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Case Studies in Low-Energy District Heating Systems: Determination of Dimensioning Methods for Planning the Future Heating Infrastructure



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Summary

The climate crisis and the new technological possibilities for building the low energy buildings give the opportunity to transform the municipal heating systems from high temperature, and high demand systems to low temperature, and low demand systems. The heating demand will be reduced significantly in the future and renewable energy has to be integrated in the design of district heating systems in proper with the non-fossil fuel based future. The paper suggests a plan for an energy efficient District Heating (DH) system with low operating temperatures, such as 55 °C in terms of supply and 25 °C in terms of return. Different case studies could be the rational basis for the integrated planning of the future's sustainable and energy efficient heating infrastructure. Firstly, consideration was given to define an optimal dimensioning method for a new settlement where low-energy houses are planned to be constructed within a case study in collaboration with Roskilde Municipality, Denmark. In this case study focus was given to the determination of the optimal substation configuration equipped at each house and optimal network layout to prevent excessive supply temperature drop occurring in summer months. The use of optimization method yielded in energy savings of 14% in terms of heat loss from the DH network, in comparison to mostly used traditional dimensioning method based on pressure gradient. Also, considering a storage tank at each substation of the houses at the low-energy DH network resulted in energy savings of 8% in preventing the heat loss from the DH network in comparison to the use of substation without storage tank. The use of by-passes at the end-users in a branched DH network could save significant energy in the point of heat loss from the DH network in comparison to forming the low-energy DH network with looped layout. Second consideration was given to define an optimal dimensioning of low-energy DH network in connection with existing settlement and with existing citywide heating system. The technical aspect of using low-temperature at existing in-house heating systems was also investigated in collaboration with Gladsaxe Municipality, Denmark. This case is used to form the operational planning. The peak-demand conditions were defined to be supplied with boosted temperature, allowing further reduction of pipe dimensions at the design stage. The existing houses in the case area were considered to be renovated to low-energy class. Dimensioning the low-energy DH network with consideration given to current heat demand situation yielded in 41% higher pipe investment cost in comparison to the pipe dimensions achieved by use of boosted supply temperature at peak-demand conditions. Thus over-dimensioned DH network for the future situation could be avoided by considering current and future heat demand situations together with boosting the supply temperature in some certain peak situations.

Keywords: *Low-Energy, District Heating, Substation Type, Low Temperature, Municipal Planning, Pipe Dimensioning, Network Layout, Operational Planning, Renewable Energy*

1. Introduction

The development expected to be achieved on European building constructions with improved energy efficiency, increases the focus on planning the rational heat supply to low-heat-demand future of the new and existing buildings [1-3]. Experiences have demonstrated so far that sustainable, energy efficient and low carbon heating infrastructure could be accomplished by use of District Heating (DH) systems dissimilar to other heating systems such as individual heating systems, and fossil-fuel based citywide heating systems [4-6]. The uncertainty in the future price of fossil-fuels should represent a source of active concern for policy makers, mostly while taking decision in determination of heating infrastructure in long term contracts [6, 7].

The starting point of the current research project came from the concerns that the cities need to increase the energy efficiency of their heating infrastructures with focus given to avoiding overcapacity in connection with the future heating infrastructure due to pervading energy savings on the demand side. Central to this balancing act of energy efficiency and avoiding over-capacity on heating infrastructure is the answer of an important question: What kind of infrastructure should be built by municipalities and their utilities with ambitious climate polities? The current research presents a research project where low energy housing and low energy district heating is seen as a whole, and therefore it suggests a new technical design for future district heating systems.

The studies [8, 9] reported that low-energy DH systems with low operating temperatures, such as 55 °C in terms of supply, and 25 °C in terms of return, are competitive with alternative heat sources from a socio-economic perspective. They also showed that in low operating temperatures the heating demand of consumers could be satisfied by use of substations equipped at each consumer's house with a convenient control in proper with low temperatures [8].

