Energy 45 (2012) 960–974

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

District heating (DH) network design and operation toward a system-wide methodology for optimizing renewable energy solutions (SMORES) in Canada: A case study

A. Dalla Rosa [a], [*], R. Boulter [b], K. Church [b], S. Svendsen [a]

[a] Technical University of Denmark, Department of Civil Engineering, Section of Building Physics and Services, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark
[b] Natural Resources Canada, CanmetENERGY, 580 Booth Street, Ottawa, ON K1A 0E4 Canada

ARTICLE INFO

Article history:
Received 23 January 2012
Received in revised form
20 June 2012
Accepted 24 June 2012
Available online 25 July 2012

Keywords:
District heating
Renewable energy
Network design
Low-temperature
Energy efficiency

ABSTRACT

This paper discusses the opportunities and challenges of implementing District Heating (DH) in Canada, with focus on the network design and operation. We selected for case study an urban area in Ottawa. First, we proved that the medium-temperature district heating (MTDH) ($70\,^{\circ}\mathrm{C} \le T_{\mathrm{supply}} \le 90\,^{\circ}\mathrm{C}$) had better energy delivery performance than high-temperature district heating (HTDH) ($T_{\mathrm{supply}} > 100\,^{\circ}\mathrm{C}$), decreasing the heat loss by approximately 40%. The low-temperature networks ($T_{\mathrm{supply}} < 60\,^{\circ}\mathrm{C}$) achieved even lower heat losses, but they required additional capital investment. The implementation of low-temperature district heating (LTDH) should be considered, thanks to the capability of including more renewable energy and excess industrial waste heat. Next, the simulations show that DH can be implemented to supply present heating loads with medium temperature DH, and operate in the future at low temperature, after energy saving measures have been implemented in the buildings. Areas having linear heat densities greater than 3 MWh/(m yr) could economically be supplied by DH. Areas with linear heat density below 1.5 MWh/(m yr) are considered not practically feasible with the current energy market situation in Canada. The paper discusses critical issues and quantifies the performance of design concepts for DH supply to low heat density areas. DH is a fundamental energy infrastructure and is part of the solution for sustainable energy planning in Canadian communities.

1. Introduction

This paper discusses the opportunities and challenges of implementing District Heating (DH) systems in Canada. DH systems are community energy systems which can provide long term achievements in terms of greenhouse gas emission abatement, energy security, local economy development, increase of energy and exergy efficiencies and exploitation of Renewable Energy (RE) [1–7]. We selected an urban area in the capital city of Ottawa, Canada, for case study; a technical-economical analysis was then carried out. A DH system consists of three main interdependent parts: the heat sources, the heat distribution system, and the buildings and their Space Heating (SH) and Domestic Hot Water (DHW) systems. Within these components there are significant variations. The buildings can vary in size, diurnal heat demand profile, annual load duration curve, type of SH and DHW systems and equipment, and type of connection to the DH network (direct or indirect SH, instantaneous preparation of DHW or energy storage for DHW preparation). The DH pipe dimensioning is affected by the heat profile, the peak demand of the buildings serviced, the type of pipe system, future capacity considerations, and ambient conditions. The heat sources have traditionally been Combined Heat and Power (CHP) plants, conventional or condensing fossil-fuel-based boilers and waste-fired boilers. In the last two decades, increasing focus has been given on the replacement of fossil-fuel energy sources with RE, such as solar, biomass and geothermal energy, as well as incorporating surplus heat from industrial processes and other energy-efficient supply systems including heat pumps and CHP with increased overall efficiency and increased electricity

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Abbreviations: CHP, Combined Heat and Power; DH, District Heating; DHW, Domestic Hot Water; DN, Nominal Diameter; EUI, Energy Use Intensity; ETFE, Ethylene TetraFluoroEthylene; GCV, Gross Calorific Value; HE, Heat Exchanger; HTDH, High-Temperature District Heating; IEA, International Energy Agency; LTDH, Low-Temperature District Heating; MTDH, Medium-Temperature District Heating; OECD, Organization for Economic Co-operation and Development; PEx, Cross-linked polyethylene; RE, Renewable Energy; SH, Space Heating; ST, Storage Tank; SMORES, System-wide Methodology for Optimizing Renewable Energy Solutions.

[*] Corresponding author. Tel.: +45 45251939; fax: +45 45883282.
E-mail address: dalla@byg.dtu.dk (A. Dalla Rosa).

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http://dx.doi.org/10.1016/j.energy.2012.06.062

Nomenclature

E	Energy [J]
D_{eq}	Equivalent diameter [mm]
G	Solar Radiation [W/m^2]
L	Length [m]
N	Number of consumers
Q	Equivalent peak heating load, including simultaneity factors [W]
S	Simultaneity factor for space heating
T	Temperature [°C]
U	Linear heat transfer coefficient [W/(m K)]
a, b, c	Coefficient for the calculation of Q
d	Media pipe diameter [mm]
i	Counter-variable
n	Number of pipe segments in the network
q	Linear heat loss [W/m]
q_{max}	Peak load of the HE for DHW [W]
z	z-factor (CHP plants)

output. Most of the literature has focused on either building installation performance [8–10] or on characteristics of the heat supply plants [11–16]. The economic optimization has often been the sole objective, even in the most comprehensive studies [17]. Instead, the scope of this paper is to provide a methodology that focuses on solutions for optimal network design and operation to enable extensive use of RE sources. The economic investigations are made to quantify the investment that would be involved in implementing and operating a DH system, while considering the socio-economical impact. The structure of the paper follows a methodology that community energy planners can apply when assessing the potential for DH implementation and comparing the alternative technologies and solutions. We aimed at organizing the successive steps of a typical feasibility study, pointing at the critical issues and discussing possible solutions. We applied the methodology to a specific case study, but it can be applied elsewhere, after making sure that the economic and technical input data match the actual conditions of the site considered. The investigations dealt with the design and performance simulations of DH networks that were optimized toward the exploitation of RE and low-grade heat. RE or heat recovery technologies are not directly treated. The objective of the paper is to demonstrate/confute the hypothesis that Low-Temperature District Heating (LTDH) and Medium-Temperature District Heating (MTDH) networks are very beneficial for including RE and surplus heat in Canadian communities.

1.1. *A system-wide methodology for optimizing renewable energy solutions (sMORES)*

Communities undertaking large scale retrofit building programs and planning of future energy supply systems need a methodology to distinguish between areas where community-based energy distribution systems could prevail and areas where individual, building-based systems should be used instead. An urban area of the city of Ottawa was designated as a test site; the area consisted of typical mixed use (commercial and residential), mixed property age and represented the attributes of many communities across Canada. It was intended therefore to utilize this test area to examine the DH potential. In particular, we investigated the impact of including the socio-economic effect of the system on the lower limit of linear heat density, adapting the European LTDH concept [18–21] to the Canadian conditions. Moreover, a methodology was proposed to achieve the technical optimization of the system in the medium, long-term time horizon. The site belongs to a larger portion of the city that was chosen for the study "System-wide Methodology for Optimizing Renewable Energy Solutions" (SMORES) [22], see Fig. 1.

1.2. *DH in Canada*

There are several issues that have created obstacles to the systematic expansion of the DH supply in Canada. Primarily, DH has been applied in Canada to complexes of large buildings with well-defined ownership, e.g. public institutions, hospitals, university campuses. Historically, the cost savings in bulk fuel purchases led to distribution systems using steam for a heat medium, minimizing the initial investment costs, but with the ensuing large operating and maintenance costs. In addition to that, policy and tradition meant that heat was mainly considered to be a by-product of electric load generation. Thus, there was a lack of appreciation of the value of the thermal component of the energy demand and of the need and the impact of integrating thermal energy planning with land use planning in community development. Secondarily, the conditions of the energy market in Canada are rather unique. The wide geography of the nation brings along many differences amongst the different provinces and territories, but common considerations are still possible. The country as a whole benefits from extensive natural resources, including water and fossil fuels, whose availability is not foreseen to lack in the short-medium term [23]. The specific climate characteristics, with very cold winters and relatively warm and humid summers in the most populated regions of the country, together with high users' requirements for thermal comfort cause high energy demand. Next, the relatively low energy taxation policy accentuates the differences between the end-users' energy prices in Canada and in other organization for economic co-operation and development (OECD) countries, as shown in Fig. 2. Moreover, the involvement of public bodies in energy planning has been often restrained by legislation leading to the high degree of single-building-oriented energy installations. In Ref. [24], the authors stated that other important factors are the lack of project champions, political leadership and a defined federal and provincial policy framework, the need to strengthen local capacity to design, build and operate community energy systems, and the industry's inability to effectively position and market DH as a viable, sustainable option. As a consequence, the implementation of energy conservation and energy efficiency policies have often been a secondary topic in the political agenda and treated as sub-optimal solutions from the economic point of view. In this light, the DH sector has developed an alternative approach, focusing on the benefits to the community other than direct energy savings; benefits such as job creation, urban planning and local economy. The public awareness of DH is increasing steadily with many communities and utilities seeing DH as a central pillar to their future growth.

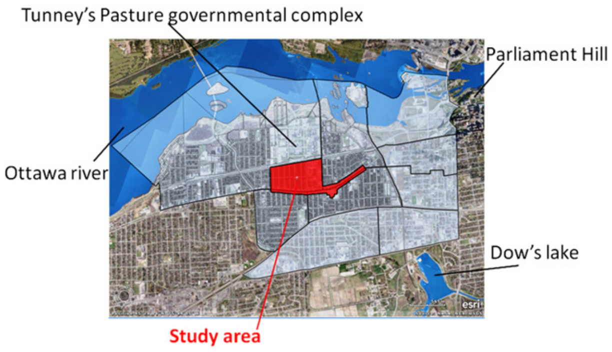

Fig. 1. Case study site in Ottawa, Ontario, Canada.

