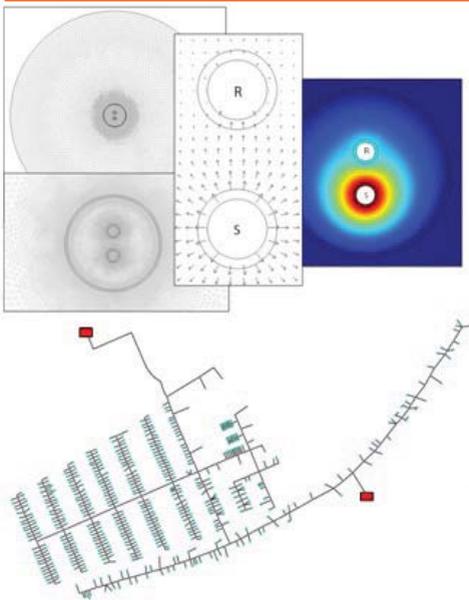


The Development of a new District Heating Concept

Network Design and Optimization for Integrating Energy Conservation and Renewable Energy Use



Alessandro Dalla Rosa

PhD Thesis

**Department of Civil Engineering
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Hvad er Sandhed andet end en Leven for en Idée?

(What is the Truth if not living for an idea?)

Søren Kierkegaard, 1835

“Così è la vita, benché raramente essa venga così descritta: un inserirsi, un derivare a suo vantaggio, un parassitare il cammino in giù dell’energia dalla sua nobile forma solare a quella degradata di calore a bassa temperatura. Su questo cammino all’ingiù, che conduce all’equilibrio e cioè alla morte, la vita disegna un’ansa e ci si annida.”

(“Such is life, although rarely it is described in this manner: an inserting itself, a drawing off to its advantage, a parasitizing of the downward course of energy, from its noble solar form to the degraded one of low-temperature heat. In this downward course, which leads to equilibrium and thus death, life draws a bend and nests in it.”)

Primo Levi, 1975

“It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects”.

William Thomson (Lord Kelvin), 1851

This doctoral thesis is submitted in partial fulfilment of the requirements for the Danish PhD degree. The title of the PhD project is “low-energy buildings and heat supply systems based on renewable energy”.

Copenhagen, 2nd April 2012

Alessandro Dalla Rosa

Preface

This thesis is based on five scientific articles which were either published (four articles) in Institute for Scientific information (ISI) journals or presented at international conferences after a peer-review process (one article). The thesis is subdivided into two separate parts, namely PART I and PART II.

The first part is an extended synopsis, which places the study in its scientific context, describes the objectives and assumptions, summarises the main results of the research work and provides the link between the appended scientific articles.

The second part is the collection of the scientific articles which the thesis is based upon.

Acknowledgements

The research presented in this doctoral thesis was conducted within the Section of Building Physics and Services, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, in the period March 2009 – April 2012.

I express sincere gratitude to my main supervisor, Professor Svend Svendsen, who not only created the conditions for making this work possible, but also has pointed me in the right direction and supported my decisions throughout my studies. He was always able to find time in his busy schedule for constructive discussions, also outside normal working hours. I am grateful to Associate Professor Jørgen Erik Christensen and Senior Researcher Hongwei Li, who have been my co-supervisors and were decisive to help me solve critical issues during my studies.

I acknowledge the staff of the Section of Building Physics and Services and my colleague researchers for their cooperation and assistance. I appreciate having spent time with them, especially during the social events, the “Tuesday and Friday breakfasts”, the “open office” meetings and the annual “Julefrokost” (Christmas lunch). I particularly thank my officemates, in order of appearance David Appelfeld, Lies Vanhoutteghem, Marek Brand and Hakan Tol, who made the atmosphere in the office lively and enjoyable and helped me cope with the frustration in some periods.

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I acknowledge the pipe manufacturing company Logstor, which provided the district heating twin pipes used in the experiments.

I extend my most sincere thanks and gratitude to my girlfriend Camilla, for bearing the unsociable aspects of a PhD project, for supporting me with patience and for accepting me as I am.

My gratitude goes also to my sister Silvia and her family for believing constantly in my capabilities.

Finally, I do not forget the friends and the other persons who make my life worth living and therefore my desire of knowledge alive: their names will not appear in this paragraph, but I will always keep them with me, together with the memories of the good time we spent together.

I dedicate this work to my parents, Maria Letizia and Giuliano, whose example has been a model of modesty and dedication, qualities I tried to apply during my education as researcher.

Copenhagen, 2nd April 2012

Alessandro Dalla Rosa

Abstract

PART I of this doctoral thesis consists of 6 chapters.

Chapter 1 summarizes the main issues caused by the use of energy resources. They involve ecological, economic, demographical and socio-political topics that are linked together and define the background of the thesis.

Chapter 2 describes the state-of-the-art of District Heating (DH) systems, with focus on the present and future situation in Denmark.

The core of the thesis consists of the development of a new DH paradigm, the “Low-Temperature District Heating (LTDH)”, the study of its potential, and investigations of technical options which improve its applicability in terms of energy performance and socio-economy. Chapter 3 describes the whole idea about LTDH.

Chapter 4 presents the hypotheses of the studies, draws the boundaries between the focus area of the thesis and other relevant aspects of the subject, describes the limitations of the work and lists the methods which were used.

Chapter 5 explains the results of the scientific content reported in the articles in PART II. Article I introduces the technical and organizational strategies that can facilitate the establishment of a successful energy planning in a community. It analyses the state-of-the-art in community energy planning, discusses critical issues, and points at the role of DH in moving towards sustainable heat supply. The articles II and III aim at providing science-based knowledge for the development of improved solutions for the DH networks; they focus on the performance simulation of DH pipelines through models for assessing the energy performance of innovative pipe geometries, materials or system configurations. The models were validated against experimental measurements on real DH pipes. Article II considers the detailed steady-state modelling and analysis of heat losses in pre-insulated DH pipes. Article III focuses on the modelling and computation of the transient heat transfer in service pipes, which are important elements of LTDH networks, particularly when supplying low heat density building areas. The purpose of article IV was to perform simulations and analyses about low-energy DH networks supplying heat to energy-efficient building areas in countries – such as Denmark – with an extensive existing DH infrastructure, quantify their technical and economic feasibility, and suggest strategies for optimizing their design and operation. Article V deals with the potential and barriers of implementing DH in Canada, where the DH market share is low. Technical-economic feasibility studies for DH networks supplying an urban area in the city of Ottawa were carried out, with particular attention to developing the potential for supplying heat derived from Renewable Energy (RE).

Chapter 6 summarises the conclusions. First of all, analysis of the case studies suggests that local authority energy plans should take the opportunities for DH implementation into account, because DH is an essential infrastructure for future,

sustainable energy systems. Energy policy should aim at organizing and facilitating the synergy between energy conservation measures and the supply of heat based on RE energy and overcome the traditional competition between the two sectors.

It is recommended that Finite Element Method (FEM) models and simulation should be used when designing new pipe geometries and systems. The reliability of the FEM models of DH pipes was validated by means of experimental data and comparison with analytical formulae and data from literature. The calculation method takes into account the temperature-dependency of the thermal conductivity of the insulation foam. It was demonstrated that the asymmetrical insulation of twin pipes in low-temperature operations leads to 4% to 8% lower heat loss from the supply media pipe than a symmetrical configuration, and at the same time the heat loss from the return media pipe can be kept close to zero. With the use of optimized double-pipe systems (a pair of differently-sized media pipes, embedded in the same insulation and casing pipe), it is possible to cut heat losses by 6% to 12% in comparison to twin pipes without increasing investment costs. Finally, the development of an optimized triple pipe solution is described.

The code modelling the transient heat transfer in DH service pipes is proven to be accurate, since it gives results that well represent the outlet temperature profile measured in the experiments with deviations of less than 0.5°C, and it is in good accordance with detailed, finite-volume simulations, for both stepwise and sinusoidal boundary conditions with regard to the inlet temperature profile. The proposed integrated solution consisting of service pipe and heat exchanger unit with a booster pump satisfies the requirement for DHW supply within 10 seconds and achieves heat savings for 200 kWh_{th}/yr with an additional electricity use of approximately 58 kWh_{el}/yr.

In Denmark, optimally-designed LTDH networks can be cost-effective in areas with a linear heat density as low as 0.20 MWh/(m·yr). For the cases considered, the levelized cost of energy is between 13.9–19.3 c€/kWh (excl. VAT) and this is approximately 20% lower than the scenario based on ground-source heat pumps. The network designs based on low-temperature operation are superior to the design based on low-flow operation. The total primary energy use in the most energy-efficient design is 14.3% lower than in standard networks and the distribution heat losses are halved. The results indicate that the LTDH concept fits the vision of the future energy-sustainable heating sector in Denmark.

In the investigations of the case studies in Canada, it was found that DH supply to building areas with linear heat density greater than 3.0 MWh/(m·yr) is competitive with the natural gas supply alternative and offers the opportunity to implement the use of RE and low-grade heat sources. The areas with linear heat density below 1.5 MWh/(m·yr) are not economically feasible with the current situation of the energy market in Canada, but could be considered for future network extensions together with the implementation of improved design and planning concepts. Moreover, medium-temperature DH networks can be designed for current heating loads while envisaging low-temperature operation in the future.

Resumé

DEL I af denne afhandling omfatter 6 kapitler.

Kapitel 1 beskriver de vigtigste problemstillinger omkring brug af energiressourcer. De omhandler miljømæssige, økonomiske, demografiske og socialpolitiske emner som kædes sammen og skaber baggrunden for afhandlingen.

Kapitel 2 beskriver *state-of-the-art* fjernvarmesystemer med fokus på den aktuelle og fremtidige situation i Danmark.

Afhandlingen er centreret omkring udviklingen af et nyt fjernvarmeparadigme, ”lavtemperatur-fjernvarme”, med særligt fokus på dets potentiale og på undersøgelser af de tekniske muligheder for at optimere denne energiløsning med henblik på energieffektivitet og socialøkonomi. Kapitel 3 beskriver hele konceptet bag lavtemperatur-fjernvarme.