So far only few show case areas in connection with low-energy DH systems connected to low-energy DH systems have been established, and all of them have been in operation with success up to now. In one of the show case areas, a low-energy DH system was established at Ringgården Housing Association, located at Lystrup, Denmark, supplying heat there to 40 flats with low operating temperatures without any complaints from consumers in the point of thermal comfort [10-12]. Another show case area entitled as "SSE Greenwatt Way development" was established at Slough (UK), supplying heat there to 9 houses in low-temperature operation, sourced from Renewable Energy (RE) heat sources such as solar plants, geothermal etc [13]. Another example could be referred to a geothermal sourced low-energy DH system, located at Kırşehir, Turkey which has been supplying heat to 1,800 dwellings with operating temperatures of 54 °C in terms of supply and 38 °C in terms of return since 1995 [14].

The ratio of the total heat demand over the heated area (known as heat density) is often used to evaluate the feasibility of establishing the DH system in a settlement. Low-demand areas located with low-energy houses may result in a low heat density area with comparatively high heat loss from the DH network, in case of traditional DH systems' being designed there [15, 16]. Thus, the focus has to be directed to define dimensioning methods for low-energy DH systems with simultaneous consideration given to both the current high demand situation and the future low demand situation in terms of existing and new houses.

2. Methods

The methods were constituted of several technical aspects in connection with low-energy DH systems. Firstly, studies regarding dimensioning method of low-energy DH systems connected to new low-energy buildings were presented for a new settlement. Then, another method was presented with focus given to dimensioning the low-energy DH network for existing buildings which were assumed to be renovated to low-energy class in an existing settlement. Finally, possible low-temperature heat sources that can be considered for connecting to low-energy DH systems were shown with the potential they have in the case of a Danish example.

2.1 Design of Low-Energy DH Network for New Settlements

2.1.1 Case Study in Collaboration with Roskilde Municipality

The design of low-energy DH systems was carried out in a case study in collaboration with Roskilde Municipality (Denmark). In this case study, a new suburban area, named as Trekroner, was planned to be established with a low-energy DH system supplying heat to 165 low-energy houses, planned to be built there (Fig. 1). The technical details regarding this case study could be reached from [17-19].

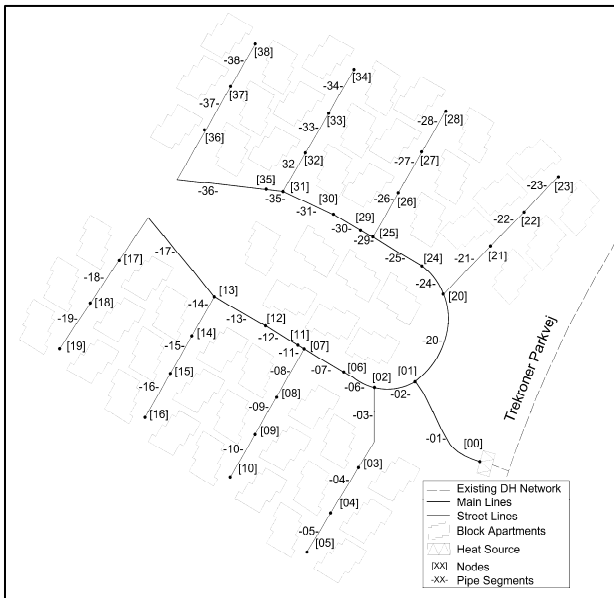


Fig. 1 Branched DH Network [17]

load, required to be supplied, at each pipe segment, allowing descending pipe diameters in the branched DH network. Contrary to the well-known, simultaneity factors are also possible to be utilized in connection with space heating since most of the Danish buildings' in-house heating systems are equipped with thermostatic valves which regulate the flow of the in-house heating system according to the indoor comfort conditions.

After determining the unique heat load for each pipe segment distinctively, the focus was given to determine a dimensioning method for the low-energy DH network with simultaneous consideration of sustainability, and energy efficiency. Traditional dimensioning methods were based on a size-searching algorithm which search for the lowest – commercially available – pipe diameter possible in the constraint of maximum velocity and/or maximum pressure gradient (unit pressure drop over length).

