD/byg-r296.ashx?la=da

[59] Patrik Abrahamsson - Efficient district heating in low-energy building areas, Master's Thesis in Chemical Engineering, Åbo Akademi University, 2014

[60] Hakan İbrahim Tol, Svend Svendsen, A comparative study on substation types and network layouts in connection with low-energy district heating systems, Energy Conversion and Management, Volume 64, December 2012, Pages 551-561, ISSN 0196-8904, http://dx.doi.org/10.1016/j.enconman.2012.04.022 http://www.sciencedirect.com/science/article/pii/S0196890412002622

[61] H.İ. Tol, S. Svendsen, Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark, Energy, Volume 38, Issue 1, February 2012, Pages 276-290, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2011.12.002 http://www.sciencedirect.com/science/article/pii/S0360544211007961

[62] Hakan Ibrahim Tol, Svend Svendsen (Technical University of Denmark) - Determination of optimum network layout for low-energy district heating systems with different substation types Conference paper, The third renewable energy congress, At Hammamet, Tunisia, Volume: 3rd, 2011 http://www.researchgate.net/publication/275890020

[63] Hakan Ibrahim Tol, Svend Svendsen, Susanne Balslev Nielsen (Technical University of Denmark) - Case Studies in Low-Energy District Heating Systems: Determination of Dimensioning Methods for Planning the Future Heating Infrastructure. Paper presented at IFME World Congress of Municipal Engineering, Helsinki, Finland, 2012 http://orbit.dtu.dk/files/51694934/Conference_Paper_Published.pdf

[64] Hongwei Li, Svend Svendsen, Energy and exergy analysis of low temperature district heating network, Energy, Volume 45, Issue 1, September 2012, Pages 237-246, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2012.03.056 http://www.sciencedirect.com/science/article/pii/S0360544212002599

[65] Maunu Kuosa, Kaisa Kontu, Tapio Mäkilä, Markku Lampinen, Risto Lahdelma, Static study of traditional and ring networks and the use of mass flow control in district heating applications, Applied Thermal Engineering, Volume 54, Issue 2, 30 May 2013, Pages 450-459, ISSN 1359-4311, http://dx.doi.org/10.1016/j.applthermaleng.2013.02.018 http://www.sciencedirect.com/science/article/pii/S1359431113001233

[66] Tol, Hakan and Svend Svendsen - Operational Planning of Low-Energy District Heating Systems Connected to Existing Buildings, Proceedings of the 2nd International Conference on Renewable Energy: Generation and Applications. 2012 http://orbit.dtu.dk/files/8167788/Operational_Planning_of_Low_Energy_District_Heating_Systems_Connected_to_Existing_Buildings_Published.pdf

[67] Arefeh Hesaraki, Eleftherios Bourdakis, Adnan Ploskić, Sture Holmberg, Experimental study of energy performance in low-temperature hydronic heating systems, Energy and Buildings, Volume 109, 15 December 2015, Pages 108-114, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2015.09.064 http://www.sciencedirect.com/science/article/pii/S0378778815303042

[68] Hao Fang, Jianjun Xia, Kan Zhu, Yingbo Su, Yi Jiang, Industrial waste heat utilization for low temperature district heating, Energy Policy, Volume 62, November 2013, Pages 236-246, ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2013.06.104 http://www.sciencedirect.com/science/article/pii/S0301421513006113

[69] Torben Ommen, Wiebke Brix Markussen, Brian Elmegaard, Lowering district heating temperatures – Impact to system performance in current and future Danish energy scenarios, Energy, Volume 94, 1 January 2016, Pages 273-291, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2015.10.063 http://www.sciencedirect.com/science/article/pii/S0360544215014310

[70] Xiaochen Yang, Hongwei Li, Svend Svendsen, Modelling and multi-scenario analysis for electric heat tracing system combined with low temperature district heating for domestic hot water supply, Building Simulation 2016, Volume 9, Issue 2, pp. 141–151 http://dx.doi.org/10.1007/s12273-015-0261-4 http://link.springer.com/article/10.1007%2Fs12273-015-0261-4