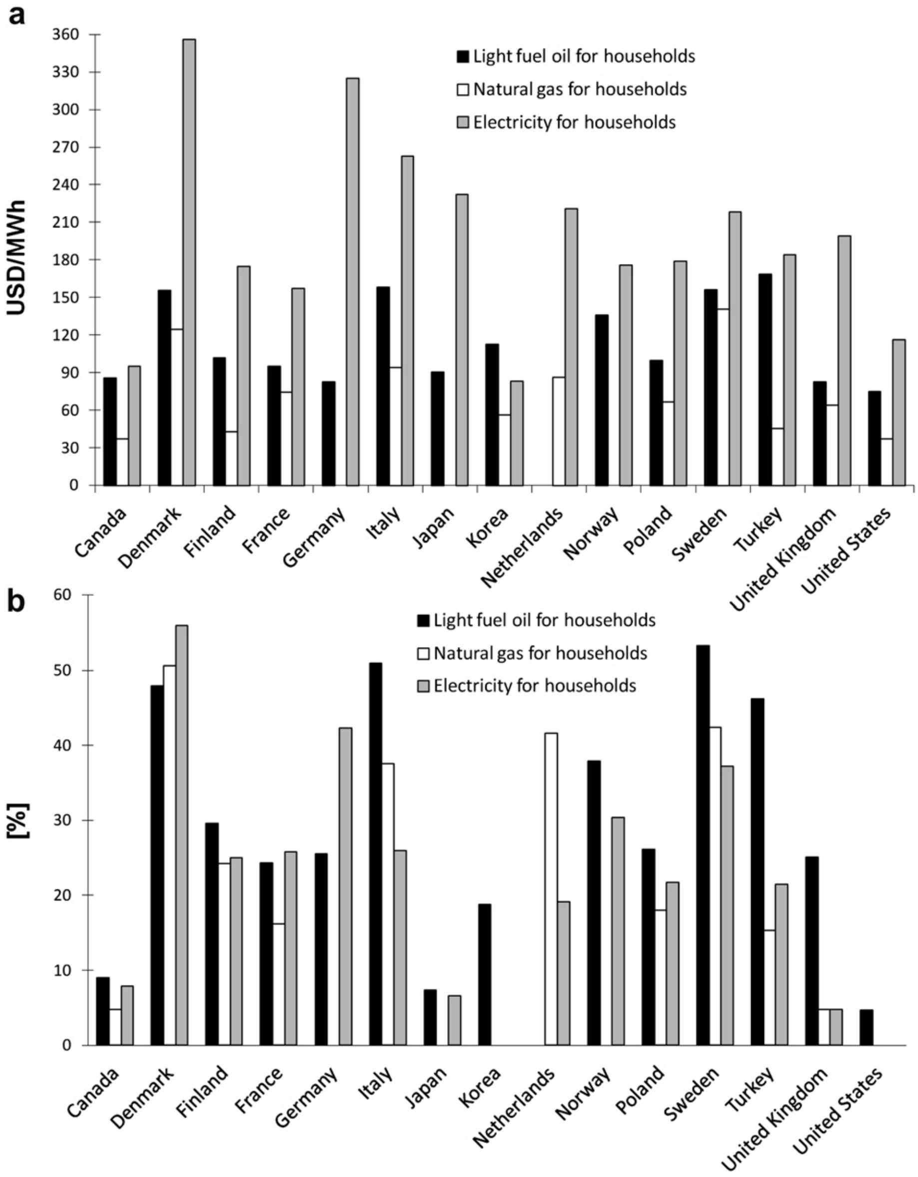

Fig. 2. Energy prices (a) and impact of taxes (b) on the total energy price for household in OECD countries in 2010. Missing columns mean that no data were available. Source: [25].

From the technical point of view, significant improvements can be made in the existing DH systems and when planning new networks. There is a general agreement that medium or low temperature hot water is a preferred option. The reasons for this include lower operating costs for distribution systems, higher operation efficiency for many heating plant configurations, the ability to use industrial or low-grade waste heat, heat pumps and RE, the opportunity to economically transport heat over longer distances and interconnect systems, and the ability to use thermal storage for load management [26]. From these general considerations, it appears clear that science-based and engineering-supported decisions are valuable and desired by decisions makers: the scope of this paper is to provide part of required information and point at the critical aspects when dealing with the network design of a community energy system.

1.3. Effect of low operating temperatures in heat production plants/heat recovery processes

If energy-efficiency and use of RE are focus targets, low operating temperatures are desirable in a DH system, both from the distribution network and the heat source point of views. The scope of this paragraph is to provide typical examples on the effect of operating temperatures on possible RE-based and/or energy efficient heat sources: small-scale and large-scale solar collectors, extraction-condensing turbines for CHP, and heat pumps. Fig. 3 shows the typical efficiencies of commercial solar collectors as function of the difference between the average temperature of the fluid in the collector and the ambient temperature, quantifying the efficiency improvements brought by LTDH and MTDH in relation to High-Temperature District Heating (HTDH). The efficiency refers to the aperture area of the solar thermal collector and is calculated according to EN 12975, with the data available on the product datasheet.

The cost of heat produced in an extraction-condensing turbine is determined by the reduction of electrical output. The electricity production reduces when heat is extracted from the turbine, indeed.

The reduction of the electricity output can be defined by the *z*-factor [29]:

$$z = E_{\text{electricity, loss}}/E_{\text{heat, production}} \quad (1)$$

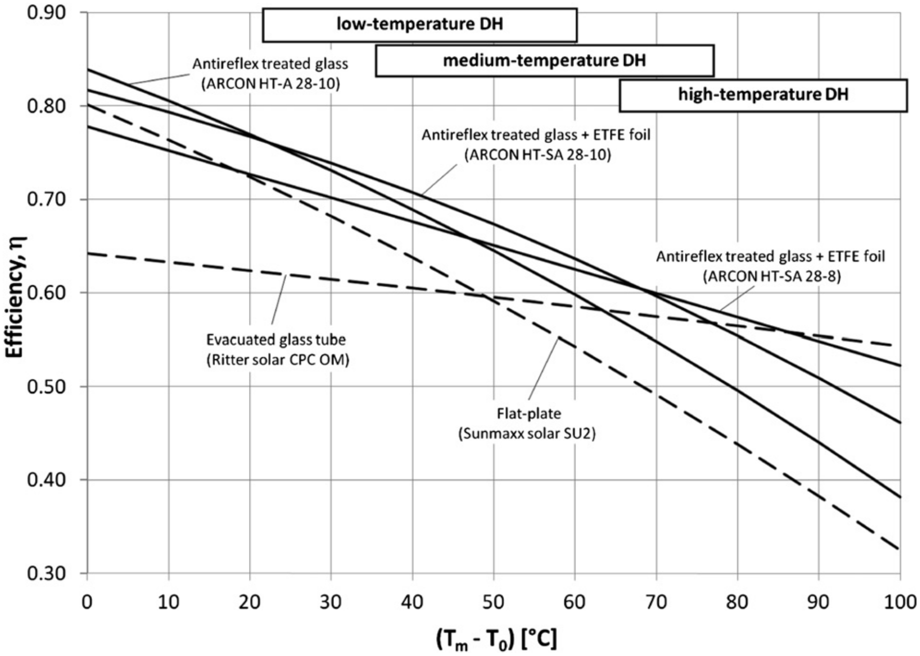

Fig. 3. Efficiency of solar collectors as function of the difference between the average T of the fluid in the collector, T_m and the ambient temperature, T_0 ($G = 1000$ W/m^2). — Large-scale solar thermal collector, source: [27]; – – – – Small-scale solar thermal collector, source: [28].

Fig. 4 shows the *z*-factor calculated for the range of temperatures suitable in this study. The vertical segments refer to the *z*-factor values that correspond to the sets of DH operating temperatures defined in this paper. It can be seen how the energy efficiency benefits from lower operating temperatures and that the *z*-factor is more sensitive to the supply temperature than to the return temperature.

The application of the electrical heat pump technology might be valuable for upgrading the exergy-content of available waste heat to a level where is suitable to be used. The integration of MTDH networks and LTDH systems by means of water-to-water heat pumps is particularly interesting. A heat pump usually acts in a closed loop. The heat rejected at the condenser (heat sink) is the sum of the heat removed from the evaporator (heat source) plus the ideal compressor work. The final energy use is then smaller than the energy supplied from the condenser due to unavoidable heat losses. The heat pump system proposed in Ref. [30] fits low-temperature applications and consists of an “open-loop” heating circuit. The return water from the MTDH network passes through the heat pump condenser so that the temperature is raised to the target LTDH network supply temperature. The return water from the LTDH network flows through the evaporator and is further

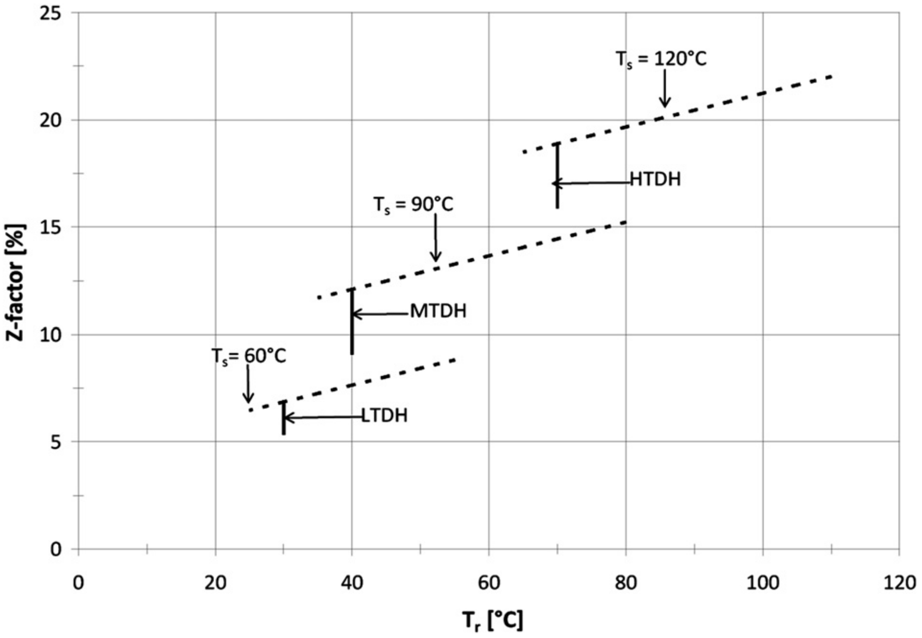

Fig. 4. *z*-Factor in an extraction-condensing turbine for CHP as function of the DH operating temperatures.

cooled before it returns back to the MTDH network. The water supplied from the condenser can drop to a temperature lower than the condenser inlet water temperature, which makes the final utilized energy exceed the energy recovered from the condenser.