Kapitel 4 præsenterer afhandlingens hypoteser og sætter fokusområdet i perspektiv i forhold til andre relevante aspekter af emnet. Metoder og begrænsninger er ligeledes beskrevet.

Kapitel 5 forklarer det videnskabelige indhold af artiklerne i DEL II af afhandlingen. I artikel I introduceres de tekniske og organisatoriske strategier, som danner baggrund for etableringen af succesrig energiplanlægning i et samfund. I artiklen analyseres desuden *state-of-the-art* indenfor energiplanlægning, kritiske problemstillinger diskuteres og fjernvarmens rolle i udviklingen af bæredygtig energitilførsel påpeges. Artikel II og III søger at give en videnskabelig baggrund for udvikling af forbedrede løsninger for fjernvarmenetværk; der fokuseres på simulerede modeller af fjernvarmerør for at kunne vurdere energiydelsen fra brug af innovative rørgeometrier, materialer og systemkonfigurationer. Modellerne blev valideret mod eksperimentelle målinger på rigtige fjernvarmerør. Artikel II omhandler detaljeret *steady-state* modellering og analyse af varmetab fra præisolerede fjernvarmerør. Artikel III fokuserer på modellering og udregning af transient varmeoverførsel i tilførende fjernvarmerør, som er vigtige elementer i lavtemperatur-fjernvarmenetværk, især ved forsyning af bebyggede områder med lav varmetæthed. Artikel IV er baseret på simulationer og analyser af netværk med lavenergifjernvarme som forsyner energi-effektive bebyggede områder i lande – såsom Danmark – med en eksisterende veludbygget fjernvarmeinfrastruktur. Den tekniske og økonomiske gennemførlighed af disse løsninger bliver vurderet og strategier for optimering af design og funktion bliver foreslået. Artikel V diskuterer potentiale for, og barrierer imod, implementering af fjernvarme i Canada, hvor markedsandelen for fjernvarme er lille. Tekniske og økonomiske gennemførlighedsanalyser blev foretaget på fjernvarmenetværk, der forsyner et tæt bebygget område i Ottawa, med særligt fokus på udvikling af potentialet for at udnytte varme udvundet fra vedvarende energiressourcer.

Kapitel 6 indeholder afhandlingens konklusioner:

Analyserne antyder, at man ved kommunal energiplanlægning bør overveje mulighederne for implementering af fjernvarme, da det udgør en vigtig infrastruktur

for fremtidige bæredygtige energiløsninger. Energipolitik bør have til formål at organisere og skabe synergien mellem energibesparende tiltag og varmeforsyning fra vedvarende energiressourcer og herved minimere konkurrence mellem de to sektorer. Det anbefales at Finite Element Method (FEM) modeller og simulationer bruges ved design af nye rørgeometrier og systemer. Driftsikkerheden af FEM modeller af fjernvarmerør blev valideret ved hjælp af eksperimentelle data og sammenligning med udregninger og formler fra litteraturen. Udregningerne tager hensyn til temperaturafhængigheden af isoleringsmaterialets varmeledningsevne. Det er blevet vist, at asymmetrisk isolering af dobbeltrør i lavtemperatursystemer fører til 4-8% mindre varmetab fra tilførende varmerør end med symmetrisk isolering. Samtidig kan varmetab fra fraførende varmerør holdes tæt på nul. Ved brug af optimerede dobbeltrørsystemer (et par rør af forskellig størrelse indpakket i samme isolering og yderrør) er det muligt at reducere varmetabet med 6-12% sammenlignet med almindelige dobbeltrør, uden at øge investeringsomkostningerne. Endelig beskrives en løsning med et optimeret tredobbelt rørsystem.

Modelleringen af transient varmeoverførsel i fjernvarmeservicerør har vist sig at være nøjagtig, da den giver resultater som stemmer overens med tilbageløbs-temperaturprofilen målt eksperimentelt med en afvigelse på mindre end 0.5°C. Der er desuden god overensstemmelse med detaljerede finite-volume simulationer for både trinvis og sinusformede grænsebetingelser mht. fremløbs-temperaturprofilen. Den foreslåede integrerede løsning som omfatter servicerør og varmeveksleren med en boosterpumpe opfylder kravene om fjernvarmeforsyning indenfor 10 sekunder og opnår varmebesparelser på 200 kWh_{th}/år med ekstra elektricitetsforbrug på 58 kWh_{el}/år.

I Danmark kan optimerede lavtemperatur-fjernvarme netværk være omkostningseffektive i områder med lineær varmetæthed så lav som 0.20 MWh/(m²·år). For de scenarier som er analyseret her, er de tilsvarende omkostninger for energiforbruget i intervallet 13.9–19.3 c€/kWh (ekskl. moms), hvilket er ca. 20% lavere end scenariet baseret på jordvarme. Netværksløsninger baseret på drift med lav temperatur er bedre end systemer baseret på drift med lavt flow. Det totale primære energiforbrug i det mest energi-effektive design er 14.3% lavere end forbruget i standardnetværk og varmetabet er halveret. Disse resultater antyder, at lavtemperatur-fjernvarme konceptet passer ind i visionen for en fremtidig bæredygtig varmesektor.

I undersøgelserne foretaget i Canada fandt man, at fjernvarmeforsyning af bebyggede områder med lineær varmetæthed højere end 3.0 MWh/(m²·år) er konkurrencedygtig i forhold til den alternative naturgasforsyning, og det giver mulighed for implementering af brugen af vedvarende energi ressourcer og ringe varmeressourcer. I områder med lineær varmetæthed under 1.5 MWh/(m²·år) er det dog ikke økonomisk rentabelt i den aktuelle situation på energimarkedet i Canada, men kunne overvejes ved fremtidige netværksudvidelser sammen med implementering af optimerede design- og planlægningskoncepter. Desuden kan middeltemperatur-fjernvarme netværk tilpasses de aktuelle varmebehov, imens fremadrettede muligheder for lavtemperatur-fjernvarme overvejes.

List of Publications

This doctoral thesis consists of an introductory section – named PART I – where the background of the study, the methodology used and the results are discussed in a comprehensive way and a second section – called PART II – which reports the fundamental publications, in the form of four scientific articles published or submitted to Institute for Science Information (ISI) journals and a peer-reviewed scientific article published in conference proceedings. The articles are listed below:

Article I

Dalla Rosa, Alessandro; Svendsen, Svend. *IEA-ECBCS Annex 51: energy-efficient communities: experience from Denmark*. Presented at: World Renewable Energy Conference, Linköping, Sweden, 2011.

Article II

Dalla Rosa, Alessandro; Li, Hongwei; Svendsen, Svend. *Method for optimal design of pipes for low-energy district heating, with focus on heat losses*. Energy 2011; 36 (5):2407-18.

Article III

Dalla Rosa, Alessandro; Li, Hongwei; Svendsen, Svend. *Modelling transient heat transfer in small-size twin pipes for end-user connections to low-energy district heating networks*. Accepted in the ISI Journal Heat Transfer Engineering, February 2012. Available online since 06-08-2012.

Article IV

Dalla Rosa, Alessandro; Christensen, Jørgen Erik. *Low-energy district heating in energy-efficient building areas*. Energy 2011; 36: 6890-99.

Article V

Dalla Rosa, Alessandro; Boulter, Raymond; Church, Ken; Svendsen, Svend. *The role of district heating towards a system-wide methodology for optimizing renewable energy sources in Canada: a case study*. Energy 2012; 45: 960-974.

Additional research studies were carried out during the 3-year PhD project “low-energy buildings and heat supply systems based on renewable energy”. The research

work is not reported in this thesis, either because the investigations are not part of the core of the dissertation topic (studies *a* and *b*), or the results are already included in the aforementioned publications (publications *d* and *e*), or I was not the main author of the publication (articles *c*, *f* and *g*). The list of such studies is reported below, with links to the sources where they can be found.

International Projects

a) Contribution to a research project in the framework of the International Energy Agency (IEA), Energy Conservation in Buildings and Communities Systems (ECBCS) programme. Title: “IEA-ECBCS Annex 51. Energy-efficient communities: case studies and strategic guidance for urban decision makers.”

Link: www.annex51.org

b) Contribution to a research project in the framework of the IEA, District Heating and Cooling (DHC) Agreement, including the integration of Combined Heat and Power (CHP). Title: “IEA-DHC/CHP Annex X. Towards fourth generation district heating: experiences with and potential of low-temperature district heating.”

Link: (www.iea-dhc.com)

Peer-Reviewed Conference Articles

c) Christensen, Jørgen Erik; Dalla Rosa, Alessandro; Nagla, Inese. *Building energy and energy supply simulations for low-energy district heating supply to energy-efficient buildings*. To be presented at: 5th International Building Physics Conference, Kyoto, Japan, 2012.

d) Dalla Rosa, Alessandro; Christensen, Jørgen Erik; Nagla, Inese. Low-energy district heating in energy-efficient building areas. Presented at: 4th International Conference on Sustainable Energy and Environment, Bangkok, Thailand, 2012.

e) Dalla Rosa, Alessandro; Li, Hongwei; Svendsen, Svend. *Steady-state heat losses in pipes for low-energy district heating*. Presented at: 12th International Symposium on District Heating and Cooling. Tallinn, Estonia, 2010.

f) Li, Hongwei; Dalla Rosa, Alessandro; Svendsen, Svend. *Design of a low-temperature district heating network with supply recirculation*. Presented at: 12th International Symposium on District Heating and Cooling. Tallinn, Estonia, 2010.

g) Brand, Marek; Dalla Rosa, Alessandro; Svendsen, Svend. *Performance of low-temperature district heating for low-energy houses*. Presented at: The Future for Sustainable Built Environments with High Performance Energy Systems. Munich, Germany, 2010.