[71] Xiaochen Yang, Hongwei Li, Jette M. Fog and Svend Svendsen (Technical University of Denmark) – Analysis and research on promising solutions of low temperature district heating without risk of Legionella, Proceedings from the 14th International Symposium on District Heating and Cooling, 2014, Stockholm, Sweden, ISBN 978-91-85775-24-8, pp. 41-48 http://www.svenskfjarrvarme.se/Global/Konferenser/DHC14/Proceedings%20DHC14.pdf

[72] Xiaochen Yang, Hongwei Li, Svend Svendsen, Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating, Energy, Volume 109, 15 August 2016, Pages 248-259, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.04.109 http://www.sciencedirect.com/science/article/pii/S0360544216305291

[73] Xiaochen Yang, Hongwei Li, Svend Svendsen, Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures, Energy, Available online 14 January 2016, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2015.12.073 http://www.sciencedirect.com/science/article/pii/S0360544215017181

[74] Xiaochen Yang, Hongwei Li, Svend Svendsen, Energy, economy and exergy evaluations of the solutions for supplying domestic hot water from low-temperature district heating in Denmark, Energy Conversion and Management, Volume 122, 15 August 2016, Pages 142-152, ISSN 0196-8904, http://dx.doi.org/10.1016/j.enconman.2016.05.057 http://www.sciencedirect.com/science/article/pii/S0196890416304356

[75] Marek Brand, Jan Eric Thorsen, Svend Svendsen, Numerical modelling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of DHW with respect to service pipes, Energy, Volume 41, Issue 1, May 2012, Pages 392-400, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2012.02.061 http://www.sciencedirect.com/science/article/pii/S0360544212001752

[76] Xiaochen Yang - Supply of domestic hot Water at comfortable temperatures by low-temperature district heating without risk of Legionella. PhD Thesis, Technical University of Denmark, 2016
www.byg.dtu.dk/-/media/Institutter/Byg/publikationer/PhD/Byg_R346.ashx?la=da
http://orbit.dtu.dk/files/124322591/Xiaochen_Yang_Til_Orbit.pdf

[77] Patricia Monzó, Alberto Lazzarotto, José Acuña, Johan Tjernström and Mikael Nygren, Monitoring of a borehole thermal energy storage in Sweden, Heiselberg, P. K. (Ed.) (2016). CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3. Aalborg: Aalborg University, Department of Civil Engineering
https://www.kth.se/polopoly_fs/1.652451!/Monitoring%20of%20a%20borehole%20theraml%20%20energy%20storage%20in%20%20Sweden.pdf

[78] A. Réveillère, V. Hamm, H. Lesueur, E. Cordier, P. Goblet, Geothermal contribution to the energy mix of a heating network when using Aquifer Thermal Energy Storage: Modeling and application to the Paris basin, Geothermics, Volume 47, July 2013, Pages 69-79, ISSN 0375-6505, http://dx.doi.org/10.1016/j.geothermics.2013.02.005 http://www.sciencedirect.com/science/article/pii/S0375650513000163

[79] J.NW. Chiu, J. Castro Flores, V. Martin, B. Lacarrière, Industrial surplus heat transportation for use in district heating, Energy, Available online 24 May 2016, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2016.05.003 http://www.sciencedirect.com/science/article/pii/S0360544216305539

[80] B. Saeb Gilani, B. Giorgi, M. Bachmann, M. Kriegel: Potential analysis of heat sharing at different temperature levels in a district. CLIMA 2016 - 12th REHVA World Congress, Aalborg, Denmark, 22.-25.05.2016. Conference Proceedings, CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3, Aalborg University, Department of Civil Engineering. ISBN: 87-91606-28-4 (vol 3), 87-91606-36-5
http://megaslides.com/doc/6051127/aalborg-universitet-heiselberg--per-kvols

[81] EnEff:Wärme – LowExTra, Low-exergy transmission pipes for storing and distributing heat http://www.eneff-stadt.info/en/heatingcooling-networks/project/details/lowextra-low-exergy-transmission-pipes-for-storing-and-distributing-heat/

[82] IÖW, LowExTra – Low-Exergy-Grids for Storing and Distributing Heat at Different Temperature Levels https://www.ioew.de/en/project-single/lowextra_low_exergy_grids_for_storing_and_distributing_heat_at_different_temperature_levels/