The increased efficiency in energy recovery from industrial processes or commercial activities and lower heat loss, and/or higher capacity in heat storages are additional advantages that arise from low operating temperature and should not be underestimated, since potentially they could contribute significantly to satisfy the demand in a fossil-fuel-free heat supply scenario.

2. Methods

This section of the article provides the essential information about the case study area and the methodology that led the network designs and the evaluation of the energy performance. Herein we explain the assumptions regarding the pipe characteristics, the building SH and DHW installations and the economical analyses.

2.1. Case studies

The study area was divided in groups of buildings with common characteristics in regards to facility type (residential or commercial), age and size. We grouped them in the 5 geographical zones listed below. The building group share on the annual heat demand of the zone is reported in parentheses:

- Zone 1: 13 high density commercial and office buildings (74%) and 2 high-rise apartment buildings (26%);
- Zone 1b: extension of zone 1. In total: 13 high density commercial and office buildings (69%), 2 high-rise apartment buildings (24%), 38 residential townhouses (7%);
- Zone 2: 407 single-family, detached houses (100%);
- Zone 3: 85 buildings in the tertiary sector, i.e. retail shops, wholesale and service buildings (43%), 15 office buildings (9%), 11 apartment buildings (48%);
- Zone 3b: extension of zone 3. In total: 99 small-scale buildings in the tertiary sector (41%), 15 office buildings (8%), 17 single-family, detached houses (3%), 16 apartment buildings (48%).

The zones were gathered in 7 patterns, modeling realistic, potential target areas and a DH network was designed for each case, see Fig. 5 and Table 1. The following assessment of the system performance offered a tool to energy planners and policy makers to explore the technical and economical possibilities to implement DH in a typical Canadian urban city and finally prepare heat plans.

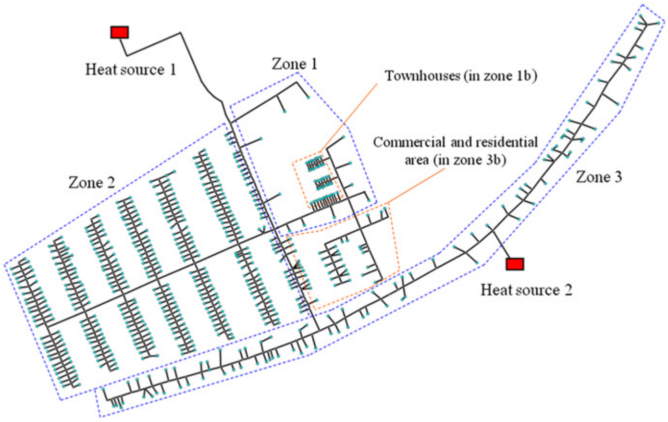

Fig. 5. Network layout in the case G. The layout in the cases A–F consists in modification of portions of it.

2.2. Network design and annual energy performance calculation

This section describes the input data, the assumptions and the procedure which were used in order to design the DH networks and calculate the annual energy performance. They consist of climatic data, information about the heat demand loads and choice of suitable operating temperature and design parameters. The ground temperature data in Ottawa were found by interpolation of the data available in Ref. [31] and they are shown in Fig. 6.

Several data sources were referenced to generate estimates for specific thermal energy demand and consumption values for the buildings within the various study areas. All information were compiled and provided the input to simulations models developed using the commercial district energy software TERMIS.

For each property parcel and relevant building included in the DH study area, specific information, such as property coding, structure coding, and building and parcel areas were compiled from property data supplied by the municipality. Such information allowed for the compilation of general building information by end-use, factoring spatial characteristics to define where each facility was located.

Natural gas consumption data for consumers in the study area was pursued and received from the gas distribution utility. However, to uphold the utility's commitment to maintain the integrity of consumer privacy, the data was received as aggregated monthly totals for the entire study area, broken down into four categories of consumer type; residential, apartment, commercial, and industrial. Though not useful in determining individual facility thermal energy use, the utility data enabled a realistic monthly distribution of energy demand to be established. This allowed for the definition of an average monthly energy demand profile in terms of percent of annual heat use by month. Consumption data was normalized for weather conditions experienced during the data collection period against climate normals for the area and profiles were assigned accordingly to each property in the TERMIS model as shown in Fig. 7.

To estimate total annual thermal energy use, building area information was applied against benchmark Energy Use Intensity (EUI) values adapted from Refs. [32,33].

Since the derived EUI values represent the total primary energy requirement at the building level, an efficiency value of 80% was assumed and applied to better estimate the total thermal energy required from the DH network.

In an effort to estimate the peak loading conditions needed for network dimensioning, thermal load factors were generated using simulation data for a set of standard building archetypes. The building simulations had been completed by NRCan personnel for a building energy archetype study using EE4 (DOE2-2.1) software factoring Ottawa weather conditions. In all cases, peak building thermal load occurred in January. The data generated is shown in Table 2.

A thermal load factor of 0.40 was assumed for single residential units.

For each building included in the DH analysis, the most appropriate thermal load factor was applied against the estimated January thermal energy use to determine an estimate of peak thermal load, as simply:

$$\mathrm{kW_{peak}} = \frac{\mathrm{kWh_{Jan}}}{744 \times \mathrm{LF}} \tag{2}$$

where $\mathrm{kWh_{Jan}}$ is the estimated January building thermal energy consumption, 744 is the number of hours in the month of January, and LF is the associated thermal load factor.

Table 1
Main characteristics of the 7 cases in the study area.

Case	Zones	Heat source	Nr.users	Heated area [$m^2 \times 1000$]	Building area/parcel area	Peak power [MW]	Heat demand		Heat density [kW h/(m^2 yr)][b]
							[GW h]	[kW h/m^2 yr)][a]	
A	1	1	15	79.9	2.7	6.8	11.4	142.2	384.0
B	1b	1	53	85.5	2.5	7.2	12.3	143.5	358.9
C	2	1	407	53.6	0.4	5.4	8.8	164.8	64.3
D	3	2	111	100.3	1.0	7.9	45.7	126.5	126.5
E	1b, 2	1	460	139.1	0.8	12.6	12.7	151.8	122.9
F	1b, 3b	2	200	197.3	1.4	15.1	26.5	134.4	185.5
G	1b, 2, 3b	1&2	607	250.9	0.9	20.5	35.3	140.9	126.8

[a] Total annual thermal energy demand per total building area.
[b] Total annual thermal energy demand per total property parcel area.

Hence, we calculated the peak heating load of the individual building by means of actual heat use data and the reference peak heating load from the correspondent building type. Those data were necessary for designing the DH network during peak load conditions and thus for dimensioning the pipelines. The network dimensioning was carried out by steady-state simulations in TERMIS [19,21].

The energy medium supply and return temperatures are a fundamental parameter in the design of DH systems and play an even more important role when trying to extend the use of RE sources and excess heat. In fact, they determine the size of the pipes, the design of the central plant – a typical example being the choice of type and size of a CHP plant – and the selection and sizing of the heating equipment within the buildings (HEs, radiators, fan coils, floor heating, etc…).

The maximum supply temperature of 95 °C sets the limit for the use of plastic media pipes and for direct-connection between the network and the building SH equipment, assured that the operating pressures in the network are compatible with the limits of the heating installations within the buildings. In addition, the temperature difference between supply and return is decisive in choosing the proper media pipe size.

The supply temperatures from the heating plant that were considered in the study ranged from high-temperature ($T_{supply} > 100\,°C$), medium-temperature ($70\,°C \le T_{supply} \le 90\,°C$) and low-temperature ($T_{supply} \le 60\,°C$) operation. The return temperature from the building installations was considered to be regulated by valves and was set to 70 °C, 40 °C and 30 °C, respectively for HTDH, MTDH and LTDH. The design envisaged a temperature boost during peak load situation, in order to increase the capacity of the system in those conditions and avoid unnecessary over-dimensioning of the media pipes. An additional important decision to be made was the variation of the supply temperature with the ambient temperature for the optimization of the network energy performance and the energy production (heat or, in case of CHP, heat and electricity). The monthly variation during the year was as according to Fig. 8. In the first part of the results section we focused on MTDH network design. The design supply temperature of 90 °C was maintained throughout all cases, because it is a typical value of maximum supply temperature that is in use in state-of-the-art medium-temperature hot water systems and it thus represent the most viable option. Moreover, it was found in Ref. [34] that it is not worthwhile to reduce the design supply temperature below 90 °C as this would lead either to higher network costs – because of the lower temperature difference between supply and return – or additional costs for building installations, if the temperature difference is maintained. In the same study it was found that the optimum temperature difference is approximately 35 °C, i.e. 55 °C return temperature for a peak supply temperature of 90 °C: this was chosen as the reference case. Nonetheless, it might be possible that alternative lower design temperatures can be justified, either because economically advantageous in a fossil-fuel-free scenario or because a sub-optimal economic solution is acceptable to a certain extent, given the potential environmental benefits of maximizing the use of excess heat and RE by means of DH. The low grade heat sources can contribute only partially to the energy supply, since they are most likely used to effectively pre-heat the return water: a reduction of return water temperatures is therefore fundamental. For the reasons mentioned above we investigated the option of choosing a design return temperature of 40 °C ($\Delta T = 50\,°C$).