It should be noted that in a closed loop piping system, once the pump is dimensioned to overcome the pressure drop through the critical route then the pump can also handle the pressure losses through the other routes parallel to the critical route. Another point has to be noted that the pressure loss occurring in a pipe segment is dependent on the diameter of it; the lower the diameter the higher the pressure loss. In accordance with these principles, an optimization model was defined with the aim of minimizing the heat loss from the DH network by means of reducing the dimension of each pipe segment in the DH network until the potential of the head lift provided by the main pump station was utilised through each route as much as possible. According to design parameters of twin pipes (AluFlex and Steel [22]), considered to be utilised for low-energy DH systems, the maximum static pressure drop limit was set as 10 bar allowing the optimization method to be modelled with the aim of reducing the heat loss instead of the overall cost. The reason of this assumption came from the studies [10, 23] regarding to Lystrup show case since it was indicated in that reports that the cost impact of pumping is significantly lower than the cost impact of heat loss in case of low-energy DH systems.

2.1.2 Optimizing the Low-Energy DH Network

In case of a traditional DH system, an area with low heat density results in significantly higher heat loss from the DH network in comparison to the heat supplied to the area [9, 10, 20]. Hence, in this case study priority was first given to decrease the overall heat load of the area, and then to decrease the pipe diameters in order to minimize the heat loss from the low-energy DH network [17, 18].

Consumers connected to a DH system do not consume heat at the same time, neither at the same rate [21]. Based on this principle simultaneity factors (also known as diversity factors) were calculated for each pipe segment of the DH network as a function of the cumulative number of consumers to which the pipe segment has to supply heat. Inclusion of the simultaneity factor at each pipe segment decreased the heat

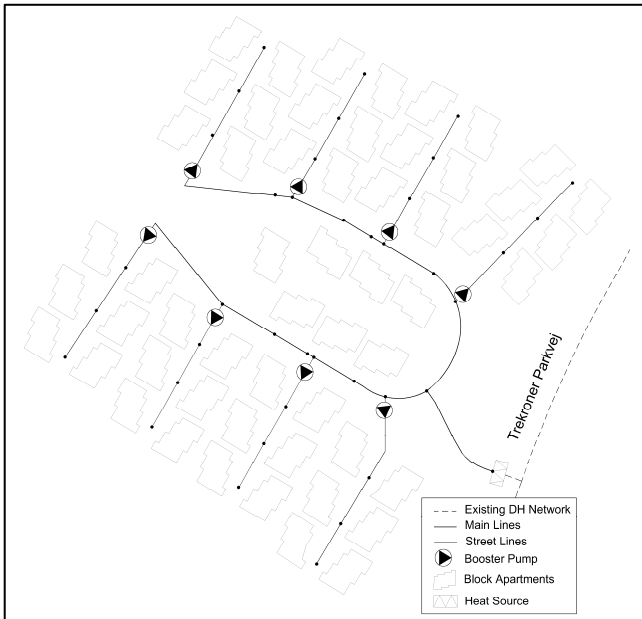


Fig. 2 The Location of Booster Pumps [17]

exchanger. Therefore, in the case of using a heat exchanger, the opportunity of reducing the pipe diameters by establishing booster pumps at the DH network was investigated (Fig. 2). The pressure drop limit value, which constraints the reduction of pipe diameters through the optimization process were here considered for short sequences of pipe segments instead of considering the route entirely.

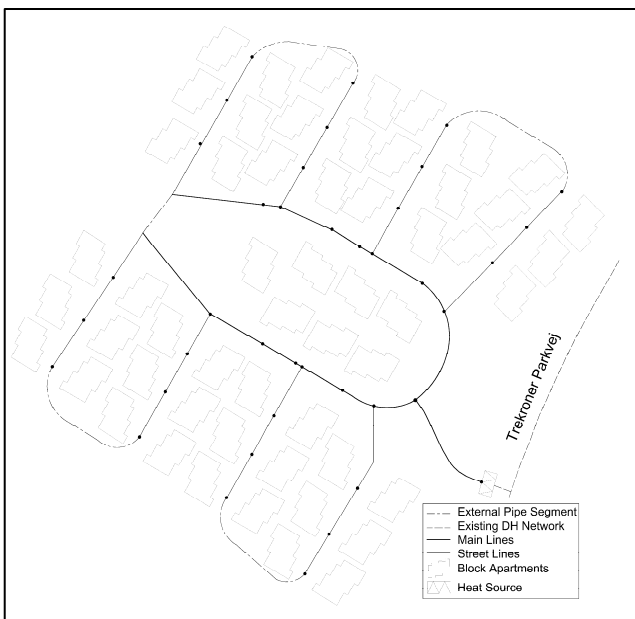


Fig. 3 Looped DH Network [17]