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Nomenclature

List of Abbreviations

BR	Building Regulation
CEESA	Coherent Energy and Environmental System Analysis
CFD	Computational Fluid Dynamic
CHP	Combined Heat and Power
DH	District Heating
DHW	Domestic Hot Water
DN	Diameter, Nominal
EPBD	Energy Performance of Buildings Directive
ETFE	Ethylene TetraFluoroEthylene
EUI	Energy Use Intensity
FEM	Finite Element Method
GCV	Gross Calorific Value
GHG	GreenHouse Gas
GSHP	Ground Source Heat Pumps
HE	Heat Exchanger
HTDH	High-Temperature District Heating
FV	Finite Volume
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LEP	Local Energy Planning
LF	Load factor [-]
LTDH	Low-Temperature District Heating
MTDH	Medium-Temperature District Heating
OECD	Organization for Economic Co-operation and Development
PB	Polybutylene
PE	Polyethylene
PE _x	Cross-linked Polyethylene
PN	Pressure, Nominal
PUR	Polyurethane
RE	Renewable Energy
SH	Space Heating
SMORES	System-wide Methodology for Optimizing RE Sources
SPS	Single Pipe System
SRES	Special Report on Emission Scenarios
ST	Storage Tank
TPS	Twin Pipe System

List of Parameters

A	Heated floor area [m^2]
c	Specific heat [$\text{kJ}/(\text{kg}\cdot\text{K})$]
ci	Carbon intensity [$\text{kg}_{\text{CO}_2\text{-eq}}/\text{J}$]
D_{eq}	Equivalent diameter [mm]
d	Diameter [mm]
E	Specific annual energy use [$\text{kWh}/(\text{m}\cdot\text{yr})$]
e	Hourly energy use [kWh]
ei	Energy intensity of the GDP [$\text{J}/\text{€}$]
G	Solar Radiation [W/m^2]
GCE	Global Carbon Emission from human sources [$\text{kg}_{\text{CO}_2\text{-eq}}$]
GDP	Global Gross Domestic Product [€]
GPE	Global Primary Energy use [J]
gdp	Global GDP per capita [€/capita]
i, j, k	Iteration indices
L	Pipe length [m]
m	Number of pipe elements in the r-direction
m_j	Mass of the j-element [kg]
\dot{m}_w	Mass flow rate of the water [kg/s]
N	Number of consumers
n	Number of pipe elements in the z-direction
P	Global population
Q	Equivalent peak heating power, including simultaneity factors
$Q_{j,j+1}$	Heat flux between elements j and j+1 [W]
$R_{j,j+1}$	Linear thermal resistance between elements j and j+1 [$(\text{m}\cdot\text{K})/\text{W}$]
$R_{\text{water,pipe}}$	Linear thermal resistance between water and pipe wall [$(\text{m}\cdot\text{K})/\text{W}$]
Re	Reynolds number [-]
r	Radial direction
S	Simultaneity factor for space heating
s	Number of time steps
T	Temperature [$^{\circ}\text{C}$]
T_{d1}	Dimensionless T [$^{\circ}\text{C}$], defined as $T_{d1} = (T_{\text{outlet}} - T_{\text{initial}}) / (T_{\text{inlet}} - T_{\text{initial}})$
T_j	Temperature at the j-node [$^{\circ}\text{C}$]
T_{max}	Maximum allowed water temperature in the pipe [$^{\circ}\text{C}$] for less than 110 h/yr
T_N	Maximum allowed water temperature in the pipe [$^{\circ}\text{C}$] for continuous operation
t	Thickness [mm]

$U_{j,j+1}$	Linear heat transfer coefficient between the elements j and $j+1$ [W/(m·K)]
U_{w1}	Linear heat transfer coefficient between water and the PEX wall [W/(m·K)]
v	Velocity [m/s]
z	Longitudinal direction

Greek Symbols

ΔL	Length of the z-pipe element [m]
$\Delta \tau$	Duration of the time step [s]
λ	Thermal conductivity [W/(m·K)]
ρ	Density [kg/m ³]
τ	Time [s]
$\tau_{0.9}$	Time constant of the temperature sensors. It is the response time to reach 90% of the temperature raise in case of a step temperature change [s]

Subscripts

bypass	Bypass in the energy transfer unit
eq	equivalent
ground	Ground
i	Hour of the day [-]
initial	Refers to time = 0 s
inlet	Refers to the coordinate $x = 0$ m, i.e. the inlet to the media pipe
j	Day of the month [-]
n	Number of days in a specific month [-]
outlet	Refers to the coordinate $x = L$ [m], i.e. the outlet from the media pipe
pipe	Steel or PEX media pipe
return	Return pipe
supply	Supply pipe
target	Refer to the target value of the parameter considered
w	Water

Definitions

The basic terms and expression used in this report are defined here below.

Media pipe: the pipe inside which the heat carrier flows, excluding the surrounding insulation. The typical materials are steel, copper or plastic (polyethylene, PE or polybutylene, PB).

Casing pipe: The plastic pipe surrounding the insulation and the media pipe(s) and in contact with the ambient material (soil or outdoor air).

House Service Connection (abbreviated in *Service Pipe*): the heat distribution pipe, comprehensive of media pipe(s), insulation and casing pipe leading from the main pipeline to the consumer installation.

Branch pipe: the heat distribution pipe, comprehensive of media pipe(s), insulation and casing pipe that is connected to a main distribution pipe and serves only a fraction of the number of buildings served by the main distribution pipe. It is a relative definition, since a branch pipe can be a main distribution pipe for another branch pipe. The term can also be used to indicate a service pipe.

Main distribution pipe: the heat distribution pipe, comprehensive of media pipe(s), insulation and casing pipe that serves more than one building.

Transmission pipe: the pipe that brings the heat carrier from a major heat source (typically a CHP plant) to a distribution network and it is operated at higher pressure and/or temperature than the distribution network.

Single pipe: the single supply or return district heating pipe, comprehensive of media pipe, insulation and casing pipe.

Twin pipe: the pair of equally-sized media pipes, embedded in the same insulation and casing pipe.

Double pipe: the pair of differently-sized media pipes, embedded in the same insulation and casing pipe.

Supply temperature [°C]: the temperature of the heat carrier in the media pipe carrying the heat from the heat source to the heat sink.

Return temperature [°C]: the temperature of the heat carrier in the media pipe carrying the heat from the heat sink back to the heat source.

Linear heat density [MWh/(m²yr)]: the ratio of the annual heat delivered to the consumers (equivalent to the heat demand) and the trench length of the DH network serving that area.

Effective width [m]: the ratio of the total land area and the trench length of the network.

Plot ratio: the ratio of the total heated floor area and the total land area.

PART I

Extended Synopsis

1 Introduction and Background

Galileo Galilei (1564 – 1642), one of the father of modern science, stated that “behind each problem, there is an opportunity” and it is therefore the scope of scientific research and engineering to analyse the problems, hypothesize possible solutions and investigate their applicability. This is valid for every scientific/engineering field, including the energy topic. This chapter summarizes the issues that the society needs to examine to overcome the problems caused by the present and past extensive use of energy resources and provides the essential background to the thesis. They involve ecological, economic, demographical and socio-political topics that are linked together by an underlying theme: the generation, distribution and use of energy.

1.1 Aim

The thesis focuses on the building heating sector and on the development of a new generation of community heating systems – namely Low-Temperature District Heating (LTDH) systems – that can combine the synergy between energy conservation measures in new and existing buildings and environmental friendly, energy-efficient heat supply systems based on low-grade heat sources and Renewable Energy (RE). The aim is to demonstrate that the LTDH is an essential infrastructure to achieve the climate goals with a holistic and integrated approach which considers technological developments, the implication to the other energy sectors, such as agriculture, industry, power and transport, reasonable economy and effective management of socio-economical risks.

1.2 Sustainable Energy

The background for this doctoral thesis consists of the challenge for the modern society to achieve the long-term goal of becoming sufficiently independent of fossil fuels by 2050, taking into account both socio-economic, environmental and energy security issues. The general objective is to contribute to the development of “sustainable energy” systems, an expression that defines the effective provision of energy to meet the present demand, but without compromising the needs of the future generations and the global ecosystems. The pillars of this definition of “sustainable

energy” are energy conservation, energy efficiency and RE, but comprehend other mutually-related factors too, which are shown in Figure 1.1. This thesis is committed to help decision and policy makers, local governments, energy utilities, energy planners and other stakeholders to achieve consensus on the most long-term sustainable solutions for the final users, the local communities and the present and future society.

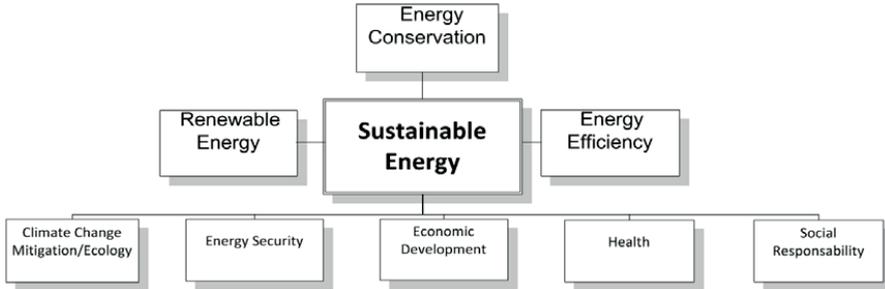


Figure 1.1 The pillars of “sustainable energy”.

1.3 Climate Change

The Intergovernmental Panel on Climate Change (IPCC) “Fourth Assessment Report: Climate Change 2007” stated that the “warming of the climate system is unequivocal” and that “most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentration” (“very likely” means that the assessed likelihood is over 90%) [1].

The changes in the climate are unquestionable, as it is evident from scientific observations such as the increase in global average air and ocean temperatures, the increase rate of the melting of snow/ice and rising global average sea level, see Figure 1.2.