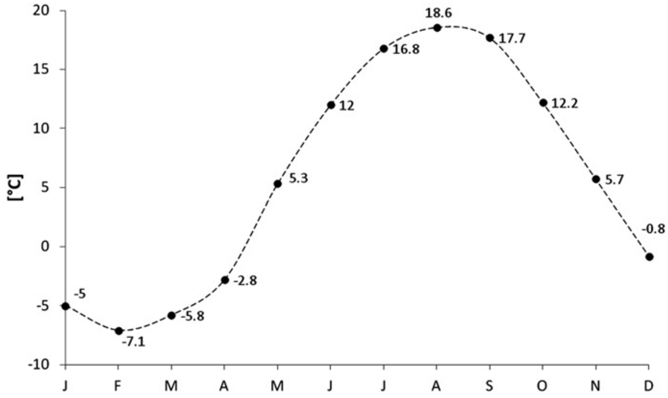

Fig. 6. Soil temperature in Ottawa at 1.0 m depth from the surface [31].

2.3. DH pipelines

The DH networks considered in this study were based on hot water operation and made use of the pipe systems which are listed in Table 3. The linear heat transfer coefficients of the pipes were calculated by means of the online tool available in Ref. [35] and according to Wallentén's formulation [36], respectively for single pipes and twin pipes. In case of networks designed partially or totally using twin pipes, the formulas for heat loss calculation follows the theory in [37]. They are:

$$q_i = \sum_{j=1}^{n} U_{ij} \cdot (T_j - T_0) \text{ [W/m]} \tag{3}$$

where q_i is the heat loss from pipe-i, n is the number of pipes, U_{ij} is the heat transfer coefficient between pipe-i and pipe-j, T_j is the temperature of the water in pipe-j, and T_0 is the temperature of the ground.

In the case of two buried pipes, the heat losses can be calculated as follows:

Supply media pipe:

$$\begin{aligned} q_1 &= U_{11} \cdot (T_1 - T_0) + U_{12} \cdot (T_2 - T_0) \\ &= (U_{11} + U_{12}) \cdot (T_1 - T_0) + U_{12} \cdot (T_2 - T_1) \text{ [W/m]} \end{aligned} \tag{4}$$

Return media pipe:

$$\begin{aligned} q_2 &= U_{22} \cdot (T_2 - T_0) + U_{21} \cdot (T_1 - T_0) \\ &= (U_{22} + U_{21}) \cdot (T_2 - T_0) + U_{21} \cdot (T_1 - T_2) \text{ [W/m]} \end{aligned} \tag{5}$$

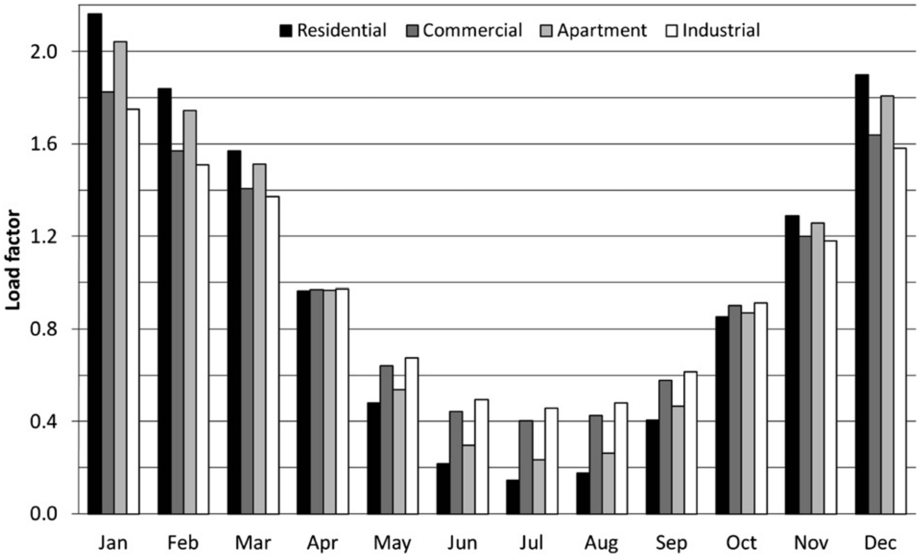

Fig. 7. Monthly heat load factors used in the annual energy simulations.

where T_1 is the supply temperature and T_2 is the return temperature.

In this study we set $U_{11} = U_{22}$ and $U_{12} = U_{21}$, which is the case of perfectly symmetrical twin media pipes, embedded in a circular insulating casing and placed at the same distance from the ground surface, in a horizontal layout. The values of the linear heat transfer coefficients $(U_{11} + U_{22})$ and U_{12} were directly entered in the input menu of the software TERMIS; this was different from previously published studies [18,19], where approximations were necessary, and it was allowed by the new capability of the software to handle more than one linear heat transfer coefficients per media pipe.

We defined the equivalent diameter of the network, D_{eq}, according to formula (4)). It was used as a resumptive quantity when comparing network design options.

$$D_{eq} = \frac{\sum_{i=1}^{n} d_i \cdot L_i}{L_{tot}} \tag{6}$$

where d_i is the media pipe diameter of the pipe-i, L_i is its length, n is the number of pipe segments and L_{tot} is the total network length.

Installation costs in highly-dense urban areas, for various pipe systems, insulation series, materials and sizes were taken from Ref. [38]. They consist of the sum of the statistically elaborated costs for pipe purchase, civil works, sand filling and labor costs for projects in Sweden, but the comparison with examples of correspondent costs in Canada showed that they are applicable also in Canada. Among these costs, the civil works connected with the excavation and backfilling predominate, above all for a development in a dense urban area. The expenditure for civil works depends essentially on the size of the casing pipe, and is the reason why we chose to use the casing pipe diameter as the independent variable, instead of the most common media pipe diameter. By doing so we differentiated the installation costs among different insulation series. In addition, we also considered the costs arising because of heat losses, e.g. the additional energy that must be produced to counteract the heat losses. Such costs were calculated considering supply/return temperatures of 80/40 °C, a life time of 25 years, and annual interest rate of 5%. The cost of heat during the time span considered – and hence the cost of the heat loss – was hypothesized to be equal to $20.50 CAD/MWh, with a linear increase of the heat price, up to the price of $37.50 CAD/MWh after 25 years. A rate of increase of heat loss equivalent to 0.2%/yr was added to the pipes without diffusion barriers, in order to take into account the aging of the insulation foam with the time. Fig. 9 shows the sum of the installation cost and the operational cost during 25 years per meter of pipe, which is denominated pipe specific net present cost. The graphs show the costs referred to the media pipe nominal diameter, for consistency with similar graphs. The cost for maintenance and the residual economic value of the pipes were not taken into account in this analysis.

Table 2
Thermal load factors for a number of reference archetypes.

Reference archetype	Thermal load factor [kW_{avg}/kW_{peak}]
Office	0.47
Stand-alone retail	0.29
Strip mall	0.36
Secondary school	0.49
Hospital	0.5
Full service restaurant	0.39
Quick service restaurant	0.45
Large hotel	0.6
Small hotel/motel	0.53
Non-refrigerated warehouse	0.13
Midrise multi-family residential building	0.51
Supermarket	0.24

The curves are valid for a downtown/urban area, which is characterized by high costs connected to excavation, traffic interruption, civil works, backfilling, etc... In fact, the initial costs depend on the type of construction area (downtown, urban area, suburban, green field) with a typical factor of 2–4 between new developments in green field areas and downtown areas. This, and the low cost of heat purchase that was assumed to resemble Canadian energy market, makes the pipeline systems with insulation series 2 or above not valuable from a mere economic point of view. In the case study considered, only a heat purchase cost above $65–$75 CAD/MWh would make the use of higher insulated pipes economically viable. We hence underline the decisive role that both the characteristic of the site and the heat price have on the choice of the pipeline system.

2.4. Building installations

The building SH and DHW installations are decisive from the economic point of view, since it must be ensured that the proper functioning of the heat emitters and the preparation of DHW

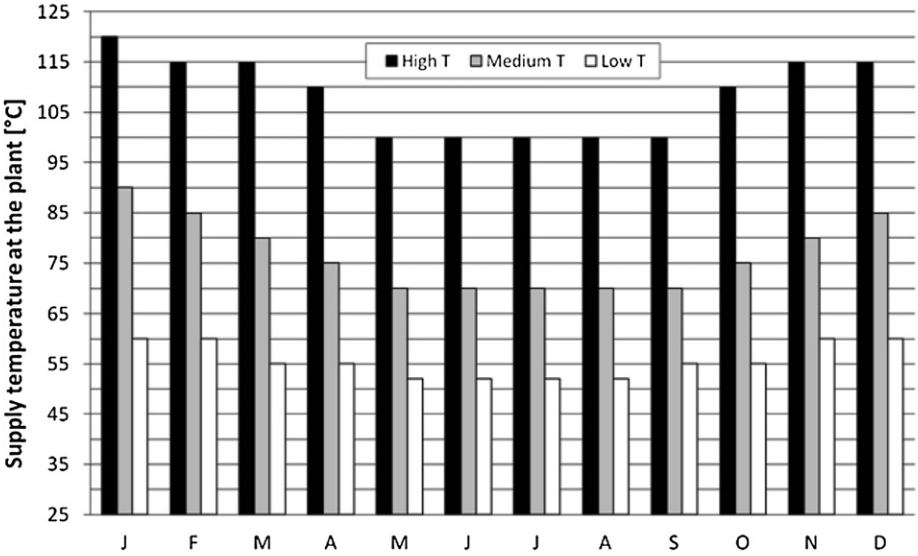

Fig. 8. Variation of the supply temperature during the year, at the heating plant, in case of high-, medium- or low-temperature operation.

within the connected buildings are not jeopardized by changes in the network operating parameters.