temperature increase at the return heat carrier medium and increased heat loss from the return line as well.

The idea behind using the looped layout came from avoiding the mixture of heat carrier mediums without equipping by-passes at the DH network. Hence the principle of using this layout was to form the DH network in loop layouts so that comparatively more consumers, connected to the same loop, could maintain the circulation of the supply heat carrier medium by use of the dynamics coming from the consumers' heat consumption [17, 19, 27].

2.1.3 Substations

Different substation types, such as using an instantaneous heat exchanger and a storage tank for domestic hot water production, were investigated for the branched type DH network in the perspective of their effects on the diameters of each pipe segment and, as a consequence, on the heat loss from the DH network. The heat demand values in connection with domestic hot water production were set as 32 kW and 3 kW in cases that the substation was equipped with, respectively, heat exchanger and storage tank (heating demand of space heating was set as 3 kW for each substation type – detailed information could be reached from [10, 24, 25]).

It is obvious that the comparatively lower heat demand for domestic hot water, ensured by the use of a storage tank leads to smaller pipe diameters in comparison to using a heat

2.1.4 Defining the Optimum Layout

Space heating is not a need in summer months, and also domestic hot water consumption is reduced due to the absence of consumers who are on vacation [17, 19, 26]. The low flow due to reduced heat demand causes significant temperature drop in supply lines. Hence, two network layouts were considered to avoid excessive temperature drop in the supply lines: branched DH network with by-passes at the end-users (Fig. 1) and looped DH network (Fig. 3) without any by-passes.

In the branched DH network the thermostatic by-passes, located at the end-users of the network, were considered to circulate the supply heat carrier medium, after its temperature drop under a certain point of temperature, through the return line. However mixing occurring due to circulating the supply heat carrier medium to the return line causes

2.2 Design of Low-Energy DH Network for Existing Settlements

The studies [14, 28] claimed that existing in-house installations could satisfy the thermal comfort of the occupants by use of low-temperature operation. The design parameters, being taken into account while sizing the existing in-house (radiator) heating systems, were based on selecting the width of the radiator systems according to the width of the windows in order to avoid cold draught problems [28]. Hence the low-temperature operation was analysed at existing radiator systems, and the effect on the dimensions of the low-energy DH network were evaluated. Also, boosting the supply temperature of the low-energy DH system in peak winter conditions was considered in this study.



2.2.1 Case Study in Collaboration with Gladsaxe Municipality

The design of low-energy DH systems was carried out in a case study in collaboration with Gladsaxe Municipality, Denmark. In this case study, an existing settlement with 783 detached single family houses located there and currently heated by a natural gas heating system was considered for the calculations (Fig. 4).

Fig. 4 Case Area, located at Gladsaxe Municipality, Denmark

2.2.2 Investigation of Existing In-House Heating System

The existing radiators were sized in accordance with the width of the windows so their original design parameters were assumed to be 9 kW in peak heat demand with temperature difference of supply and return of 50 °C (based on the studies [28, 29]). However the current heat demand value of the existing houses was assumed to be 8.1 kW, and after the renovation of the houses to low-energy class (in accordance with the heat demand requirements defined with the software Be06, which was later updated to Be10 at 2011 [30]) the heat demand value was assumed to be 6 kW. The performance of the radiator heating systems was evaluated by use of log mean temperature difference (LMTD) equation [31, 32].

