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LOW TEMPERATURE DISTRICT HEATING NEWTORK PLANNING WITH FOCUS ON DISTRIBUTION ENERGY LOSSES

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ABSTRACT

An integrated conceptual planning framework has been developed to assist designing for high resource efficient, low carbon urban district heating systems. This paper focuses on distribution energy losses of a district heating system for an existing urban settlement. The planning framework consists of a methodological approach and a set of simulation tools to investigate two scenarios – low temperature and high temperature district heating networks. In this framework a dynamic building simulation program predicting energy demand of a case study area, an industrial software tool for piping systems design, and a mathematical optimization tool are integrated for assessing energy and exergy losses. Some preliminary results are shown at the end of the paper demonstrating the benefits of low temperature district heating networks and potential of the planning framework.

Keywords: ***low temperature district heating, distribution heat losses, building energy demand, urban heat maps***

1 INTRODUCTION

District heating has been considered as an environmental friendly and financial favourable option opposed to individual heating system. Potential benefits of district energy systems include reduced operational complexity of heating systems, safer operation, reduced space requirements for building owners and tenants, and possibility of greater control of heating fuels at communities and societal level, such as utilization of solar thermal energy, industrial waste heat, waste heat from CHP. Currently penetration of district heating (DH) into the heat market varies by country, for example, ranging from around 50% in Demand, Sweden and Finland, around 15% in Germany and to around 1-2% in the Netherland and the UK (authors' estimation based on various resources). Uptake of district heating is influenced by many different factors including density of buildings in the area, environmental conditions, and availability of heat sources, economic and legal framework. Nevertheless, some technical and economic barriers identified for implementing district heating systems includes the following concerns.

- Significant heat losses formed in transportation and due to sparse buildings stocks and the distance between heating power plants and end users.
- Substantial capital investments such as pumping systems which are usually have longer life spans than building heating equipment.

Those concerns prevent low carbon retrofitting of existing building heating systems. In responding to the challenges, a new integrated framework has been developed in this research to support informative decision making in the design process. In particular, low temperature district heating is investigated against the hypothesis of its greater potentials in improving heat distribution efficiency and minimizing exergy losses.

In order to deliver a highly efficient and low carbon urban energy system, urban energy designers often have to face great challenges in carrying out inter-disciplinary research. In this new framework, integrated technical analysis can be carried out to assist planning for a low carbon district heating system. Heat losses, pumping electricity consumption, and exergy efficiency (1,7) are the indicators for assessing heating systems are tested. This framework can provide a systematic, transparent, and efficient manner to select an option out of a limited number of alternatives.

2 METHODOLOGY - A CONCEPTUAL FRAMEWORK

2.1 System structure of the framework

In this research, a conceptual planning framework based on integrated simulation platform is established to evaluate operational performance of the energy system. An overview of the methodological framework applied in this research is illustrated as in figure 1. The main components in the framework can be divided into two main parts: operational side and analytical side. This framework is based on an integrated hourly simulation. In the operational side, energy demand, supply and whole energy system performance can be modelled and then data can feed in the integrated analytical process.