[83] Daniel Rohde, Trond Andresen and Natasa Nord: Interaction between a building complex with an integrated thermal energy system and a district heating system, Heiselberg, P. K. (Ed.) (2016).CLIMA 2016 - 12th REHVA World Congress, Aalborg, Denmark, 22.-25.05.2016. Conference Proceedings, CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3, Aalborg University, Department of Civil Engineering. ISBN: 87-91606-28-4 (vol 3) https://www.researchgate.net/publication/306379584_Interaction_Between_a_Building_Complex_with_an_Integrated_Thermal_Energy_System_and_a_District_Heating_System

[84] Fabio Zanghirella, Jonata Canonaco, Giovanni Puglisi and Biagio Di Pietra: Introducing distributed solar thermal heat in a small-scale district heating system, Heiselberg, P. K. (Ed.) (2016).CLIMA 2016 - 12th REHVA World Congress, Aalborg, Denmark, 22.-25.05.2016. Conference Proceedings, CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3, Aalborg University, Department of Civil Engineering. ISBN: 87-91606-28-4 (vol 3) https://www.researchgate.net/publication/303549897_Introducing_distributed_solar_thermal_power_in_small-scale_district_heating_systems

[85] Petr Ovchinnikov, Anatolijs Borodiņecs, Renārs Millers, Utilization potential of low temperature hydronic space heating systems in Russia, Journal of Building Engineering, Volume 13, 2017, Pages 1-10, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2017.07.003 (http://www.sciencedirect.com/science/article/pii/S235271021730219X)

[86] Jelena Ziemele, Armands Gravelsins, Andra Blumberga, Dagnija Blumberga, Sustainability of heat energy tariff in district heating system: Statistic and dynamic methodologies, Energy, Volume 137, 2017, Pages 834-845, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2017.04.130 (http://www.sciencedirect.com/science/article/pii/S0360544217306965)

[87] Anna Volkova, Vladislav Mašatin, Andres Siirde, Methodology for evaluating the transition process dynamics towards 4th generation district heating networks, Energy, Volume 150, 2018, Pages 253-261, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2018.02.123 (http://www.sciencedirect.com/science/article/pii/S0360544218303578)

[88] Muhammad Imran, Muhammad Usman, Yong Hoon Im, Byung Sik Park, The feasibility analysis for the concept of low temperature district heating network with cascade utilization of heat between networks, Energy Procedia, Volume 116, 2017, Pages 4-12, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.05.050 (http://www.sciencedirect.com/science/article/pii/S1876610217322579)

[89] Markus Köfinger, Daniele Basciotti, Ralf-Roman Schmidt, Reduction of return temperatures in urban district heating systems by the implementation of energy-cascades, Energy Procedia, Volume 116, 2017, Pages 438-451, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.05.091 (http://www.sciencedirect.com/science/article/pii/S1876610217322981)

[90] Ministerul Energiei - Strategia Energetică a României 2016-2030, cu perspectiva anului 2050, 19 decembrie 2016, pp. 30-32 http://mmediu.ro/app/webroot/uploads/files/2017-03-02_Strategia-Energetica-a-Romaniei-2016-2030.pdf

[91] Strategia pentru mobilizarea investițiilor în renovarea fondul de clădiri rezidențiale și comerciale, atât publice cât și private, existente la nivel național, p.3 www.mdrap.ro/.../Strategie_renovare_cladiri_2017%20final_23octombrie2017.pdf

[92] Programul Operaţional Regional 2014-2020 (şi anexele aferente) - versiunea aprobată 18 martie 2016, pp.116-117 http://www.fonduri-ue.ro/por-2014

[93] Mircea Bediman, Maria Crăciun: Reglarea furnizării căldurii în sistemele de termoficare urbană, în: Instalaţii de încălzire şi reţele termice. Ed. didactică şi pedagogică Bucureşti, 1985 – pp. 333-356

[94] Prof. univ. dr. Mircea Beldiman: Reglarea furnizării căldurii, în: Enciclopedia tehnică de instalaţii - Manualul de instalaţii Ediţia a II-a, Instalaţii de încălzire. Ed. Artecno Bucureşti, 2010 – pp. 556-560