2.2.3 Dimensioning Method Considering Current and Future Heat Demands

The dimensioning method was carried out with simultaneous consideration of current and future situations at which the heat demand values were considered to be high demand and low demand, respectively. Dimensioning the DH network in accordance with the current high demand values could result in over-dimensioned DH network for the future low demand situation. Boosting the supply temperature at the high demand situations, however, could avoid having over-dimensioned DH network [33, 34]. The control philosophy, boosting the supply temperature, could also be used for low-energy DH systems in future situations in which all houses were converted to low-energy class. Thus simultaneous consideration of boosting the supply temperature at both situations (current and future) was used as a basis for optimization of a DH network connected to existing settlements, also regarding the thermal performance of the existing radiator heating systems.

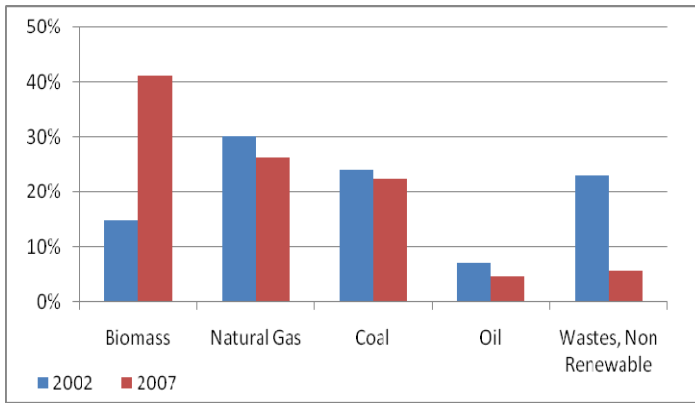


Fig. 5 Heat Source Distribution for DH in the Years of 2002 and 2007 (based on [35, 36])

likely be available in other countries as well. The present heat sources used for DH systems in Denmark can be seen at Fig. 5.

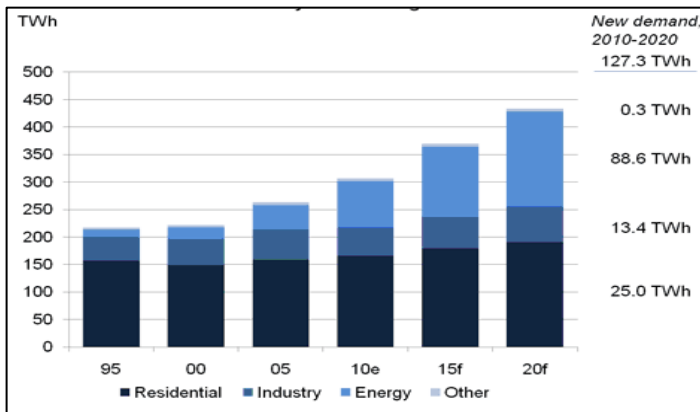


Fig. 6 Demand Forecast of Biomass [37]

while taking decisions for long term contracts. Some source to low-energy DH systems can be seen below.

2.3.1 Waste Heat Recovery from Industrial Facilities

A former study points out that in Denmark there is a theoretical potential of 139 PJ (38,6 TWh) in waste heat from industrial facilities [38]. The waste heat can be utilized in DH network, which will otherwise be lost. Even low temperature heat released as waste from the industrial processes can be utilised, thanks to low operating temperatures. Also, the cooling need in some of the industry facilities could be utilized as a heat source to supply heat to low-energy district heating systems at low operating temperatures.

2.3.2 Geothermal Energy

Also low-temperature operation can give the opportunity to exploit geothermal energy with low investment. The temperature change gradient below the surface of the ground ranges between 25 - 30°C/km in Denmark [39]. Reasonable temperatures such as 70 °C can be achieved from a geothermal source, 2 km below the ground level [40]. The heat produced does not necessarily need to be boosted by use of heat pump for low-energy district heating systems. In the long run, a geothermal production at 25 to 40 PJ/year (equivalent to 20 to 30% of the overall heat demand of district heating) in Denmark could be achievable in a reasonable investment cost [41].