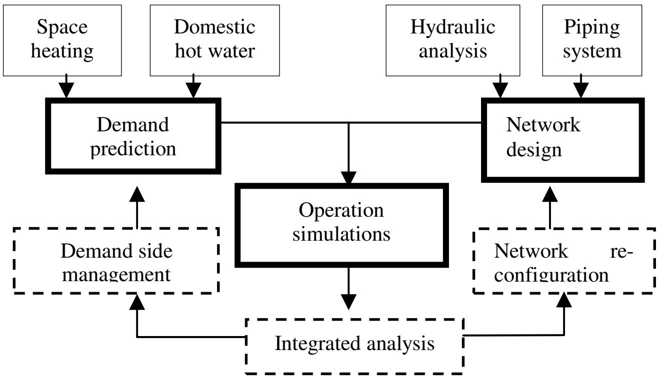

Figure 1: An Integrated Planning Framework

2.2 Energy demand predictions

Different buildings types have different occupation patterns, e.g. civic and schools building are occupied mostly during day time and residential building usually during night times, and thus heat demands vary accordingly. Typical design year (TRY) is usually used predict building energy demand. However, more robust methods preparing for extreme cold winter scenarios need to be taken into considerations for detailed heating systems design. Diversity of energy usage patterns is a critical element when predicting energy demand of a heating network. A number of methods are available to model the impacts of diversity. One simplified method is to use an average or "typical" load profile and scaling it to suit the project based on an assumption that the probability of the peaks in energy demand of large hot water draw off occurring at the same time is quite small. Another option explored in this research is the use of a dynamic simulation tool to create the demand profile, such as HTB2 (2).

2.2 Heat supply networks and heat losses

A range of techniques are available to reduce energy demand such as improvements of building insulations, ventilation controls, and equipment efficiencies. A number of researchers (3) have investigated impacts of demand side management on energy systems, such as demand reduction, energy storage and match demand to supply. Apart from demand side approaches, infrastructure re-configuration is critical for developing future urban heating networks. Urban cascading heating energy systems, and utilisation of industrial waste heat are considered as promising methods to re-configure urban energy systems. The concept of the energy cascading means that the heat is multistage utilisation of heat energy. For example, the energy at temperatures over 1000°C obtained by burning fuel is firstly used for electricity generation, then steam for heating process is produced by the discharged heat from the electricity generation. The heat from this stage further satisfied heating demand of lower temperature usually required.

Energy losses from distribution pipeline network significantly affect the advantages of heating system (5,6,7). Thus, heat losses from distribution networks should be modelled and minimized. Heat loss formed in a channel at a certain instant of time is modelled as in the following equation *E1*, where T_{out} is calculated in equation *E2.*

$$Q_{loss}=c_p m\,(T_{in}-T_{out}) \qquad E1$$

$c_p =$ *specific heat capacity (J/kg°C)*
$m =$ *mass flow rate (kg/s)*
$T_{in}=$ *Pipe inlet temperature (°C)*
$T_{out}=$ *Pipe outlet temperature (°C)*

$$T_{Out}=(T_{in}-T_g)e^{\frac{\lambda l}{m c_p}}+T_g \qquad E2$$

$l =$ *pipe length (m)*
$T_g=$ *Ground temperature (°C))*

λ = heat transition coefficient (W/m °C)

The ideal hydraulic power to drive a pump depends on the mass flow rate, the liquid density and the differential height; either it is the static lift from one height to another, or the friction head loss component of the system, or it can be calculated as in E3

$$P_h = q\,\rho\,g\,h / (3.6x10^6) \qquad E3$$

where

P_h = power (kW)
q = flow capacity (m^3/h)
ρ = density of fluid (kg/m^3)
g = gravity (9.81 m/s^2)
h = differential head (m)

2.3 Exergy analysis

In terms of energy system assessment, it is generally accepted that the concept of the first law of thermodynamics is used when comparing different heating sources providing similar heat outputs. Therefore, the energy efficiency, defined according this first law, tends to be the only indicator used in practice. Energy analysis, however, does not reveal imperfection of energy conversion system, where high quality energy is converted into low quality heat. In this case an additional analysis – exergy analysis – has to be used. Exergy analysis provides an alternative measurement to improve performance of complex energy systems. The authors argued that both energy and exergy (as a standard of energy quality) need to be used for system analysis in order to see the full picture