The effects on the climate of the GreenHouseGases (GHGs) emitted by human activities are proved, and without the implementation of intense climate change mitigation policies and related sustainable economic development practices, global GHG emissions are predicted to continue to grow over the 21th century and beyond. Figure 1.3 refers to the Special Report on Emissions Scenarios (SRES), published in [3]. The SRES were grouped into four scenario classes (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions and climate change (see Table 1.1).

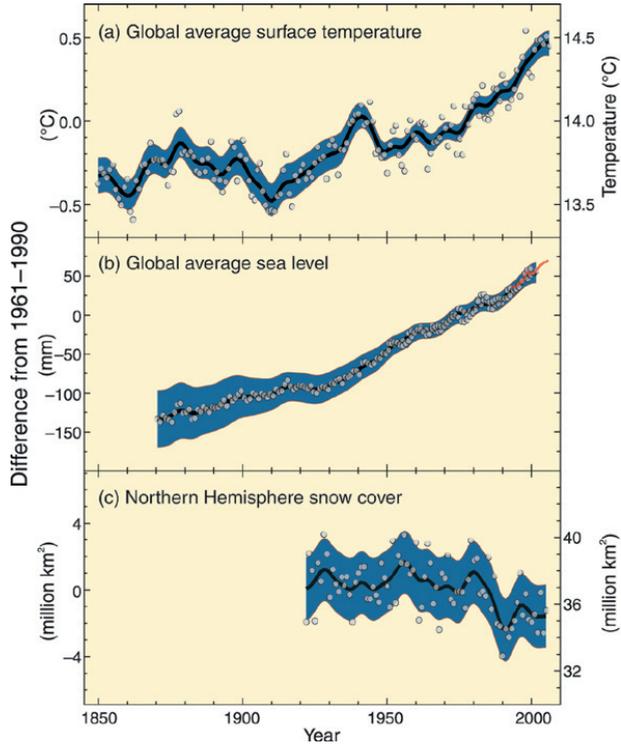


Figure 1.2 from top to bottom: observed changes in the global average surface temperature; global average sea level from tide gauge (blue) and satellite (red) data; snow cover in the period March-April in the northern hemisphere. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show annual values. The shaded areas depict the uncertainty intervals. Source: [2].

Table 1.1 Projected global average surface warming until 2100 in the four group of Special Report on Emission Scenarios (SRES). Adapted from [2].

	Scenarios with Economic Focus	Scenarios with Environmental Focus
Globalisation Scenarios	A1: rapid economic growth 1.4 - 6.4°C	B1: global environmental sustainability 1.1 - 2.9°C
Regionalisation Scenarios	A2: regional economic development 2.0 - 5.4°C	B2: local environmental sustainability 1.4 - 3.8°C

With the goal of keeping the unavoidable increase of the global temperature at the level of 2 – 2.4°C, the total concentration of CO_{2-eq} is to be maintained between 445 and 490 ppm. This is necessary to ensure that climate changes do not accelerate beyond the point where the global warming effect would become self-reinforcing. The estimation of the total atmospheric CO_{2-eq} concentration for all long-lived GHGs was about 455 ppm in 2005, while the corresponding value of the net effect of the

anthropogenic forcing agents was 375 ppm CO₂-eq. As consequence, the IPCC estimated that the anthropogenic emissions of GHG must peak no later than the year 2015 and also, that the emissions of GHG must be reduced by 50-85% by 2050 compared with the year 2000.

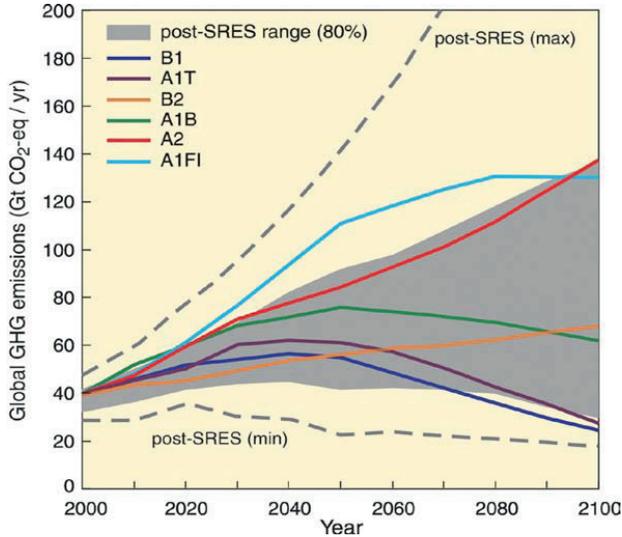


Figure 1.3 Projection of global GHG emissions. Coloured lines: SRES scenarios; gray shaded area: 80th percentile range scenarios for post-SRES scenarios (after the year 2000). Dashed lines show the full range of post-SRES scenarios. Source:[2].

However, the objective of limiting to 2°C the temperature increase was based on a reduction to approximately 350-400 ppm of CO₂ in the atmosphere. The most recent observations and model analyses showed that a reduction to 350 ppm CO₂ in the atmosphere are necessary and that anthropogenic GHG must be avoided almost entirely to avoid irreparable damage to the climatic balance [4], [5]. In 2011 the concentration of CO₂ in the atmosphere was about 389 ppm and the current trend shows a dangerous concentration growth (see Figure 1.3). Hence, this strengthens the necessity to develop plans for phasing out fossil fuels. Mitigation efforts and investments over the period 2010-2030 have a large impact on opportunities to achieve lower stabilization levels. Delayed emission reductions significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts, indeed (see Table 1.2).

Table 1.2: Climate change mitigation scenarios. Adapted from [6].

Global mean T increase [°C]	Stabilization level [ppm CO ₂ -eq]	Period of GHG emission peak*	Reduction of average annual GDP growth rate in 2030 [%]
2.0 – 2.4	445 – 490	2000 – 2015	< 0.12
2.4 – 2.8	490 – 535	2000 – 2020	< 0.12
2.8 – 3.2	535 – 590	2010 – 2030	< 0.10
3.2 – 4.0	590 – 710	2020 – 2060	< 0.06

* It refers to the mandatory time period for emission peak to guarantee the correspondent stabilization level.

1.4 Energy, Ecology, Economics, Demography and Geopolitics

Energy, ecology, and economics issues are linked together in a complex net of relations, which was first recognized and discussed by H.T. Odum (1924 – 2002). The statistical study of human populations (demography) and the relation between politics and territory on international scale (geopolitics) complete the framework and define the background of this dissertation, which is briefly presented in this subchapter.

1.4.1 The Kaya Identity

The “Kaya identity” [7] relates the factors that determine the level of human impact on climate. It states that the total GHG emission level can be expressed as the product of four inputs: population, GDP per capita, energy use per unit of GDP and carbon emissions per unit of energy consumed. The Kaya identity is expressed in the form:

$$GCE = P \cdot (GDP / P) \cdot (GPE / GDP) \cdot (GCE / GPE) = P \cdot gdp \cdot ei \cdot ci \quad (1.1)$$

where:

-) GCE is the Global Carbon emissions from human sources [$\text{kg}_{\text{CO}_2\text{-eq}}$]
-) P is the global population
-) GDP is the global Gross Domestic Product [€] and $gdp = (GDP/P)$ [€/capita] is the GDP per capita
-) GPE is the Global Primary Energy use [J] and $ei = (GPE/GDP)$ [J/€] is the primary energy intensity of the global GDP
-) $ci = (GCE/GPE)$ is the carbon intensity of the primary energy [$\text{kg}_{\text{CO}_2\text{-eq}}/\text{J}$]

The uppercase variables are extensive variables, while the intensive variables are lowercase. The four variables in the right side of the equivalence are a measure for, respectively, demography, wealth, energy intensity and carbon intensity. The potential to influence the first two variables, population and global GDP per-capita is low, whilst the latter two variables, energy intensity and carbon intensity can be influenced by technological choices and political decisions. This underlines the strong correlation among demography, environment, energy and economy.

1.4.2 Urbanization

The stable increase of the urban population combined with the reduction of the rural population growth rate results in urbanization, i.e. in increasing proportions of the population living in urban areas. During 2008, for the first time in history, the proportion of the population living in urban areas reached 50%. In the more developed regions, the proportion of urban population was already above 50% in 1950, while in the less developed regions the same level will be reached around the year 2020. Globally, the level of urbanization is expected to rise from 50% in 2008 to 70% in 2050. The economically developed regions are expected to see their level of urbanization rise from 74% to 86% over the same period (see Figure 1.4). In the less developed regions, the proportion of urban population is expected to increase from 44% in 2008 to 67% in 2050 [8].

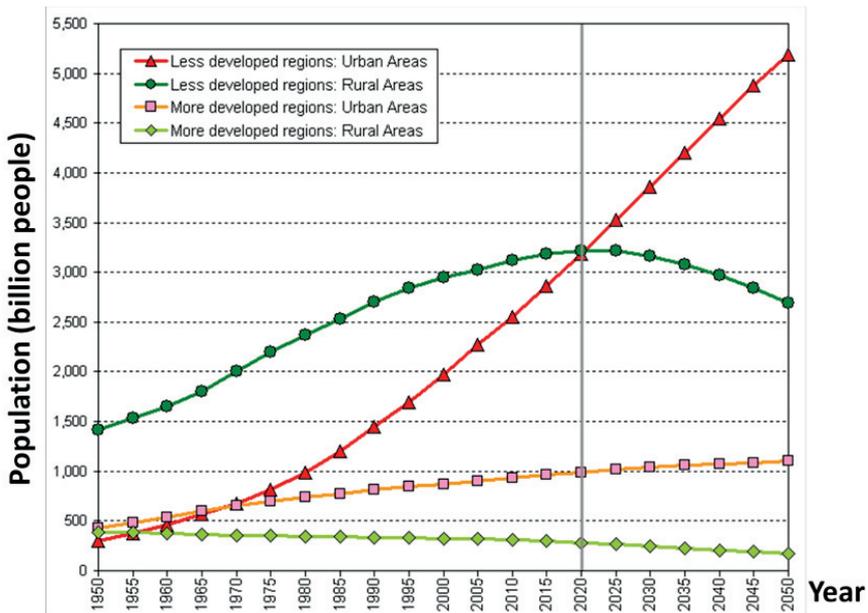


Figure 1.4 World urban and rural population by development regions (in million). Source:[8].