2.3 Potential of Low-Temperature Heat Sources

The low-temperature operation gives the chance of exploiting the low-temperature heat sources without a need for heat pumps used for increasing the supply temperature to the levels in accordance with the requirement of traditional DH systems. Meanwhile, the efficiency of extracting heat from cogeneration plants increases due to low temperature operation [8, 9, 12, 31]. Some of the alternative heat sources in proper with low-temperature operation were presented for the Danish cases, which could most

However, it should be noted that the demand of using biomass is increasing due to not only heating purposes but also industrial demands, as can be seen from demand forecast in terms of biomass given at Fig.(6) [37]. It is possible to exceed the economical balance point of supply and demand in terms of biomass in the future, which makes the price of biomass uncertain. Relying on only biomass or on any type of heat source carries the possibility of lack of reliability and uncertainty of the price. Hence in the point of reliability, determination of heat source for low-energy DH systems should also represent a source of active concern

some heat sources which can be utilized as a

2.3.3 Condenser Heat Recovery from Chillers

The condensing heat which is normally released to air from the cooling tower of a refrigeration process can be utilized as heat supply to low-energy DH systems. A refrigeration process with a 900 – 9,800 kW cooling capacity can provide heat of 400 – 11,700 kW in 43 °C, allowing higher $COP_{Cooling\&Heating}$ of 11.4 in comparison to relying only on cooling with $COP_{Cooling}$ of 6.3 (based on the brochure [42]). A potential survey of the chillers in Denmark and the method to exploit this waste heat could be beneficial in the environment point of view.

2.4 Discussion

In the following, the design method for low energy district heating is discussed in the two dominating situations in an urban context: design for a new settlement and design for an existing settlement.

2.4.1 Case Study – A New Settlement

The detailed technical results regarding to this case study were presented at [17-19]. Three different dimensioning methods were used to dimension the low-energy DH system. A traditional method “Maximum Pressure Gradient Method based on Critical Route” and its modified version “Maximum Pressure Gradient Method based on Multi-Route” were applied for the case area, Trekroner low-energy DH system. According to the critical route, the maximum pressure gradient was calculated as 1,617 Pa/m, which was used later as a limit for each pipe segment until the minimum possible pipe diameter was found per each. However, the pipe segments belonging to other routes could be dimensioned according to the unique maximum pressure gradient of the route that the pipe segment belongs to, which was the basis of the dimensioning method “Maximum Pressure Gradient Method based on Multi-Route”. The further potential of head lift provided by the main pumps station (which was calculated as 8 bar) was exploited by use of the optimization method in question, which was based on the pressure drop itself, not the pressure gradient though. After the optimization applied, the pressure drops observed through each route were found, respectively, as 6.56, 7.05, 7.64, 5.51, 6.53, 7.64, 6.40, and 7.73. With exploitation of the pressure drop, 14% reduction in heat loss from the DH network was yielded in comparison to the method “Maximum Pressure Gradient Method based on Critical Route” and 2% reduction in comparison to the method “Maximum Pressure Gradient Method based on Multi-Route”.

A substation with storage tank resulted in 8% reduction in heat loss from the DH network in comparison to using a substation with heat exchanger at each substation. Installing booster pumps (with a head lift of 3.8 bar) at the start of each street of a DH network connected to consumers’ substations equipped with heat exchanger resulted in 2% heat loss in comparison to the DH network without booster pumps installed. In the point of avoiding an excessive temperature drop at the supply line during summer months; due to the low-temperature operation, significant temperature increase at the return line was not observed as could be seen at traditional DH systems. Also, the temperature drop was observed to be higher in case of forming the looped layout in comparison to having a branched DH network.

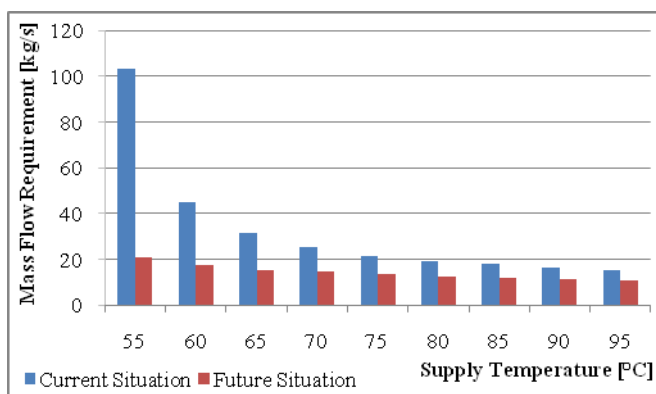


Fig. 7 Mass Flow Requirement for Current and Future Situations [34]