According to the first law of thermodynamics energy cannot be created or destroyed. Therefore energy inputs to the buildings, such as: heating, cooling or electricity are exactly the same as the outputs under steady-state conditions, or including energy storage in a dynamic system. Energy supplied to the building in the form of heat is used to compensate the energy transfer from the walls to the environment and due to ventilation. In energy terms the efficiency of such system is 100%. However, the quality of the supplied heat to the building is higher than the quality of the heat which is transferred to the environment, because the temperature is higher. This quality can be assessed using exergy analysis. The exergy of the input heat is calculated:

$$E_{in} = (1 - T_0/T_{in})Q_{in} = \tau_{in}Q_{in} \qquad E4$$

$$E_{out} = (1 - T_0/T_r)Q_{out} = \tau_r Q_{out} \qquad E5$$

Here T_0 is the refererence environment temperature in Kelvins, T_{in} is the the temperature of the heat source and T_r is the room temperature (K). Assuming that input heat Q_{in} and output heat are equal Q_{out} the output exergy is calculated:

$$E_{out} = (\tau_r/\tau_{in})E_{in} \qquad E6$$

As exergy is not conserved the exergy destruction is calculated:

$$E_D = E_{in} - E_{out} = E_{in}\,(1 - \tau_r/\tau_{in}) \qquad E7$$

Exergy efficiency is calculated:

$$\Psi = E_{out}/E_{in} = 1 - E_D/E_{in} \qquad E8$$

In the above example “energy losses” do not exist, as all energy (heat) is used for space heating and there are no unaccounted energy which would not be used for the sole purpose of space heating. Therefore, exergy losses associated with energy losses also do not exist, but is only destroyed as explained above.
When exergy analysis is applied for district heating networks, the situation is different. The main purpose of exergy analysis is to calculate the exergy losses associated with energy losses. The exergy losses are calulcated using the equation (E4):

$$E_L = (1 - T_0/T_w)Q_L \qquad E9$$

Here T_w is the the temperature of the district heating water (K) and Q_L is the heat energy loss. Water temperature in the DH system is calculated as logarithmic mean temperature:

$$T_w = (T_{win} - T_{wout})/ln(T_{win}/T_{wout}) \qquad E10$$

Here T_{win} and T_{wout} are the inlet and outlet water temperatures of the district heating water in a the pipe segment (*K*).

3 A case study – designing a synthetic district heating system

3.1 Site and energy demand predictions

Currently only around 1.5 % of UK heat demand are met by district heating. Analysis shows that in the right conditions, district heating could supply up to 14% of the UK heat demand (8). A case study is carried to investigate the potential of low temperature district heating in UK climate with a focus on distribution energy losses; the site chosen is located in South Wales. The building stock on site consist of two public buildings (a primary school and a civic centre) and 300 residential houses (mainly on a south facing hills), and 50 shops fronts as shown in figure 2.

Figure 2: A case study site in South Wales, UK

Heating energy load profiles of the buildings vary depending on many factors such as building orientations and fabrics, occupant's behaviour. It is beneficial for district heating system to supply relatively constant heat throughout the year. Appropriate simulation of demand patterns could possibly provide more realistic predictions. In this research, a dynamic building performance simulation tool HTB2 (2) is used to predict energy demand for space heating. Due to different occupancy profiles, residential, schools and shops have different space heating patterns as shown in figure 3. Domestic hot water (DHW) is a very import aspect in designing a district heating system. Diversity of DHW demand needs to be taken into account when loads are combined for a multi-unit building. However, there is a lack of research in diversity of hourly domestic hot water demand. Based on a range of literature (9,10,11), generic profiles were generated in this paper as shown in figure 4 indicating different DHW consumption features of three types of building.

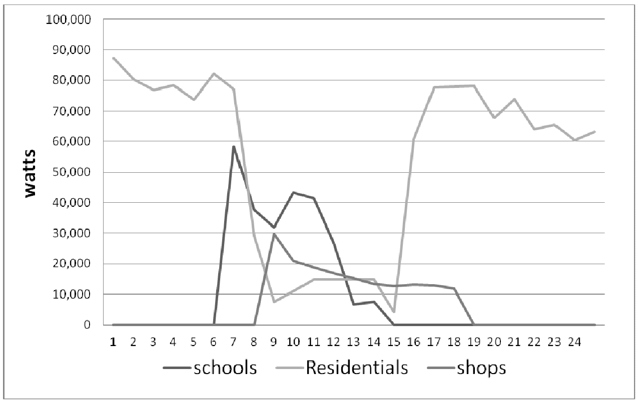

Figure 3: Hourly total heat energy demand of three types of properties in a winter day