With an expected world population of nearly 9.20 billion people in 2050 and the need for a democratic economic and living standards growth, particularly in the less developed regions, it is easily predictable that the values of the first two terms of the Kaya identity, connected to demography and wealth, will increase. In order to keep the world carbon emission inside the required targets, it is clear that the energy intensity and the carbon intensity terms must decrease. The urbanization is a challenge that includes social, economic and ecological issues; on the other hand – and for the energy point of view – it also offers the chance to effectively implement community energy systems that could contribute to the sustainability of the community itself. More than 6 billion people will live in urban areas by 2050, most of them in developing and less-developed countries, where the energy infrastructure will be newly designed, thus giving the opportunity for smart energy planning: smart cities, which are energy-efficient, focused on the inhabitants needs and driven by best available technologies. When masterminding such energy-sustainable urban infrastructures, DH can have a key role.

1.5 Security of Energy Supply

Energy security is an expression that associates the specific national interest of each country and the availability of the global natural resources for energy use. It is based on the consideration that access to energy sources is essential to the functioning of modern economies. Nevertheless, the uneven distribution of energy supplies among countries has led to significant vulnerabilities, including the political instability of several countries that are major net energy exporters, competition over energy resources, political and cultural conflicts, and reliance on fossil-fuel supply from outside one country confines.

The Organization of Petroleum Exporting Countries (OPEC¹) claims to have 80 years of oil reserves remaining at its current rate of production, while non-OPEC oil producers' reserves might last less than 20 years. As fossil fuel consumption increases, and reserves deplete, those countries with the remaining reserves will gain greater global importance and political influence. A small number of countries are responsible for more than 55% of the crude oil production in 2010: the Arab League² countries (29.7%), the countries belonging to the OPEC, but not to the Arab League

¹ Algeria, Angola, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, Ecuador and Venezuela

² Algeria, Bahrain, Comoros, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, State of Palestine (as it is recognized by the members of the Arab League), Qatar, Saudi Arabia, Somalia, Sudan Syria, Tunisia, United Arab Emirates, Yemen

(Iran, Angola, Nigeria, Venezuela, Ecuador, 13.4% in total) and Russia (12%). Most of these countries suffer political instability or cannot be considered fully-developed democracies.

Similarly, more than $\frac{3}{4}$ of the proven natural gas reserves in 2010 were concentrated in the following countries: Russia, Iran, Qatar, Turkmenistan, Saudi Arabia, UAE, Nigeria, Venezuela, Algeria, Iraq, all of which are countries with political instability or that cannot be considered to have fully-developed democratic systems.

About coal, approximately 83% of the production in 2010 took place in highly-industrialized, developed countries, i.e. USA, EU countries, Australia, South Africa or in the two most important developing economies: China, responsible for 48.3% of global coal production in 2010, and India [9]. Although it is estimated that just the proven coal reserves can satisfy current global demand for 100-150 years (930 billion tons of recoverable coal reserves versus a demand of 7.075 billion tons in 2010, [10]), coal is the most carbon emission intense type of fossil fuel and therefore the highest priority to be replaced to mitigate climate changes.

The comparison between Figure 1.5, mapping conflicts in 2010, and Figure 1.6, showing the map of fossil fuel world production in the same year, suggests that many of the regions responsible for most fossil fuel production (and also the related natural reserves) are areas suffering war conflicts or political instability.



Figure 1.5 Map of the countries with one or more war conflicts in 2010. Source:[11]

The events in North Africa and the Middle East in 2011 confirmed this statement. Geo-political discussions are beyond the scope of this thesis, but given that the stable supply of energy is a fundamental factor to guarantee economic development and enhancement of living conditions, it is possible to conclude that the issues related to the provision and use of energy go well beyond mere market considerations and are critical for future world political equilibrium.

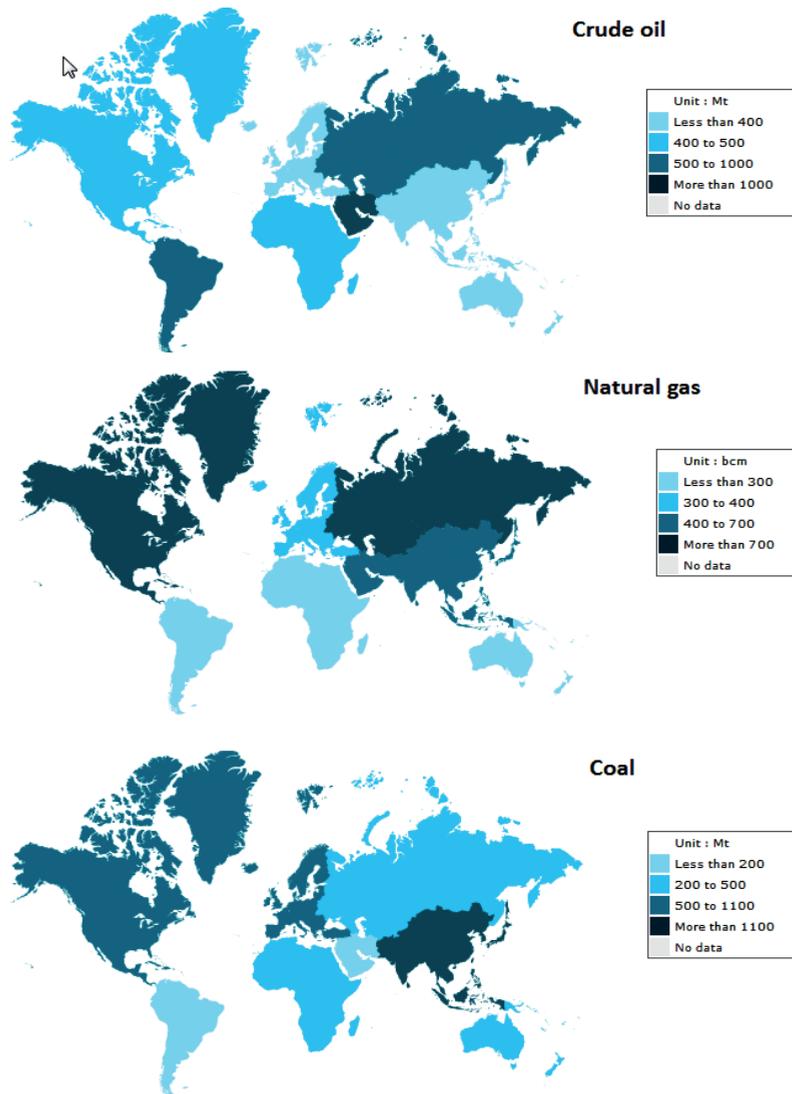


Figure 1.6 Map of the world production of fossil fuels in 2010. Source: [10].

2 District Heating in Denmark

The complexity of the issues related to the production, distribution and use of energy which are described in chapter 1 is so vast that there is not a single technology that has the potential to simultaneously solve all the problems, but it is more likely that a set of technologies must be developed, implemented and effectively coordinated by policy measures. This research work deals with a proposal that could be part of the solution for the heating sector and at the same time considers as background the basic implications for the other energy sectors (electricity production and its distribution, transportation, industry etc...). The topic of this thesis is District Heating (DH); chapter 2 depicts the present situation and the possible future scenarios of the Danish DH sector, since Denmark is among the countries with a long experience in the sector and a well-developed DH infrastructure. On the basis of this, an innovative DH paradigm is introduced in chapter 3.

The heat generated in Denmark in facilities connected to DH was 148,827 TJ in 2010 [12]. There are about 450 DH schemes with a total trench length of more than 27,000 km. The total installed capacity exceeds 17 GW_{th}. Primary energy derived from sources other than fossil fuels amounts to 47% (see Figure 2.1), principally comprising biomass (27%) and biodegradable and non-biodegradable waste (17%), whilst minor contribution came from biogas, geothermal energy, solar energy and other RE sources (4% in total). The fossil-fuel component of the primary energy is linked to CHP plants and the peak-load boilers connected to their operation. Biomass has been used and is being used to displace coal, which is the most carbon-intensive fossil fuel: the use of coal dropped from being equivalent to 23.1% (in 2003) to 18.9% (in 2010) of the primary energy.

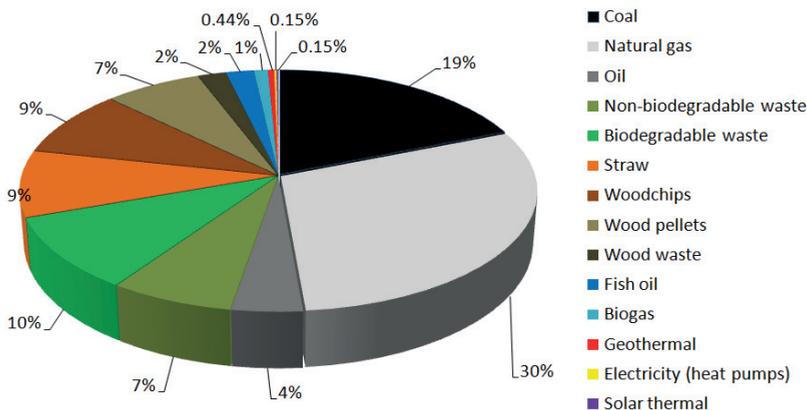


Figure 2.1 Heat supply in Denmark in 2010: heat sources and fuels. Source: [13].