2.4.2 Case Study – An Existing Settlement

Since the existing radiator systems equipped at existing houses were over-dimensioned based on their parameters considered while sizing them, the heat demand required by the consumers was satisfied in terms of thermal comfort with an indoor temperature of 20 °C. Detailed technical information could be reached from the former study [34]. The mass flow requirement for the whole case area could reach almost to 100 kg/s at the case of 55 °C supply in terms of current heat demand values considered while the mass flow

requirement could be at the level of 20 kg/s with the same supply temperature in the future situation (Fig. 7). However, from the same figure, it can be seen that by boosting the supply temperature to 75 °C in the current situation, and to 65 °C in the future situation the mass flow requirement for the current and future situations could be equalized.

In case the operational planning was considered with boosting the supply temperature at peak-demand conditions for only the future situation, then one solution could be supplying at the peak-demand times with a temperature of 65 °C and at the rest of the time in a year with 55 °C. With this control philosophy, the equalized mass flow requirement for future situations was found to be 15.5 kg/s. From this basis, the mass flow for the current situation could be reached by boosting the supply temperature to 95 °C for only peak-demand times. One should note that peak-demand times were observed to occur only 8 hours during a year for this case area.

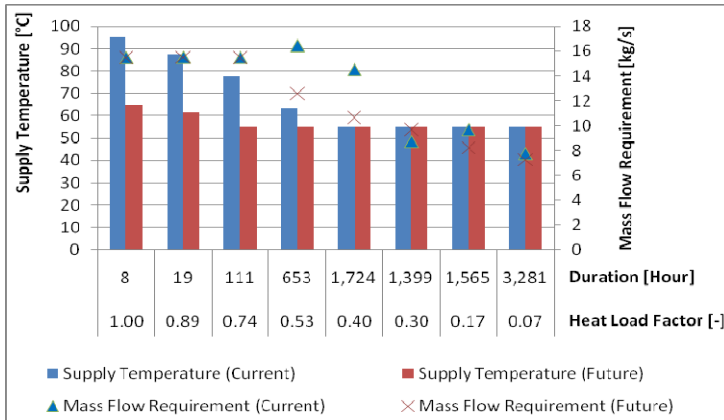


Fig. 8 presents the operational planning of the level of supply temperature and the response observed from the overall heated area as total mass flow requirement. As can be noted from the figure the mass flows were equalized in one certain level, available for each situation. Then the low-energy DH system could be dimensioned according to this mass flow requirements.

The operational planning of future situation yielded 4% reduction in the pipe investment cost in comparison to dimensioning the DH network without boosting the supply temperature at peak-demand conditions in future situation.

For the case in which the DH network was dimensioned according to the current high-heat demand situation, the pipe investment cost was found to be 41% higher than the case in which the DH network was dimensioned according to the future situation with boosted supply temperature applied.

2.5 Conclusion

The overall aim of this paper has been to introduce the concept of low-energy DH systems with low-temperature operation temperatures such as 55 °C in terms of supply and 25 °C in terms of return with case studies, comprising dimensioning the low-energy DH network for a new settlement and for an existing settlement. General conclusions can be drawn in the point of utilising low-temperature concept in the planning of the future energy infrastructure. One can note that the dimensioning methods proposed within this paper have to be carried out in accordance with the specific design parameters of each unique district. Significant savings can be achieved by use of the proposed optimization method with considerations given to using a storage tank at the substations of each house of the district. Also, the temperature drop through the DH network can be avoided in a more energy efficient way by use of branched DH network with by-passes equipped at the end-users in comparison to looped DH network. One can note that the heat demand of the existing houses can be satisfied with low-temperature operation. However, the over-dimensions possible to be obtained at the piping network could be avoided by means of operational planning such as boosting the supply temperature during peak conditions.

3. Acknowledgement

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