[95] Florin Iordache: Energetica echipamentelor şi sistemelor termice din instalaţii, Ed. CONSPRESS, Bucureşti, 2010, pp.117-124

[96] Florin Iordache, Energetica echipamentelor şi sistemelor termice din instalaţii, Ed. CONSPRESS, Bucureşti, 2010, pp.65-69

[97] Florin Iordache – Instalaţii de încălzire centrală. Reglajul termic calitativ centralizat – Revista Română de Inginerie Civilă, volumul 8 (2017) nr.1 – ISSN 2068-3987 – ed. Matrixrom 2017, Bucureşti, pp. 18-30

[98] Tomasz Cholewa, Alicja Siuta-Olcha, Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building, Energy and Buildings, Volume 104, 1 October 2015, Pages 122-130, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2015.06.083 http://www.sciencedirect.com/science/article/pii/S0378778815300967

[99] Florin Iordache, Bogdan Caracaleanu, Vlad Iordache: Modernizarea instalaţiilor de încălzire centrală. Aspecte energetice - iarna 2003/2004, în: Expertizarea şi reabilitarea sistemelor de alimentare cu căldură şi instalaţiilor interioare de încălzire centrală, Editura CONSPRESS, Bucureşti, 2006, pp.64-71

[100] Florin Iordache, Cristina Stănişteanu, Clădiri reabilitate termic – consecinţe energetice, Revista Română de Inginerie Civilă, volumul 9 (2018) nr.1 - editura MATRIXROM, Bucureşti

[101] Florin Iordache, Cristina Stănişteanu, Clădiri reabilitate termic – consecinţe energetice, în - Florin Iordache Coordonator – Echipamente şi sisteme termice. Metode de evaluare energetică şi funcţională (culegere de articole) - ISBN:978-606-25-0325-3 – Editura MATRIXROM, Bucureşti, 2017, pp. 29-37

[102] Florin Iordache, Mihai Ionescu, Virgil Păun, Randamentul unui sistem districtual de încălzire centrală, în – Florin Iordache Coordonator – Aspecte termoenergetice in domeniul clădirilor si sistemelor de alimentare cu căldură al acestora (culegere de articole), Editura MATRIXROM, Bucureşti, 2015, pag.187-194

[103] Adrian Marin, Cristina Stănişteanu, Florin Iordache, Reţele termice de distribuţie. Aspecte energetice, Revista Română de Inginerie Civilă, volumul 9 (2018) nr.2 – Editura MATRIXROM, Bucureşti

[104] Florin Iordache, Energetica echipamentelor şi sistemelor termice din instalaţii – ISBN 987-973-100-115-9, Editura CONSPRESS, Bucureşti, 2010, pag. 203-210

[105] Florin Iordache, Energetica echipamentelor si sistemelor termice din instalaţii – ISBN 987-973-100-115-9, Editura CONSPRESS – ISBN 978-606-25-0325-3, Bucureşti, 2010 pag. 197-202

[106] Florin Iordache, Identificarea hidro-termică a reţelelor termice, în: Florin Iordache Coordonator – Echipamente şi sisteme termice. Metode de evaluare energetică şi funcţională (culegere de articole) - ISBN 978-606-25-0325-3, Editura MATRIXROM, Bucureşti, 2017, pp.38-44

[107] Cristina Stănişteanu, Florin Iordache, Alimentarea centralizată cu energie termică de joasă temperatură. Justificare energetică şi economică – Revista Română de Inginerie Civilă – Editura MATRIXROM, Bucureşti, 2020 (în curs de apariţie)

[108] Florin Iordache, Aspecte termo-energetice în domeniul clădirilor şi sistemelor de alimentare cu căldură al acestora (culegere de articole), ISBN 978-606-25-0145-7, Editura MATRIXROM, Bucureşti, 2015

[109] Florin Iordache, Comportamentul dinamic al echipamentelor şi sistemelor termice (ediţia 3-a), ISBN 978-973-755-423-9, Editura MATRIXROM, Bucureşti, 2008