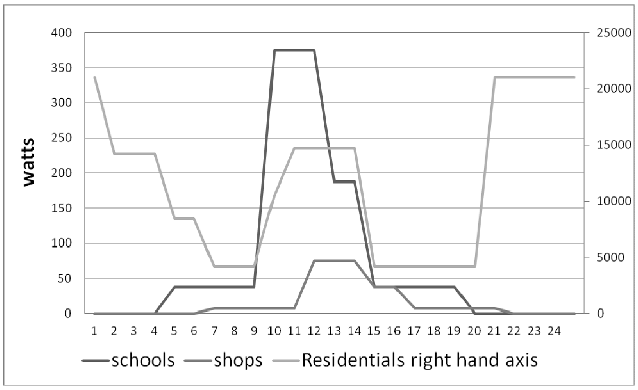

Figure 4: DHW heat demand of three types of properties (Residential street with the right hand Y Axis, School and shops with the left hand Y Axis)

The relation between energy demand and energy supply is very important. In order to simulate the heat energy supply in DH system in the area, different energy consumption patterns of buildings has to be taken into account and diversity factor has to be used. Total hourly energy demand (space heating and domestic hot water) are produced as in table 1. Average hourly demand in each day as shown in figure 5.

Table 1: Total energy demand in a typical weather year

	Space heating (kWh)	DHW (kWh)	Total (kWh)
Civic	70,177	1,300	71,477
Residential	2,729,318	1,148,961	3,878,279
Shops	69,520	900	70,420
Total	2,869,015	1,151,161	4,020,176

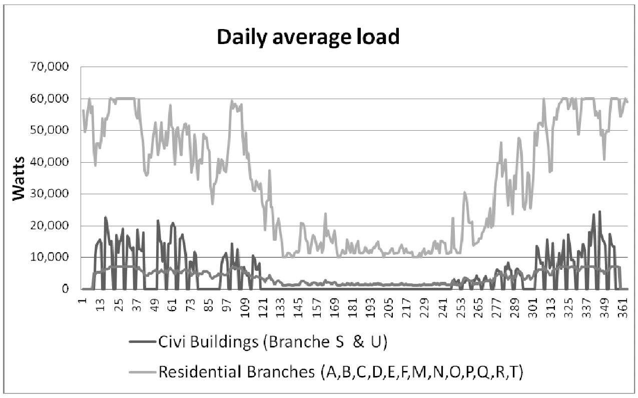

Figure 6: Average hourly heat energy demand of the total building stocks on the site in a year

3.2 Network Design

A distribution network is developed according to the site plan using Google Sketchup® net feature - geo-location with Google Maps to provide maps and topography shown in figure 7, branch name and length are shown in figure 8. In total there are 21 branches in this synthetic heating network. Table 2 shows the peak load for each branch, and figure 9 shows the load duration curve profile for calculation heating supply and heat losses.