Direct systems or indirect systems are available for SH purposes and research and development projects continuously offer new or improved options [39,40]. A direct connection between the heat distribution network and the building SH system is possible when the maximum design temperature and pressure of the DH system are compatible with the design parameters of the heat emitters. The direct connection brings economic benefits, thanks to savings in the substation equipment, e.g. HEs, circulation pump, control and safety devices. Moreover, the lower supply temperature might bring lower heat production costs. The economic analysis applied in this paper dealt with supply temperatures equal or lower than 90 °C and with maximum design pressure of 10 bar. The latter is considered a target value in the network designs reported in this paper, since it represents a limit for using plastic pipe systems [20] and it is in the range of the suggested operating pressures [34]. This is acceptable for direct connection, and the reason why we did not consider any additional costs for SH connection. It is important to underline that the proper choice of building system characteristics must be considered to ensure compatibility with the network. This is generally not an issue since a wide range of devices with the required properties are available in the market (radiators/convectors, radiant floor heating systems, fan coil systems, etc…).

Table 3
List of the main pipe systems, or combination of pipe systems, available in the market [35].

Material name	Pipe type	Insulation series	Size (DN)	T_N [°C][b]	T_{max} [°C][c]	PN [bar]
Steel	Single	1, 2 and 3	20–1200	140	150	25
	Single		20–600	140	150	25
	Single		20–500	140	150	25
Steel	Twin	1, 2	20–28	120	120	25
PEx	Single	1, 2 and 3	16–28	85	95	10
	Single	1, 2 and 3	20–110	85	95	6
	Twin	1, 2	16–50	85	95	6
Aluflex[a]	Single & Twin	1, 2	16–32	95	105	10
CuFlex	Single	1, 2	15–35	120	120	16
	Twin	1, 2	15–28	120	120	16

[a] Layers of PEx/Aluminium/PE.
[b] Maximum water temperature allowed for less than 110 h/yr [°C].
[c] Maximum water temperature allowed for continuous operation [°C].

An instantaneous DHW heating system consisting of one or more plate heat exchangers (HEs) or units with storage tanks (ST) are the two main options for providing DHW in building installations connected to a DH network. The associated substation influences not only the energy use and the level of thermal comfort of the users, but the overall energy performance of the network and of the heating production plant. It is therefore necessary to plan and design using an integrated approach. In this study we focused on the effect that the DHW unit type has at the network level. Different unit types result in different peak heating loads in the building service pipe, and to the use of different values of simultaneity factors for the calculation of the DHW and SH peak loads when dimensioning the distribution media pipes. Consequently, the design of the network may vary dramatically between a building with an instantaneous DHW system and one with a ST system, where the maximum DH water flow is leveled out by smoother DHW heating loads. The assumptions used when evaluating the differences between the use of HE and ST units were as follows:

- In commercial buildings (area 1a and area 3) the hypothesis is that the peak load is dominated by the SH demand in periods with very low outdoor temperature. Hence the simultaneity factors used during the dimensioning of media pipes serving more than one customer referred only to SH load demand. They were calculated with the following formula:

$$S(N) = 0.62 + 0.38/N \tag{7}$$

Where N is the number of consumer served by the pipe and $S(N)$ is the simultaneity factor applied to the pipe serving N consumers.

- The same as above applies to residential dwellings (part of area 1b and area 2) equipped with ST units. It is assumed that DHW heating has priority over the SH supply, thus avoiding the situation of having simultaneous demand of energy for DHW heating and SH.
- In residential dwellings (part of area 1b and area 2) equipped with HE units, the peak load is due to DHW preparation. A peak load of 32 kW was assumed and the formula below was applied, with regard to peak heating loads including the simultaneity factors [41]:

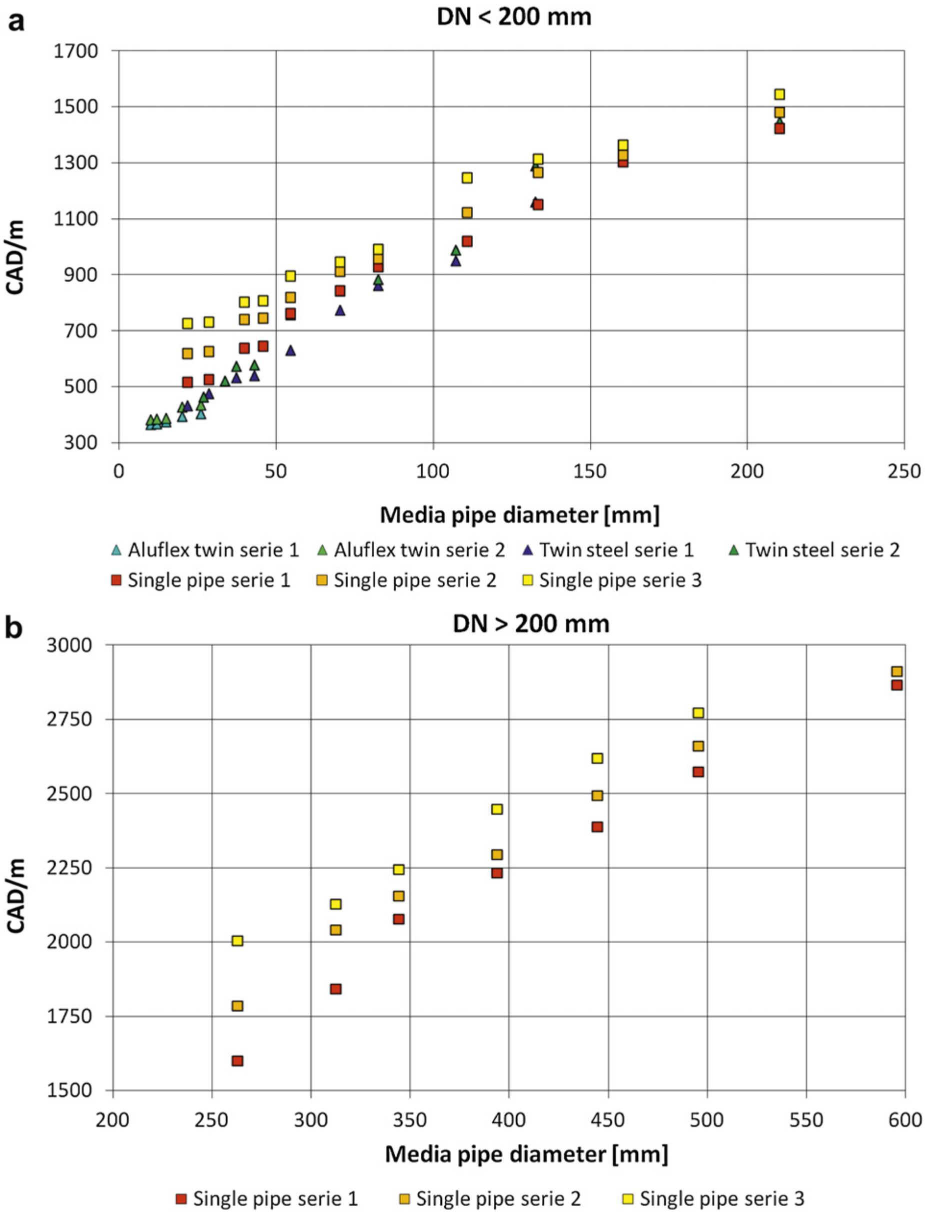

Fig. 9. Specific net present cost for single and twin pipes in a highly-dense urban area in Ontario, Canada; a) single and twin pipes with DN < 200 mm; b) single pipes with DN > 200 mm.

$$Q(N, q_{\max}) = a \cdot N + b(q_{\max}) \cdot N^{0.5} + c(q_{\max}) \text{ [kW]} \tag{8}$$

where Q is the equivalent peak heating load the media pipe must be capable of supply, $q_{\max}$ is the peak heating load of the HE unit (32 kW), $a = 1.19$, $c(q_{\max}) = 13.1(q_{\max}/32.3)^{2.3}$, $b(q_{\max}) = q_{\max} - a - c$.

2.5. Economics

The assumptions used for economic calculations included: return of investment 5%, time horizon 25 years; heat production/purchasing cost $20.50 CAD/MWh (price for the energy utility, assumed equal to the market price of natural gas in Ontario, Canada [43]); utility electricity price $100 CAD/MWh [44]; both the heat and the electricity price were predicted to increase each year linearly as the same percentage rate of natural gas market price, giving a total price increase of 83% over 25 years. The currency exchange rates, the prices and costs were as on 31st October 2011. The aim of the economic analysis was to find the end-user energy price that results in a net present value of zero, with the hypothesis mentioned above and considering the investment and operating costs. The tariff followed the annual rate of increase of the natural gas market price, the heat price and the electricity price. This was equivalent to calculating the end-user heat price that provided the required return of the investment and covered the annual operating costs. The costs could then be related to the typical energy selling prices for DH or other fuels and an assessment made as to whether these differences were important enough to influence the viability of the DH scheme.