DH penetration in the residential sector is significant in Denmark; in fact, DH supplies 62% of residential buildings, see Figure 2.2. Moreover, 69% of the heat distributed through DH is supplied to residential buildings, whilst the remaining part is supplied to public, commercial and office buildings. As a result, approximately 1,583,000 households in Denmark were heated by DH at the beginning of 2011. Compared to 2007, a growth of 3% in the number of households connected to DH has occurred, mostly displacing the number of oil furnaces which dropped by about 10% from 2007 to 2010.

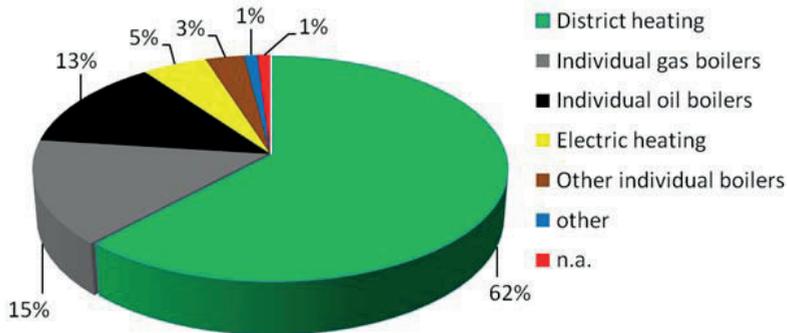


Figure 2.2 Heat supply in the Danish residential sector in 2010. Source: [13].

Figure 2.3 shows that the contribution of centralized CHP plants to the total heat production was stable in the period 2003-2010, with a share of 44 – 46%; nonetheless, in the same period the switch between fossil fuels and biomass started. The contribution of decentralized CHP decreased from 26% in 2003 to 19% in 2010, replaced by heat production plants, which increased by more than 7% in the same period, reaching quota 19.5% in 2010; that has been mainly the consequence of the implementation of RE-based heat production facilities. The improvement of the heat production side occurred in the private sector as well, where the heat generated in heat-only plants decreased from 7% to 3.5% and the heat production in private CHP facilities increased from 8% to 11.5%.

Biomass has been identified as a main contributor to increase the RE share and has a strategic role towards a carbon neutral heat supply by 2035. The price increase of biomass fuels for DH over the period 1997-2010 was less steep, in relative terms, than the fossil-fuels curves, with the exception of wood pellets, which increased significantly over the period 2005-2007: straw +23%, wood chip +36%, wood pellets +79%, oil +107%, natural gas +76% (Figure 2.4). Nonetheless, if the period 2005-2010 is taken as reference, the fuel price trend is more similar: straw +37%, wood chip +38%, wood pellets +51%, oil +41%, natural gas +37%. On one hand, it can be expected that the price gap between biomass fuels and fossil fuels will increase further in the future, due to diminishing availability of fossil fuels resources, competition in the procurement and geopolitical issues; on the other hand, the

increase demand for biomass fuels will most likely increase the purchase price too. Taking into account that the use of biomass as fuel for transport can potentially cause critical competition conditions for the biomass procurement, it can be concluded that biomass should be used as transition fuel only and that long-term investments in biomass-based heating production facilities should be generally avoided.

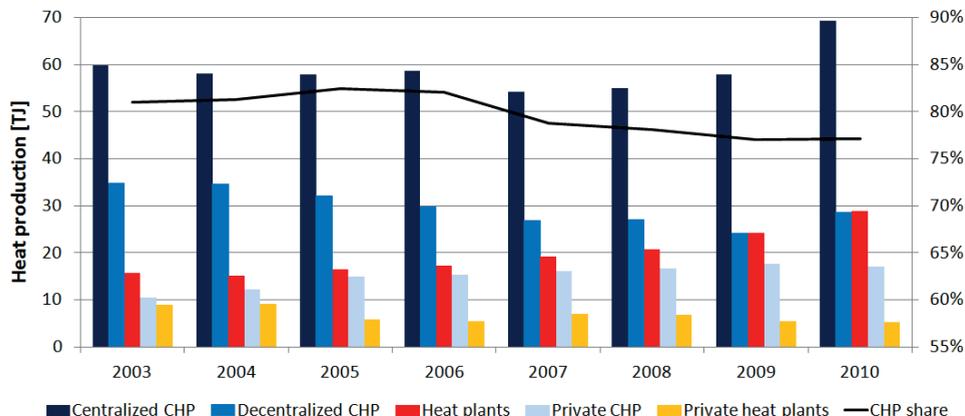


Figure 2.3 The cogeneration in the heating sector in Denmark. Heat production (left axis), CHP share on total heat production (right axis). Source: [13].

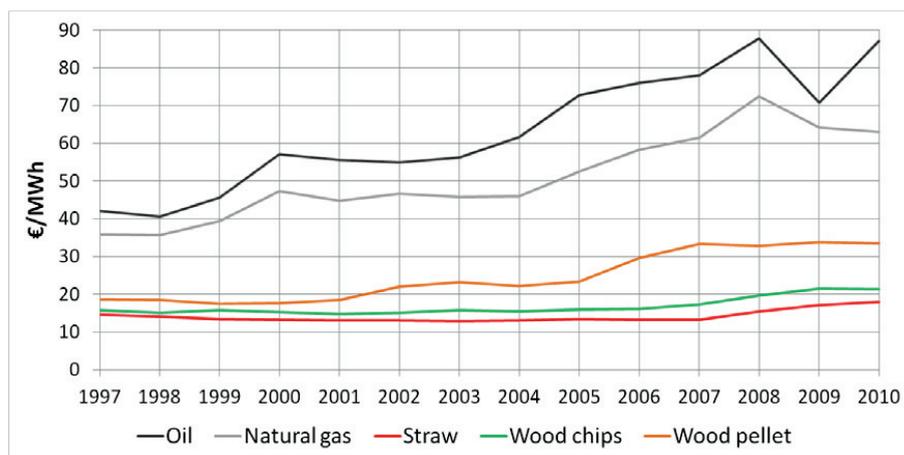


Figure 2.4 Fuel prices development in Denmark in the period 1997-2010. The prices are calculated as annual average of the prices published quarterly. Source: [13].

It is possible to summarize the main characteristics of the DH sector in Denmark, on the basis of the statistics collected in 2011 by the Danish District Heating Association for around 270 of the 450 DH distribution companies present in the market [12]. The following data regard the network and the energy figures and represent a statistical sample of 200 companies:

- Most of the DH companies serve between 100 and 10,000 customers and in a cost-effective way (see Table 2.1 and Figure 2.6). As Figure 2.6 shows, the linear heat density of the networks typically ranges from 0.4 MWh/(m²·yr) to 2 MWh/(m²·yr), pointing that DH networks are very spread and already nowadays supply medium-to-low heat density areas. The x-axis expresses the number of customers as the number of meters installed at the boundary between the DH network and the end-user side; in the practice, a single meter can be installed in a building with multiple users, such as multi-family buildings.

Table 2.1 Distribution of household costs for the district heating supply in Denmark in 2011. Source: [12].

	Production Costs	Distribution Costs	Administration Costs	Total Costs
[€/MWh]	71.06	16.67	5.26	93.00
[%]	76	8	6	200

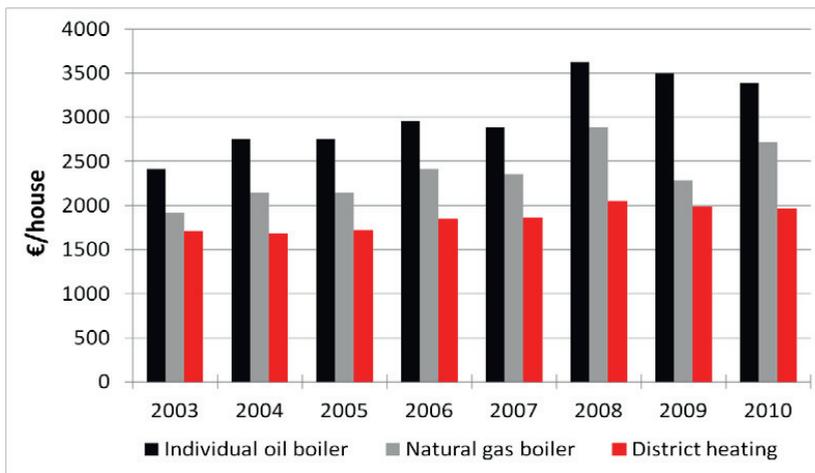


Figure 2.5 Average annual heat bill for a standard single-family house in Denmark in 2009 (heat demand = 18.1 MWh, heated area = 130 m²). Source: [13], [14].

- The extensive development of DH in Denmark has historical reasons and was allowed, among other things, by the firm political decision of supplying the base-load heat demand via CHP. The relatively cheap heat made profitable to extend the pipeline to suburban areas and bear a share of heat loss that would otherwise be unsustainable. The length of the service pipes is at present time approximately 41% of the total length of the distribution networks, the length of the transmission lines in large, city-scale networks being neglected in this calculation. On one hand the extension of DH distribution is such that it offers a unique opportunity to develop a low-carbon infrastructure for heat, but on the other it requires the implementation of measures aimed at reducing the distribution heat losses.

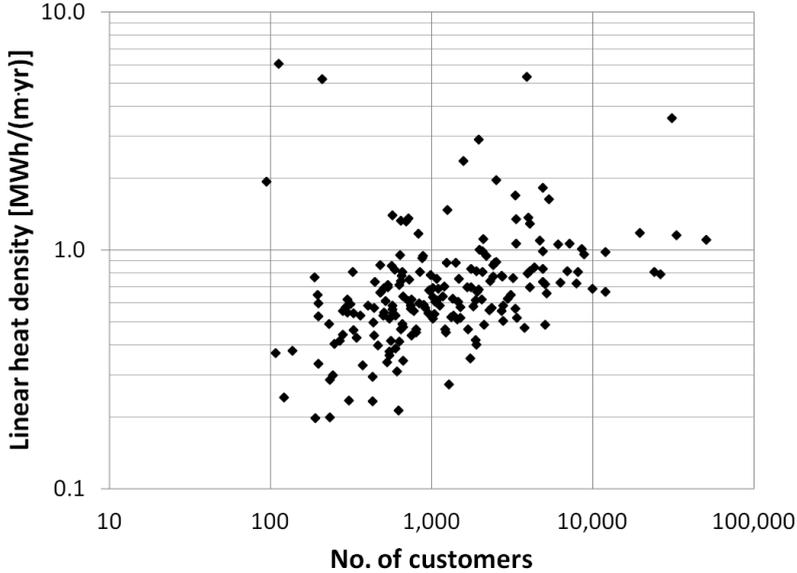


Figure 2.6 Linear heat density vs. number of customers in 200 existing DH networks in Denmark, based on heat use data in 2010. Source: [12].