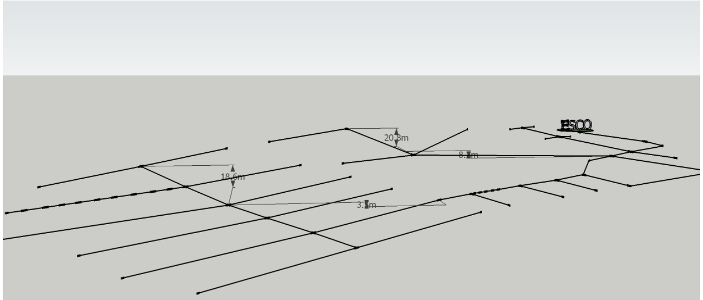

Figure 7: Distribution network in Sketchup

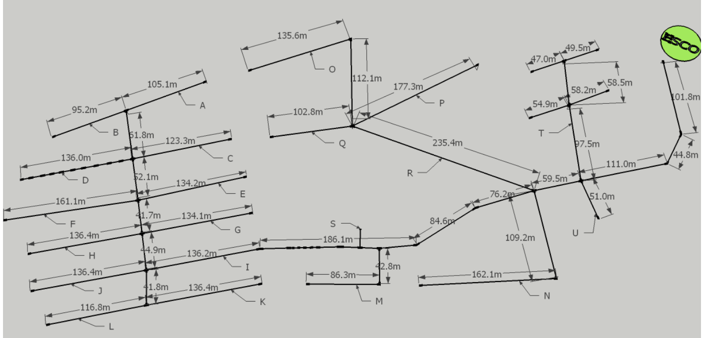

Figure 8: A Schematic view of the distribution network

Table 2: Branch Peak Load

Branch name	Types of building	Peak load KW
A	Residential	80
B	Residential	76
C	Residential	96
D	Residential	96
E	Residential	96
F	Residential	96
G	SHOPS	96
H	SHOPS	96
I	SHOPS	96
J	SHOPS	96
K	SHOPS	96
L	SHOPS	96
M	Residential	100
N	Residential	88
O	Residential	120
P	Residential	100
Q	Residential	100
R	Residential	100
S	Civic	150
T	Residential	100
U	School	150

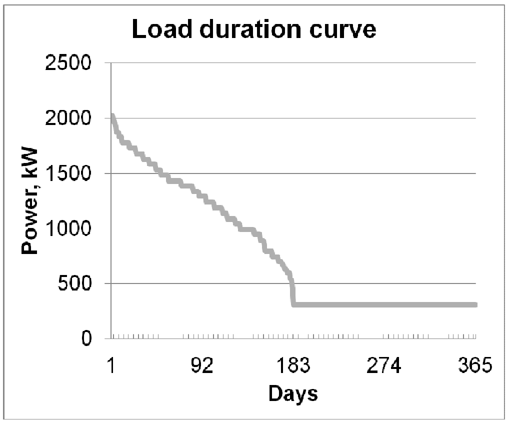

Figure 9: Load duration curve

PSS SINCAL heating software (12) was used to design the low temperature DH (LTDH) and high temperature DH (HTDH) systems. It was assumed that pipes were laid in the ground. An average constant ground temperature of +7℃ was used in our calculations. Both LTDH and HTDH systems were designed using target pressure loss value of 200 Pa/m (13). Selected pipe diameters were used as input to the optimisation model. Calculations of heat loss and pump energy consumption were conducted using FICO^{TM} Xpress optimisation tool.

3.3 Optimization model

FICO^{TM} Xpress software was used to find the optimum supply temperature and mass flow rate in the DH system. The optimisation model was formulated as a nonlinear objective function with nonlinear constraints. FICO^{TM} Xpress optimisation tool allows the modelling and solving of large and complex optimisation problems. In this study, successive (sequential) linear programming (Xpress-SLP) was used. Xpress-SLP is a solver for nonlinear optimisation problems. It uses successive linear approximation which has been developed from techniques used in the process industries and it can solve large problems with many thousands of variables [12].

The objective of the optimisation model is to minimise total electrical energy consumption and heat losses in the DH network. The optimisation objective function is:

$$\min\ E = \sum_{t=1}^{n} \left\{ 24 \times \left(P_{p,t} + Q_{loss,t} \right) \right\} \qquad E11$$

Optimization constraints are supply temperature, flow rate and pressures loss. Supply and return temperatures in the pipes are set within these limits:

$$T_{s,\min} \le T_s \le T_{s,\max} \qquad E12$$
$$T_{r,\min} \le T_r \le T_{r,\max}$$