2.6. Low-energy density areas

In the context of this paper, a low-energy density building area is defined as such when the heat demand density is below 90 MWh/(m^2 yr) and the linear heat density of the DH network is below 1.2 MWh/(m yr). Buildings in such areas are generally single residential dwellings. Case C, as defined in Table 1, was selected for this investigation. The DH supply in low-energy density areas is generally critical from the economic point of view, due to the relatively high prices of the levelized cost of energy. This is the main reason why DH networks serving building areas with such characteristics operate at present time only in countries with an optimal framework conditions, fundamentally northern or central European countries, and only at some extent. Successful applications must consider socio-economical aspects, such as the cost of energy production, energy and carbon taxes, and environmental awareness, as well as historical and political aspects. These include the responsibility that central and local authorities have in energy planning, the role of utilities dealing with energy supply, and the structure and level of social participation with energy issues. The heating demand intensity in the housing and building sectors is foreseen to decrease in industrialized countries over the next decades. This should be made possible thanks to the implementation of energy savings measures driven by energy policies that make action to enhance security of supply and environmental protection. This further decreases the heating demand density in affected areas and brings up the need to find solutions for effective and efficient heat supplies. We discuss below some of the main concepts that must be taken into account when targeting low-energy density residential areas: the choice of the end-user substation, the design of the distribution network layout, the rate of customer connection and the options to apply suitable operating temperatures.

2.6.1. *Energy transfer station units for DHW heating*

We investigated the effect of the type of end-user energy transfer stations on the network design and total economy. Two in-house units were evaluated: a solution based on ST and a unit with HE for DHW preparation. We considered a direct connection of the building SH system to the DH network.

2.6.2. *Pipeline layout*

Areas with low linear heat demands and high share of service pipes benefit from a careful pipeline route design, which could give valuable capital and operation costs savings. In this analysis we compared the traditional design, with a service pipe serving each building, to what we named “T-connection”, where a service pipe supplies two buildings and to a possible application of the “house-to-house” design [45] (Fig. 10).

2.6.3. *Degree of connection*

The customer penetration, i.e. the rate of end-user connection, is very important in a fully liberalized market, where the end-users cannot be obliged to connect to the network. The costs incurred in developing and operating a DH network include those associated with the distribution piping, the cost of the house service piping, the cost of any utility owned equipment such as energy transfer stations installed within connected houses, as well as the cost of the energy supplied to customers. The specific costs, i.e. the network investment cost per customer for the distribution network and heat losses are heavily dependent on the number of customers connected to it. The specific costs for the substation and service pipes, in contrast, can be supposed to be constant [42]. The feasibility of a new network is affected by how many customers can be expected to connect from the very beginning. There is a lower limit for the rate of customer connection that defines whether a specific project is profitable or not; that can be generalized in terms of linear heat density. Such investigation is important in the preliminary feasibility study because it gives information on the marginal income (utility point of view) and the specific investment savings (customer point of view) per additional connection and could indicate the amount of resources that can be put aside for marketing effort. This is certainly valuable above all in market situations where mandatory connection is not common practice, as it is in North America. Finally, the additional costs for a later connection are often unreasonable for single customers and a high degree of connection is thus very valuable from the very early stages.

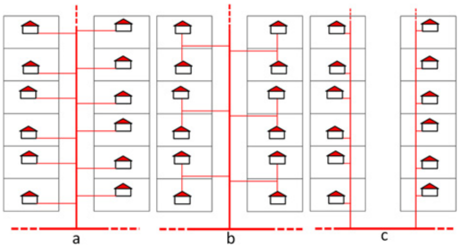

Fig. 10. Sketch of possible designs of service pipelines: a) traditional; b) “T-connection”; c) “house-to-house”.

2.6.4. *Temperature cascading in the network*

From the DH network perspective it is desirable to explore the concept that is referred to here as “temperature cascading”, where the network is divided in two or more sub-systems. Each sub-grid can potentially have specific operating temperatures and flows, so that it matches the exergy requirements of the specific buildings it supplies: the result is an improved system energy-efficiency and an increased opportunity to incorporate RE sources. There are three main options for applying temperature cascading. The first is the use of a mixing shunt on a scheme with a higher operating temperature and using the resultant mixed water to supply a scheme with lower operating temperature. For example, in connecting a MTDH system to a LTDH system, the supply and return flows of the MTDH are mixed and controlled so that the LTDH supply temperature is reached. The second option envisaged the use of one or more HEs where the return temperature is used to pre-heat the supply temperature of a DH network operating at a lower operating temperature. This is particularly applicable to cascading energy between systems that have different pressure requirements. The third concept envisaged the efficient heating of the LTDH supply temperature by a water-to-water heat pump which operates in an open loop, as described in Ref. [30]. In this study we chose to apply the first concept, since it is the simplest and easiest to implement and could therefore be widely put into practice. We selected the network associated with case E, as described in Table 1, as a suitable example for analysis.

2.7. *The planning of “future-proof” DH networks*

The implementation of a DH scheme is capital intensive; the investment affects the energy supply of the community for decades and it remains a key energy element of the energy infrastructure, which must be capable of adapting to the evolving scenario. In fact, DH gives the flexibility of effectively balancing the heat sources and switching among different fuels, as it has historically happened in countries with mature DH systems; from the DH origins with massive use of carbon-emission-intensive fossil fuels such as coal and heavy oil, to the introduction of gas and waste-to energy in a successive period, and the current switch toward RE and low-grade sources. At the same time the heat demand may vary, not only for socio-economic and cultural reasons [19], but also because of stricter building energy regulations, both for new constructions and energy retrofit of existing buildings. In the results section we describe an example of how to best design a DH network that can satisfy the present heat loads and dealing with the future challenge of having a lower heat demand and strict energy-efficiency requirements.

3. Results and discussion

In presenting the findings of this study, we first discuss the choice of piping system, i.e. single and twin piping, media pipe material and level of insulation. Secondly, we examine how the design temperature level affects the network energy performance and economy. Next, after selecting the MTDH as the most suitable concept to be applied at present time, we show the effect of increased supply/return temperature differences, achieved by lower return temperatures: this is in fact the strategy which would give the greatest benefit to a RE-based and excess heat-based heat supply system. Finally, the results focusing on options to address areas with low energy densities are reported.

3.1. Choice of the piping system

The model results highlight the superiority of twin pipe systems over single pipe systems in regards to energy performance and cost, as shown in Table 4. We can therefore conclude that twin pipes should be used wherever possible, leaving the use of single pipes to media pipe sizes larger than DN 200. This is due to the lower installation costs of twin pipes, the casing pipe size being equal. This is particularly true in urban areas, where the installation costs are predominant. Using pipes with series 2 and series 3 insulation would guarantee additional energy savings. However, the results indicate that the economic value of such increased energy savings does not justify the higher investment for using the more highly insulated pipes. The results are independent of the linear heat density of the network. The study of the other areas was then carried out by selecting the proper pipe sizes, among the options given by the twin pipe series 1 group. Under different circumstances, such as different energy prices and construction area characteristics, the results could differ; hence the procedure must be repeated using the correct figures that apply to the specific case.

3.2. Operating temperature levels

Table 5 shows the effect of the operational temperatures on the network design for case B (high linear heat density) and case C (low linear heat density), as described in Table 1. There were three sets of design operational temperature, according to the definition of HTDH, MTDH and LTDH of chapter 2.3.

Table 4
Comparison of distribution heat loss and network investment costs for different pipeline systems in two case studies. Case A: high heat density area; Case C: low heat density area.

Heat demand [GW h/yr]		Pipeline system	Material	Insulation	Heat loss [MWh/yr]	Investment [CAD × 10^6]
Case A	11.4	Single pipes	Steel	Series 1	316.1	1.255
			Steel	Series 2	265.7	1.426
			Steel	Series 3	246.7	1.520
		Twin pipes	Steel/Aluflex	Series 1	205.6	1.151
			Steel/Aluflex	Series 2	164.1	1.265
Case C	8.8	Single pipes	Steel	Series 1	1186.8	5.077
			Steel	Series 2	995.6	6.134
			Steel	Series 3	891.4	7.198
		Twin pipes	Steel/Aluflex	Series 1	735.2	4.155
			Steel/Aluflex	Series 2	604.8	4.449

Table 5
The effect of the operational temperatures on the network design in the areas B and C.

		Design supply/return temperatures [°C]		
		120/70	90/40	60/30
Case B	D_{eq} [mm]	58.2	57.9	59.1
	Heat loss [MWh/yr]	371.3	233.1	184.1
	Pumping energy [MWh/yr]	33.0	36.7	60.9
	Investment cost [CAD × 10^6]	1.360	1.363	1.535
	End-user tariff [CAD/MWh]	28.2	28.0	29.0
Case C	D_{eq} [mm]	28.1	25.9	29.6
	Heat loss [MWh/yr]	1155	735.2	484.6
	Pumping energy [MWh/yr]	35.9	35.0	58.3
	Investment cost [CAD × 10^6]	4.184	4.155	4.421
	End-user tariff [CAD/MWh]	49.8	48.6	50.0

The capital expenditure for medium-temperature operation was comparable to the high-temperature operation case. In fact, the pipes size were equivalent and the only difference was the necessity of using steel or copper pipes in case of high-temperature operation, while plastic pipes could be used in case of medium-temperature and low-temperature operation. Nevertheless, the medium-temperature case was superior to the high-temperature case, in regards to the energy performance, cutting the heat loss by approximately 40% and having similar pumping requirements. This was independent of the energy demand figures of the building area that was supplied by DH. The low-temperature networks achieved even lower heat losses, but they required more energy for pumping purposes and additional capital investment, which was due to the use of larger media pipes in order to overcome the decreased available differential temperature. In a socio-economic perspective the low-temperature operation should be taken into consideration, thanks to the capability of including a larger share of RE and waste or recovered heat, at only a marginal cost for the end-user. We underline that the focus here is on the relations among operational temperatures, energy performance and economic figures from the DH network point of view. In practice, different operation strategies bring different house and building installation systems and different costs for the heat source, which would alter the overall economic figures. Nevertheless, the same methodology can be applied in the specific case, by adding the economic figures for the building SH and DHW installations and the cost of the heat. This would finally enable decision-making based upon a multi-criteria method, where economic, technical, environmental and social aspects must be simultaneously taken into account in a system-wide perspective, including the end-user side, the heat source side, and the DH network in between.