- In 2010 the heat loss represented 17% of the total heat delivered to the transmission and distribution pipelines, whilst a DH utility had in average a share of heat loss equal to $20 \pm 5\%$, indicating that heat losses have generally less impact on large systems.

- The electricity use in 2010 for pumping purposes was equivalent to 9.9 ± 6.7 kWh_{el}/MWh_{th}. Despite the higher economic and exergetic value of electricity in comparison to heat, the role of energy savings in pumping operation is generally less critical than the role of heat loss. This is amplified in low heat densities areas [15]. Anyway, the energy optimization of network operation should always consider the total combined effect of heat losses and pumping energy.

- The average operating temperatures testify that Medium-Temperature District Heating (MTDH) is well established in Denmark. Considering the operating temperatures in more than 250 DH systems in 2010, the average values were:

$$T_{supply} = 78.7 \pm 7.4^\circ\text{C}, T_{return} = 41.4 \pm 10.6^\circ\text{C} \quad (\text{heating season: 01/11/09} - 30/04/10)$$

$$T_{supply} = 73.3 \pm 5.8^\circ\text{C}, T_{return} = 44.1 \pm 8.4^\circ\text{C} \quad (\text{non-heating season: 01/05/10} - 31/10/10)$$

In general terms, the status of the DH sector in Denmark is in line with the short-term plan to reduce Danish CO₂ emissions and with the long-term vision of a transition to an energy supply system based exclusively on RE, but important issues must be addressed.

The need for significant reductions of building energy use and for a wider exploitation of surplus heat and RE mean the current MTDH technologies have become barriers to

further increase the market share. The concepts for designing and operating DH systems need to be re-examined under the new energy regulations and the development trends in the energy sector, in order to sustain economic competitiveness and realize long-term sustainable development. This becomes the main driver to bring forward the concept of the LTDH system. In fact, the relative heat loss along traditional DH networks becomes significantly high, when the building SH demand drops to approximately one-quarter of the current level. Moreover, the future (and present) limits to the exploitation of high-exergy resources such as fossil-fuels for heating, should drive the scientific and engineering community to find alternatives in the field of low-grade heat sources and RE energy, whose availability is extensive, though their utilization often requires capital-intensive investments. The immediate and effective solution is to reduce the temperature level in the network.

2.1 The Plans for the Future

2.1.1 Heat Plan Denmark

In 2006, 46% of the heat demand in Denmark was supplied by DH and by 2010 the DH share reached 50% . The study “VarmePlan Danmark” (Heat Plan Denmark, [16]) investigated the potential for expanding the DH share by mapping the expansion possibilities through the information available in the Bygnings og BoligRegistret (BBR, Building and House register) and Geographical Information Systems (GIS). A major conclusion of the survey was that it is desirable, from the socio-economic point of view, to increase DH supply up to 70% of the heating demand; in detail that can be achieved cumulatively by:

- an increased engagement in the existing areas supplied by DH (result: 53% of the heating demand);
- expansion to neighbouring areas currently equipped with natural gas furnaces, oil boilers and wood stoves (result: 63% of the heating demand);
- the connection of areas heated by natural gas up to 1 km from the existing DH areas (result: 70% of the heating demand).

Energy and economic performance data for DH supply were calculated not only considering present heat demand, but also in the situation where the average SH demand is reduced by 25%, 50% and 75%. The analyses showed that DH networks can be adapted to the long-term savings strategy. Nonetheless, it is required that the DH sector achieves energy savings, mainly by means of lower operating temperatures, which require investments in building SH and DHW installations. In addition, lower operating temperatures would result in better utilization of low-grade

heat and RE energy and would therefore fit the plan for a fossil-fuel-free heat supply sector.

Among the individual-building heating options, the heat pumps were assessed as the most competitive alternative to DH in building areas with a low heat density and too far away from existing DH networks. The report concluded that the most practicable and effective solution would be to combine a progressive expansion of DH areas with individual heat pumps in the remaining dwellings. The challenge in local heating planning is thus to arrange the expansion in an optimal way and achieve the most cost-effective area delimitation between the collective heat supply and the individual heat supply.

The report “VarmePlan Danmark 2010” (Heat Plan Denmark 2010, [17]) presented two proposals to implement such a vision: a “rapid development” plan and a “moderate expansion” plan. The “moderate expansion” plan focuses on achieving the carbon-neutrality in the heating sector by 2050 – as the heating sector is the one that can be addressed at great extent and in a cost-effective way with current technologies – and envisages that the electricity and transportation sector will still partially run on fossil fuels at that date. The “rapid development” plan is relevant if Denmark is to be completely independent of fossil fuels in all energy sectors (electricity, heat and transportation) by 2050. Such a plan requires intense and coordinated efforts at many levels in the form of policy regulations, financial grants and incentives to coordinate and optimize the investments both in the energy utilities sector and in the construction sector. It is important to notice that the background for the DH sector is the same for both scenarios and it consists of the following points:

- generally, the existing DH systems have a long residual life and they can be operated with a strategy that combines the decrease of the supply temperatures and the extension to the adjacent settlements. The extension is possible without capital intensive investment to the existing networks, if extra heating power capacity is provided by regular maintenance and energy-efficient renovation of the distribution systems, energy savings at the end-user side and lower return temperatures.
- The existing DH systems can be further enhanced, especially by increasing the interaction between end-users, heat distribution and heat production.
- Heat production can be made more efficient and increasingly exploits low-grade surplus heat, which replaces fossil-fuels consumption.
- It might be economically advantageous to extend the DH supply, including new energy-efficient building constructions.
- It is assumed that the heat users, independently whether in the future are heated with DH, heat pumps or other RE-based systems, will reduce the heating demand and the required temperature by their DHW and SH installations. The level of energy savings achieved depends strongly on the decisions of many local stakeholders and it is based on socio-economic criteria. Nonetheless, it is the policy makers’ responsibility to

establish the regulations and incentives that promote those individual actions that are beneficial to the entire society.

The “rapid development” scenario is presumed in this doctoral thesis because it is considered as an example of holistic and integrated approach towards energy sustainability. Moreover, the Danish society and political establishment have confirmed that they are ready for the challenge represented by the “rapid development” of a nearly-carbon-neutral energy system. The Danish Government has stated in an official document that a carbon-neutral heating sector by 2035 is one of the milestones of the national energy plan [18].

Three implementation phases towards a 100% RE heating sector by 2050 were proposed in [17] and are listed below, together with their main milestones (see also Figure 2.8 and Figure 2.9).

Phase 1 (2010 – 2020)

- 25% reduction of SH demand, which corresponds to approximately 20% of net heat demand;
- reduction of yearly-averaged DH return temperature to 40°C;
- 100% DH supply to all new developments in urban areas;
- expansion of DH to supply 70% of the heat demand;
- share of individual heat pumps: up to 25%;
- maintain the total heat demand supplied by individual gas-fired boilers at 5%;
- phase-out electricity and oil for individual heating;
- introduce biogas for DH purposes;
- expansion of the exploitation of biomass for DH;
- expansion of large-scale solar thermal heating to a total of 4 million m² collectors;
- implementation of large-scale resistance heaters (with thermal storage) and electrical heat pumps for DH to regulate the electrical power system;
- full use of the cogeneration potential from the remaining coal and gas fired plants;
- implementation of new biomass-fired CHP plants in replacement of coal;
- use of the flue gas condensation technology in CHP biomass-fired power plants, so that the overall efficiency is increased from approximately 90% to approximately 105%;
- development of geothermal energy facilities, to be used as base-load in the future carbon-neutral heat supply system.

Phase 2 (2020 – 2030)

- Reduction of the SH demand by approximately 1%/yr, thus achieving savings equivalent to 35% of the SH demand in 2010;

- reduction of yearly-averaged DH return temperature to 35°C;
- phase-out of natural gas, replaced by individual heat pumps, that now supply 30% of the heating demand;
- increase the number of small-scale heat pumps and develop further the solar thermal sector, up to additional 2 million m², supplemented with biomass in case of large customers in rural areas;
- utilization of biogas for cogeneration of heat and power during periods of high electricity prices;
- increase the capacity of inter-seasonal heat storage;
- expansion of large-scale solar heating to a total of 8 million m², equivalent to 0.5% of the country surface area in at least 300 installations, capable to provide 10% of the DH heat supply;
- further development of geothermal energy.

Phase 3 (2030 – 2050)

- The heat demand in 2050 reaches 50% of 2010 levels through energy savings in the building stock;
- phase-out of biomass for base-load supply by replacement with surplus heat, large-scale heat pumps and resistance heaters (in periods with overproduction of wind power), solar and geothermal plants, seasonal storage;
- use biomass boilers only during peak-load periods and for back-up purposes.