Here $T_{s,min}$ = 70℃, $T_{s,max}$ = 120℃, $T_{r,min}$ = 40℃ and $T_{r,max}$ = 70℃ for high temperature DH system during the winter season, and $T_{s,min}$ = $T_{s,max}$ = 70℃, $T_{r,min}$ = $T_{r,max}$ = 30℃ during the summer season. For low temperature DH network $T_{s,min}$ = $T_{s,max}$ = 70℃, $T_{r,min}$ = $T_{r,max}$ = 30℃ temperatures for the whole year were used. These temperature limits are used in traditional DH networks and depends on the DH system design. The flow rate in the system was set to be within minimum and maximum limits:

$$\dot{m}_{\min} \le \dot{m} \le \dot{m}_{\max} \qquad E13$$

The total pressure loss in the DH system did not exceed the maximum differential pressure of pump.

$$\Delta p_p \le \Delta p_{p,\max} \qquad E14$$

The optimisation model was validated using the commercial software PSS SINCAL (12).

Based on the calculated results the heat loss and electrical energy for pump were calculated. Two cases were investigated: high temperature district heating (HTDH) system (120°/70°) and low temperature district heating (LTDH) system (70°/40℃). Supply temperature varied between 70° and 120℃ in HTDH system.. The variation of the return temperature was between 40℃ and 70℃ during the winter season. During the summer season constant supply and return temperatures were set to 70° and 30℃.

In the LTDH system the supply and return temperatures were set at constant 70℃ and 40℃ respectively over the year. Flow rate varied according to the heat demand. Constant supply temperature was chosen, because in the DH system heat was used for two purposes: heating and domestic hot water (DHW) system. The temperature in the internal building heating system can be low (for example 30-35°). But it cannot be reduced in DHW system due to the risk of legionella. The minimum required temperature for DHW system is 55℃. Therefore, taking into account heat losses and required temperature difference at the users heating substation, the optimum supply temperature of 70℃ was chosen.

Flow rate also varied in both systems depending on the heat demand. The optimal operating regime was found using the optimisation. Heat loss in each pipe section was obtained using equations E1 and E2.

The total heat loss in the DH pipe network was found as the sum of heat losses in each pipe section. Pump power (kW) was calculated using equation 15:

$$P_p = \frac{\Delta p_p \dot{m}}{1000 \rho \eta_p} \qquad E15$$

Here Δp_p – pressure drop in the pipe network, Pa; m – mass flow rate, kg/s; ρ – water density, kg/m^3; η_p – pump efficiency.

When the supply temperature cannot be reduced due to limitation for DHW system the only variable which can be changed in order to meet the energy demand is the mass flow rate. Therefore, using constant supply temperature the LTDH system operates in Variable Flow Constant Temperature (VFCT) regime. It is different for HTDH system. The supply temperature in the HDTH can vary between 70°C and 120°C and mass flow also varies. Therefore, the optimisation technique allows us to calculate the optimal supply temperature and mass flow rate. The calculation shows that using HTDH approach the system operates in Variable Flow Variable Temperature (VTVF) regime. It is worth to note that the LTDH can also operate in VTVF regime if higher supply temperature is used. For example the LTDH would operate in VTVF regime if $70° < T_s < 80°$ were chosen. Heat load duration curve for DH network was calculated using the heating degree days and constant base temperature of 15.5°C. Therefore, although this method is extensively used for planning of DH systems, it does not show the real buildings energy demand in a typical weather year (as in Table 1). In most cases it overestimates the energy demand. More investigations are needed in order to study how the variable energy demand in buildings could be met using DH network in the most efficient way.

In this study optimised supply and return temperatures and mass flow rates were calculated. The results are shown in figure 10. It can be seen from the figure 10 that in optimised HTDH system the mass flow rate is higher than that of LTDH. The reason for that are high supply and return temperatures and as a consequence of that – high heat losses. In order to reduce heat losses the optimiser reduces supply and return temperatures within the set limit. Due to this reduction the mass flow rate has to be increased in order to meet the energy demand. Therefore, in the HTDH system both temperatures and the mass flow rate are higher than that of the LTDH system.