Next, we want to show with an example the benefit of utilizing a medium/long-term integrated approach that includes both the heat demand of the buildings, its future trend and the various options to supply the heat. An essential goal for the policies in energy sustainability is to decrease the energy requirements of the buildings, so it can be foreseen that in the future the heat demand of buildings will dramatically decrease. Let us consider the case C as example, as defined in Table 1, with a future peak load and energy demand that are respectively 2/3 and 1/2 of the present values. During the planning phase to supply the present heat demand with a focus on environmental and energy-efficient issues, the energy planner might choice a LTDH network, which would turn into a sub-optimal solution in a situation where connected buildings undergo major energy retrofits, and thus reducing their overall

Table 6
Information about the DH networks supplying the case studies (A–G).

	Design T [°C]	A	B	C	D	E	F	G
Trench length [km]		1.7	2.2	9.7	3.3	11.3	6.7	15.6
Effective width [-]		17.8	15.4	14.1	30.2	15.2	21.3	17.8
Linear heat density [MWh/(m yr)]		6.8	5.5	0.9	3.8	1.9	3.9	2.3
Heat loss[a] [MWh/(m yr)]	90/55	257.6	294.4	844.7	400.8	1061.0	809.7	1538.1
	90/40	205.6	233.1	735.2	350.2	797.1	692.9	1198.8
Heat loss/energy production [%]	90/55	2.2	2.3	8.7	3.1	4.8	3.0	4.2
	90/40	1.8	1.9	7.7	2.7	3.6	2.6	3.3
Pumping energy [MWh/(yr)]	90/55	40.6	48.8	51.5	49.1	105.4	102.3	145.6
	90/40	19.0	36.7	35.0	45.2	56.7	106.1	99.2

[a] Twin pipe series 1.

thermal energy demand. In fact, the LTDH network that was dimensioned to satisfy the present demand would be over-dimensioned for the future lower demand. It would be more profitable and energy-wise to design a MTDH network for current needs and operate the same network according to the LTDH principle, once the buildings have been energy upgraded. The simulation shows that the present MTDH network can in the future be low-temperature operated, without any major changes in the network. This planning strategy would bring energy savings in the future operation of the network in comparison to the case where the network was low-temperature-designed from the beginning. The network dimensioned for low-temperature operation and the current heat demand would increase the initial investment by 12%. This would increase the heat loss by 17% when supplying the future heat demand, in comparison to the future low-temperature operation of the network that was originally designed for medium-temperature. The conclusions are that the design of DH networks should consider the overall, long-tem development of the heating market, including both the trends in the heating demand and in the heat generation, and that energy-efficiency measures in the energy supply system achieve the full potential only after addressing the possibility of decreasing the heating demand.

3.3. Design operational temperatures

Next, we investigated the effect of alternative return temperatures and supply-return differential temperatures on the network costs and energy performance. We chose to consider the 90/55 °C design (supply/return) as a reference case and investigate the effect of increasing the design differential temperature from 35 °C to 50 °C, giving a design return temperature of 40 °C. Table 6 and Fig. 11 shows how a lower return temperature at a fixed supply temperature guarantees a lower levelized cost of energy, thanks to the savings both in investment and operational costs. Moreover, we can conclude that areas with linear heat density greater than 3 MWh/(m yr) should be supplied by DH, because they are competitive with the existing natural gas supply: the end-user tariffs were calculated as equal or below $32.50 CAD/MWh, while in 2011 the household average price of natural gas was $40 CAD/MWh. We underline that this excludes the costs for the conversion of the building installations, which could alter the overall cost figures. On the other hand, areas with linear heat density below 1.5 MWh/(m yr) are considered not practically feasible with the current situation of the energy market in Canada, but should be considered for future network extensions. The cost penalties of higher supply-return differential temperature may prevail over the reduction of network costs and heat production costs obtained with using lower supply temperatures, from a mere economic point of view. Nevertheless, in a framework where the integration of RE is prioritized, this might be done at a reasonable additional cost, which must be quantified in the specific case and needs further research. We carried out a sensitivity analysis of how the end-user tariff is affected by the variation of the discount rate, the heat purchase costs and the investment costs for the network. The results in Fig. 12 indicate that the end-user tariff is highly-dependent on heat costs and investment costs for heat purchase. It is interesting to notice that the tariff in new DH schemes of medium linear heat density in green field areas – for example the point at linear heat density equal to 2 in the curve where investment costs are half as the reference curve – might be similar to the one in high linear density, urban areas – as, for instance, the points

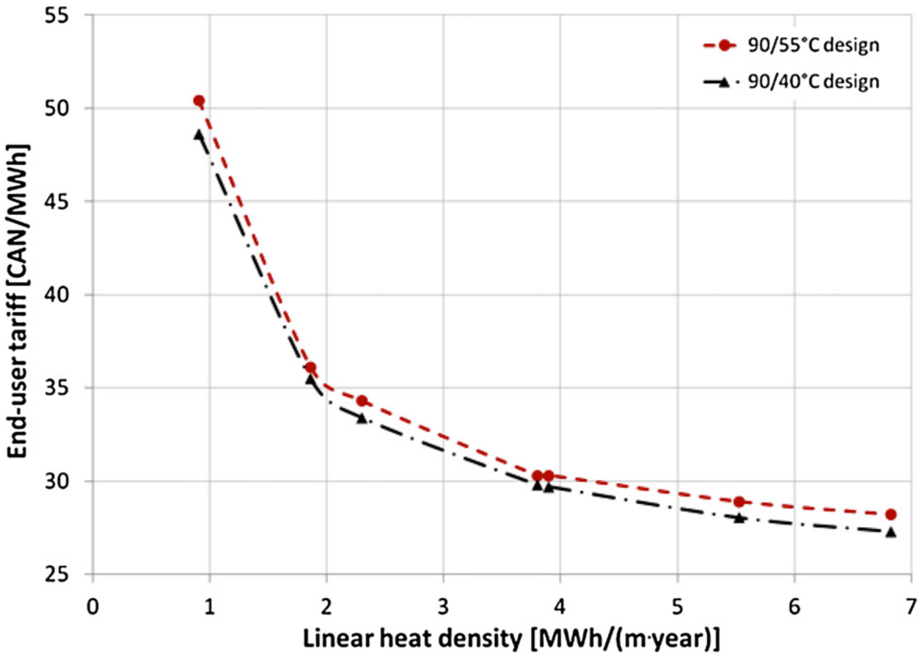

Fig. 11. End-user tariffs as function of the linear heat density.

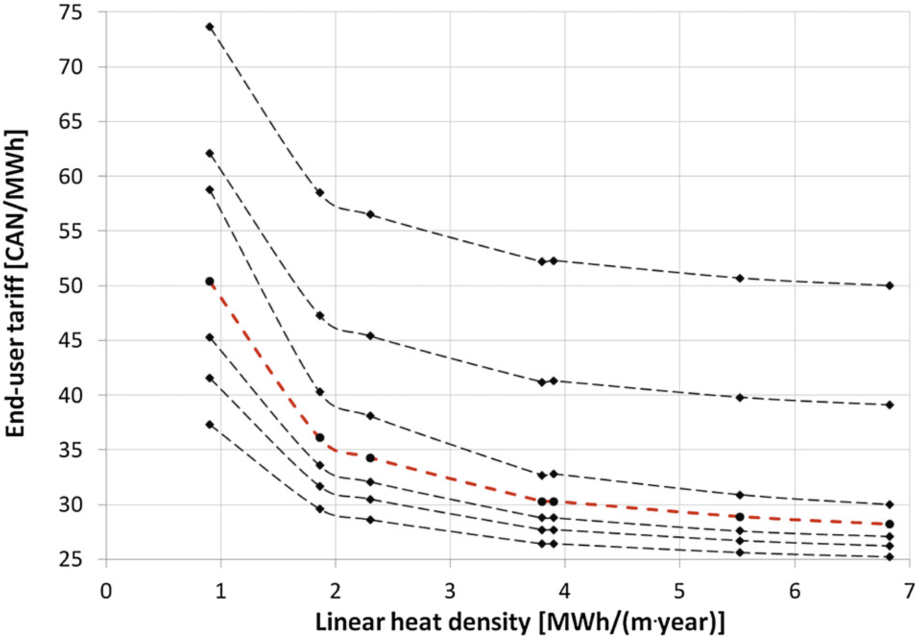

Fig. 12. Sensitivity of the end-user tariff to economic parameters, network investment costs and energy costs. The reference curve (red, dotted line) corresponds to the case with 90/55 °C design temperatures (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

at linear heat density between 5 and 6 MW h/m yr in the reference curve.

3.4. *Options in low-energy density building areas (case C)*

In the following paragraphs we discuss the investigations of the main issues that characterize the DH supply of low-energy density building areas.

3.4.1. *In-house unit for DHW heating*

The end-user tariff is calculated with the assumption that the DH utility owns the energy transfer station or in-house DHW heat transfer unit. This might be an advantageous approach when the conversion of the existing DHW system at the end user's side is a critical barrier, because it decreases the economic investment for the end-user, while it pays back the DH utility investment through a higher specific heat cost for the customers. Under the hypothesis of this study, the scenario with in-house DHW systems using ST units is equivalent to the scenario with HE substations from the economic point of view, because the savings in the pipeline investments are counteracted by greater substation costs for the ST units (Table 7).