Heat loss duration curve and pump power load duration curve are shown in figure11. As it is expected heat losses and pump energy consumption are higher in the HTDH system compared with the LTDH system. During the summer time the mass flow rate is reduced significantly and pump power decreases.

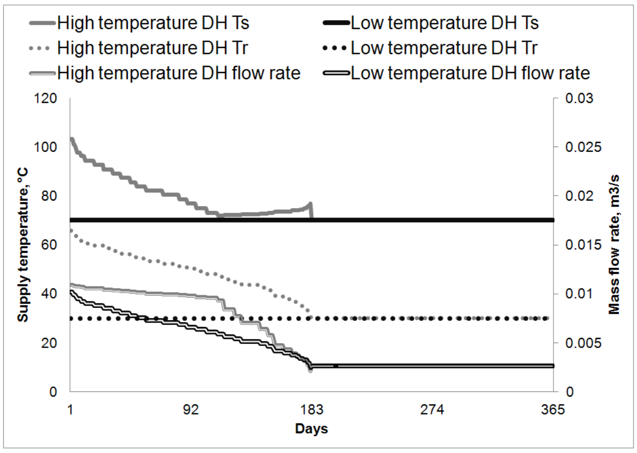

Figure 10: Supply temperature and mass flow duration curves duration curves

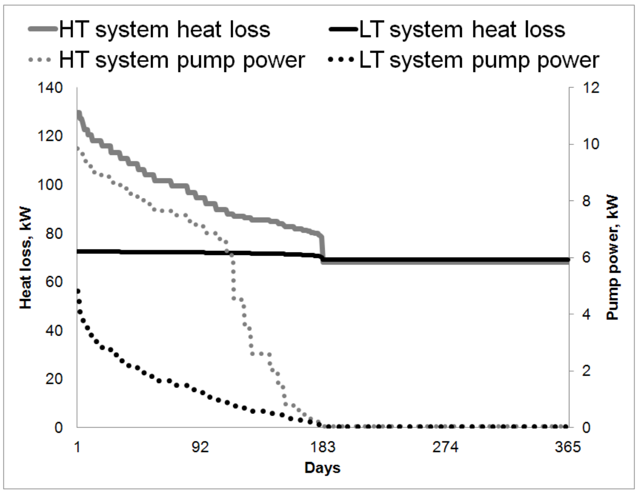

Figure 11: Heat losses duration and pump power load curves

Summary of heat losses and electrical energy consumption for pump in the LTDH and HTDH systems are presented in Table 3. It can be seen that the energy loss fraction of total delivered energy is only 11% and 9% for the HTDH and LTDH systems respectively. The reduction of energy loss by circa 17% is observed in the LTDH system compared with the HTDH system. The reduction by 58% (18 MWh/year) in electrical energy consumption is even more significant.

Table 3: Energy losses

	Heat energy loss MWh/year	Electrical energy loss MWh/year	Total loss MWh/ year	Total delivered	fraction of distribution energy losses
HTDH	734.7	31.4	766	4020	19.1%
LTDH	621	13	634	4020	15.8%
saving	114	18	132		

Given the world's finite natural resources and growing energy demands, it is increasingly important to understand resource usages to improve systems while reducing environmental impact. In order to examine the difference in the material usage in the LTDH and HTDH piping systems, an embodied energy calculation exercise is carried out. Based on an UK-based database for embodied energy and carbon emission (15) and recent studies on embodied energy calculation methodologies (16), average embodied energy values for each material within the pipe network is applied to the system. According to (15), embodied energy values for these materials can vary by +/- 35%, depending on several variables, such as processing techniques. Average value from a UK database (15) is used for this paper. The calculation results can be seen in table 4, with the LTDH requiring 35 MWh more embodied energy than the HTDH, which is compared with 114 MWh of operational energy savings in a year. That is, the operational energy savings of the LTDH system covers the material embodied energy investment in less than four months. This demonstrates the benefits of LTDH from the perspective of embodied energy in distribution pipes.

Table 4: Embodied energy of pipes

Embodied Energy	LTDH	HTDH	Difference
Steel in pipes (MJ)	1,027,898	917,695	110,203
Mineral Wool in pipes(MJ)	54,793	48,403	6,390
PUR in pipes (MJ)	193,629	181,959	11,670
Total Embodied Energy (MJ)	1,276,320	1,148,057	128,263
Equivalent in MWh:	354	318	35

3.4 A scenario with 20% energy demand reduction

End-use energy savings and the expansion of district heating are often discussed to heating sector more sustainable (14). However, there is very little research in assessing magnitudes of its impacts on energy losses during distribution. The authors investigated a scenario with 20% demand reduction (reduced from 6893 MWh/year to 5515 MWh/year). The calculations are presented in Table 5. It can be seen that very limited impacts on reduction in heat losses in heating distributions, however significant reduction in terms of electrical energy consumptions. Total losses only realized 2.3% and 1.7 for HTDH and LTDH respectively. However, in the energy reduction scenario, mass flow and pressure reduced lead to significant pumping energy consumptions (20 % and 54% for HTDH and LTDH respectively). However, electricity and heat energy has different carbon emission factors. Quality of energy in terms exergy is introduced in the next section offering a method to address this issue.

Table 5: Energy losses in 20% demand reduction scenario

	Heat energy loss MWh/year (% of reduction)	**Electrical energy uses MWh/year** (% of reduction)	**Total loss MWh/year** (% of reduction)	**heat delivered with 20% reduction MWh/year**	**Energy loss fraction**
HTDH	723 (1.5%)	25 (20%)	748 (2.3%)	5515	13%
LTDH	617 (0.6%)	6 (54%)	623 (1.7%)	5515	11%

3.5 Exergy losses analysis

Exergy losses is an alternative indicator to is be used for this purpose. Heat losses during the transport of hot water (supply and return) through pipes cause exergy losses, as shown in the following equation for calculating exergy losses formed form heat losses (4):

$$Ex_{loss}= (1-To/Tw)Q_{loss} \qquad E\ 16$$

where T_O is the reference temperature, (here ground temperature at 7 ^{o}C is used), T_w is the logarithmic average temperature of the supply pipeline T_{win} and return pipeline T_{wout}, calculated using equation (E10). It can be seen from table 6, the LTDH produced heat saving 15% of HTDH, and exergy saving 53%. The more appealing results based exergy analysis will help promoting LTDH to wider audience.

Table 6: Simplified exergy loss calculation

	HTDH	LTDH	Saving
T_0 (k)	280	280	
Ts (k)	393	343	
Tr (k)	343	303	
Tw (k)	368	323	
Heat loss (MWh)	734	621	15%
Exergy loss (MWh)	175	82	53%

5 CONCLUSIONS AND FUTURE WORK

Recently a number of practitioners, researchers and governmental bodies are proposing new urban district heating networks in UK. In this paper, some technical and economic barriers are identified, and accordingly a conceptual planning framework is proposed and explored to resolve the complexity. In this framework, dynamics in energy demand are investigated; energy and exergy losses during distribution are selected for integrated assessment criteria. An illustrative case study presented demonstrates potential capacities of the framework.

The primary results show benefits of low temperature district heating outperformed high temperature districting system with optimized variable temperature and variable mass flow rates The indicative results show potential energy and exergy saving from low temperature district heating systems. This conclusions is based on detailed analyses of

- Heat demand for space heating and domestic hot water
- District heating network design
- Heat losses from distribution and pumping electricity consumptions

Nevertheless, in order to determine more accurate magnitude of impacts of the different designs on whole district heating system, significant work needs to be carried to collect and analyze more data and case studies, especially when matching demand and supply. In collaboration with a number of specialists and stakeholders, research is being carried out by the authors to explore potentials of low carbon district heating networks in UK.

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