3.4.2. *Pipeline layout*

The share of service pipes in the total pipeline length is 65% for the traditional-layout case, as depicted in Fig. 10, which indicates the potential for route optimization. The house-to-house connection avoids additional excavation work for the installation of service pipes, and results in a reduction in total trench length of 23% compared to the traditional layout, see Table 8. Nevertheless, it is hardly applicable, because of the issues related with dealing with a multitude of property owners during implementation and maintenance. The "T-connection" achieves savings in capital and operational costs in comparison to the traditional layout and it is more practical than the house-to-house concept. Moreover, it makes better use of the heat load capacity of the service pipes, e.g. it increases the usage of the service pipes in terms of kW h/(m yr), which is valuable outside the heating season. The suggestion is particularly interesting in applications for new developments in green field zones, where the piping layout can be planned together with the layout of the buildings and the other infrastructure.

Table 7
Comparison of in-house substations for single-family buildings.

		Storage tank	Heat exchanger
D_{eq} [mm]		25.9	29.6
Heat loss [MWh/yr]		735.2	788.6
Pumping [MWh/yr]		35.0	22.2
Investment [CAD × 10^6]	Network	4.16	4.33
	Substation units[a]	0.842	0.704
End-user tariff [CAD/MWh]		53.7	53.8

[a] HE unit with direct connection of SH: 1730 CAD/unit; ST unit with direct connection of SH: 2070 CAD/unit; excl. taxes and installation.

3.4.3. *Degree of connection*

Fig. 13 shows how the final users' connection rate affects the distribution heat loss and the tariff for the customers. The curves follow a linear pattern for connection rates greater than 60% and an exponential one at lower percentages, likewise occurred in Refs. [19,45]. Heat planning is therefore necessary, since the DH distribution is already critical in low heat density areas, at current market conditions, and uneconomical in cases of partial customer connection.

3.4.4. *Temperature cascading in the network*

Model case E, as defined in Table 1, consisted of two zones: a zone with mainly commercial buildings and high thermal loads (1b) and a low energy density residential area (2). We explored the possibility of integrating MTDH in the commercial zone ($T_{supply, design} = 90\ °C$) with LTDH in the residential zone ($T_{supply, design} = 60\ °C$). A shunt mixes the supply and return water of zone 1b and then supplies the zone 2. Table 9 reports the essential results. On one hand, the integration of MTDH and LTDH requires approximately 4% additional investment in the network and has potentially higher retrofit costs at the house level due to larger heat transfer surfaces; on the other hand, it saves both operating costs (heat

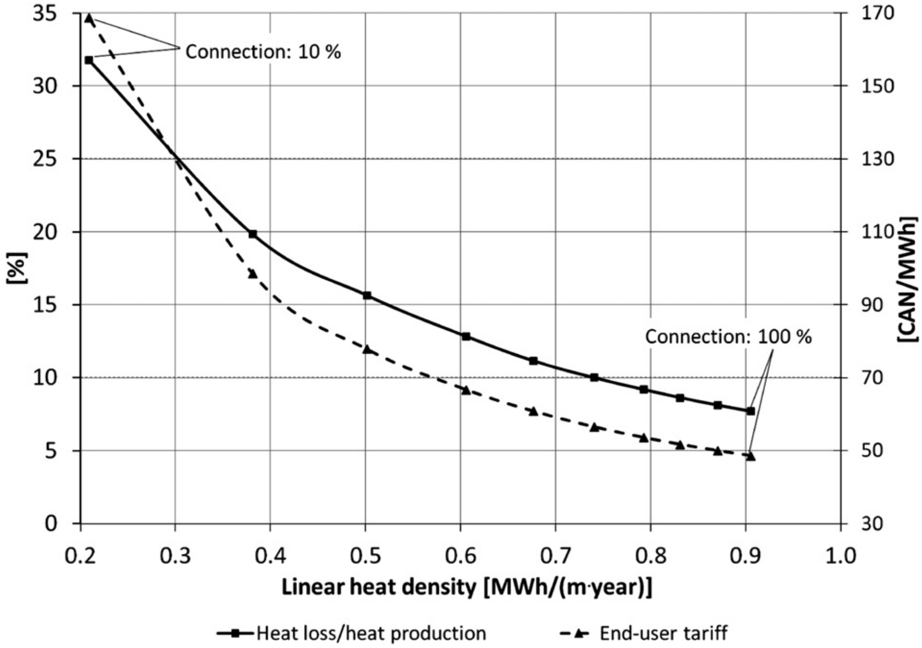

Fig. 13. Degree of connection in the single-family house settlement (area 2, case C). Energy performance and specific network investment cost as functions of the linear heat density. Heat production at 100% connection rate: 8.81 GW h/yr; trench length at 100% connection rate: 9736 m.

Table 8
Effect of alternative service piping layouts in a single-family, low energy density area.

	Traditional	T-connection	House-to-house
Trench length [m]	9736	8688	7462
Effective thermal width [−]	23.1	25.9	30.2
Linear heat density [MWh/(m yr)]	0.9	1.0	1.2
Heat loss/energy production [%]	7.7	7.1	7.1
End-user tariff [CAD/MWh]	48.6	46.3	44.2

Table 9
Integration of MTDH and LTDH with a mixing shunt. Comparison with a reference MTDH network.

$T_{\mathrm{supply}}/T_{\mathrm{return}}$ [°C] (zone 2)	Heat loss [MWh/yr]	Pumping [MWh/yr]	$T_{\mathrm{return,plant}}$ [°C]	Investment cost [CAD × 10^6]	End-user tariff [CAD/MWh]
90/40	797.1	56.7	39.9	5.166	35.5
60/30 with shunt	705.0	43.7	36.4	5.352[a]	35.8

[a] Excl. the investment cost for the mixing shunt.

distribution and pumping energy) and heat generation costs, thanks to the 3.5 °C yearly-averaged, lower return temperature at the plant. Consequently, the strategy of assigning the lowest suitable operating temperatures in different zones of a DH network helps realize energy-efficient measures and the integration of RE/low-grade heat sources with reasonable economy.

4. Conclusions

The importance of the thermal component of the energy use and the impact of integrating thermal energy and land use planning has been underestimated in Canada. The main reason has been that the limits of sustainable community developments are masked by relatively low energy costs and by nil or low carbon pricing. There is need of improving the understanding at the municipal level of how integrated community energy solutions are introduced, implemented, and sustained The leadership in the local authorities is critical to the success of DH projects, indeed. DH must be part of the strategy to help municipalities achieve their objectives toward energy sustainability.

First, the results of the case studies examined enable us to conclude that the use of twin pipes for DH distribution and service piping should be preferred in urban areas where possible. The use of single pipes should be left to media pipe sizes larger than DN 200. Secondly, the MTDH had better energy performance than HTDH, decreasing the heat loss by approximately 40% and having similar pumping requirements: this was independent of the characteristics of the building area supplied. The low-temperature networks achieved even lower heat losses, but they required more energy for pumping purposes and additional capital investment due to the use of larger media pipes needed to overcome the decreased available differential temperature. In a socio-economic perspective the LTDH should be taken into consideration, due to the capability of including a larger share of RE and waste or recovered heat, at only a marginal cost for the end-user. Next, the simulation results show that MTDH networks can be implemented to serve current heating loads while enabling flexibility to provide energy needs in the future, after energy saving initiatives have been widely implemented in the buildings, to be low-temperature operated, without any major changes in the network. This planning strategy decreased the capital investment in the case study by 12% and heat losses by 17% in the future operation of the network in comparison to the case where the network was originally designed according to low-temperature operation. This highlights that energy-efficiency measures in the energy supply system achieve the full potential only after the possibility of decreasing the heating demand has been addressed.

The areas with linear heat density greater than 3 MWh/(m yr) could be supplied by DH, because they are competitive with the natural gas supply alternative and offer the opportunity of implementing the use of RE and low-grade heat sources. We underline that this excludes the costs for the conversion of the building installations, which could alter the overall cost figures. On the other hand, areas with linear heat density below 1.5 MWh/(m yr) are considered not practically feasible with the current situation of the energy market in Canada, but should be considered for future network extensions. There are design and planning concepts that can enhance the profitability of DH supply to those areas. We demonstrated that the "T-connection" of service lines achieves savings in capital and operational costs in comparison to the standard layout and it is more practical than the "house-to-house" concept. Heat planning by local authorities is required and should be complemented by provincial and federal policies, being the DH distribution critical in cases of partial connection of the customers. Assigning the lowest suitable operating temperatures in different zones of a DH network helps realize energy efficient measures and integration of RE/low-grade heat sources with reasonable economy. In the case study, for example, the integration of MTDH and LTDH by a mixing shunt required approximately 4% additional investment and saves both operating costs (heat distribution and pumping energy) and heat production costs, thanks to the 3.5 °C yearly-averaged, lower return temperature at the plant. Under the hypothesis of this study, the scenario with ST units is equivalent to the scenario with HE substations from the economic point of view, because the savings in the pipeline investments are counteracted by the greater costs for the ST energy transfer units.

A general conclusion is that DH can be widely implemented in urban areas in Canada with reasonable economy, but must be quantified for the specific case conditions. The process should begin with the most attractive areas, i.e. the ones with the highest potential linear heat density and thermal effectiveness. With the implementation of MTDH networks, the future lower building demands must be taken into account, preparing the networks for low-temperature operation and extension to areas with lower heat densities. This needs strong political support, since, in turn, it places DH as a fundamental energy infrastructure and as part of the solution for the integration of RE and energy sustainability in a community.

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