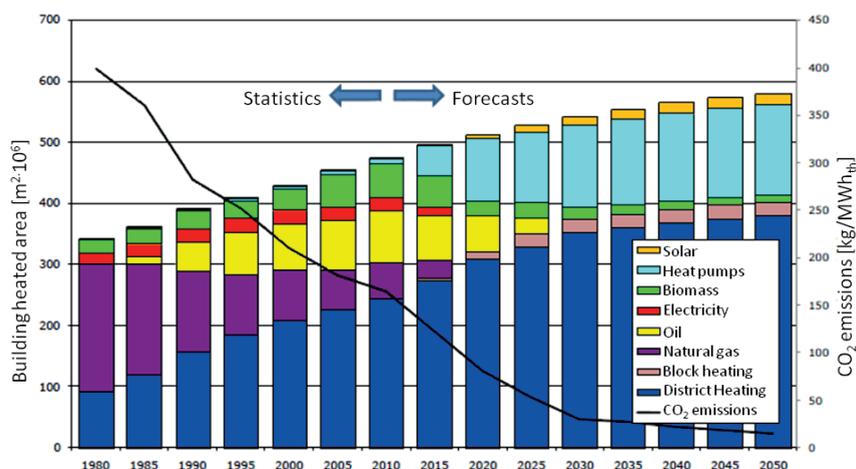


Figure 2.7 Historical data and future projections about total heated area, CO₂ emissions and heat supply for the “rapid development” scenario. Source: [17].

The scenario envisages the progressive reduction of the heat demand – although the concurrent increase in the total heated area – the almost complete phase-out of fossil fuels for heating purposes by 2030 and the phase-out of biomass for heating purposes

by 2050, assuming that other sector (mainly industry and transportation) will have the priority on biomass exploitation.

It is worth mentioning that the “moderate expansion” scenario envisages the same long-term outcomes as the “rapid development” scenario, with respect to the phase-out of fossil fuels by 2050. The main differences are: in the period 2020-2030, the natural gas consumption is higher and in turn the electricity use for heat pumps is lower. In comparison to the “rapid expansion” scenario, where the SH demand is 50% of the heat demand in 2010 by 2050, the goal is to achieve 25% savings in SH and therefore the use of biomass and carbon-neutral electricity in 2050 is greater.

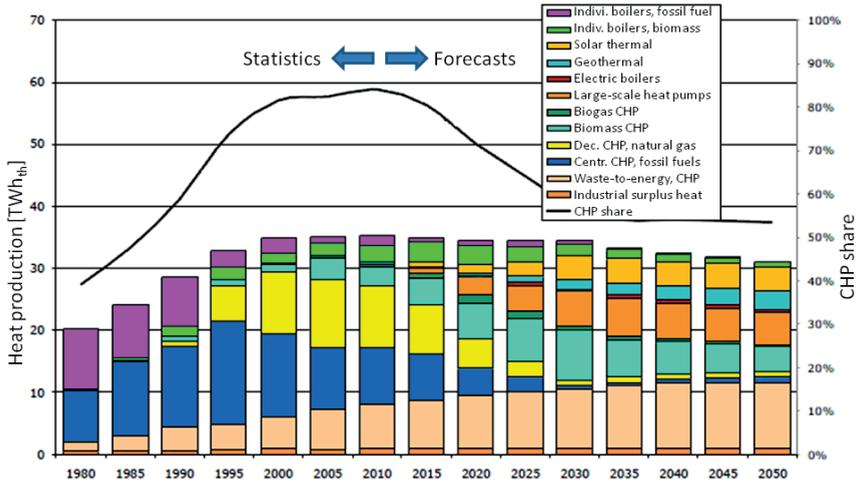


Figure 2.8 Historical data and future projections about total heat production, heat supply technologies and CHP share for the “rapid development” scenario, including energy savings. Source: [17].

2.1.2 The IDA Climate Plan 2050

The report “IDA Climate Plan 2050” [19], took the results of the report “Heat Plan Denmark” and integrated them in the plan towards a 100% RE energy system by 2050. The outcome was a vision of the Danish energy market in 2050 – see Figure 2.9 – and the definition of what is necessary to do in each energy sector, namely energy production, agriculture/foods and materials, industry, buildings and transport. The investigations comprehended the relations among sectors too. For the heating sector, the report focused on exploiting the synergy between a simultaneous and coordinated expansion of DH and implementation of heat savings. The study showed that the reduction of heat demand and the expansion of DH supply achieve a greater advantage when they are optimally combined, in terms of economy, CO₂ emissions and total energy efficiency.

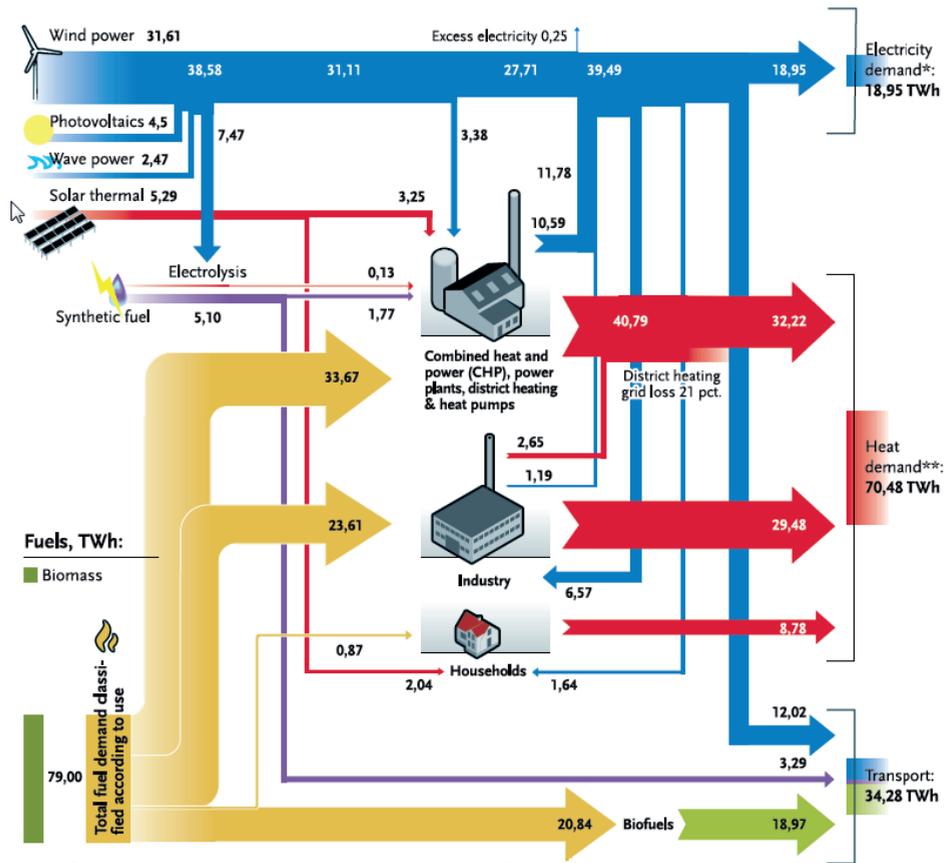


Figure 2.9 Primary energy supply of the 100% RE scenario, according to the IDA climate plan 2050. Source: [19].

2.1.3 The CEESA Project

The research project “Coherent Energy and Environmental System Analysis” (CEESA, [19]) recognized the need for new system thinking and new planning principles for energy investments. In fact, in a future 100% RE system, it is necessary to integrate the electricity, heat and transport sectors in a much more effective way than in the traditional energy supply systems based on fossil fuels; this is mainly required because of the dominant contributions from intermittent RE sources and the limited potential for the sustainable use of biomass. Nonetheless, the project showed that this could be done in an efficient and cost-effective way. However, planning of the transition requires a longer time horizon than the commercial market can offer; hence, it was proposed that the balance between the commercial market and societal planning is shifted to the advantage of societal planning to avoid short-term investments that jeopardize long-term, abiding benefits. The role of energy planning – including heat planning – is therefore central.

Moreover, the accomplishment of the paradigm shift from a fossil-fuel based society to a RE-based society requires that the transition to the new system is supported by strong and efficient energy conservation policies. In Denmark, wind power and biomass are expected to be the two future dominant energy resources; in order to ease the pressure on wind and biomass resources and the related investments and risks, energy conservation and the inclusion of contributions from additional sources such as solar and geothermal energy become fundamental. Finally, the report recommended that it is strategic “to assure an energy-efficient use of low-temperature sources from CHP, waste incineration, industrial surplus heat and geothermal energy. In this scenario, a new generation of low-temperature district heating infrastructure becomes essential”.

2.2 The Barriers

The CEESA report found three main barriers to the successful implementation of a 100% heat supply sector, which introduce the need to find synergies between heat conservation measures and the investments in a RE-based heat supply. The project proposes solutions to overcome those barriers.

The first barrier deals with present market conditions in the DH sector. The technical analysis in “Varmeplan Danmark 2010” showed that it is desirable from the socio-economical point of view to reduce the heat demand in buildings by 50% by 2050. The DH tariff system in Denmark is characterized by a 25% to 65% fixed price, with 50% as average value, and therefore the economic incentive to invest in heat savings measures does not fit the long-term, profitable goal for heat demand reduction. The time perspective is fundamental, as buildings currently undergoing energy renovation will then be maintained at that level typically for 40-70 years. Therefore, building renovation should encompass a 50% reduction of SH demand, otherwise it is very likely that RE-based supply systems will be built and operated with a sub-optimal economic performance. This is the case both for buildings within and outside DH supply. Although DH networks are suitable infrastructure for a future RE supply system, DH companies take a short-time view compared with the time horizon that is needed when making major changes in the energy system. The tariffs generally correspond to the average heat generation costs in the existing supply system. Instead, in a long term perspective, where the goal is an economical optimization of the demand and supply activities, the price should be set according to the long-term marginal costs of the future heat supply system and be solely based on the heat use.

Secondly, it is not easy to obtain finance for long-term investments in improvements in energy efficiency in the building sector.

Thirdly, there is lack of consultancy assistance and process guidance.

The proposal to remove the latter two barriers consists of combining financial attractive public-guaranteed loans, e.g. for 30 years and with an interest rate about 3%, and guarantee engineering/science-based decisions for building renovation. This is possible only with strong political support and if the majority of DH systems, which to a large extent are technical monopolies, remain publically owned.

3 Low-Temperature District Heating

The core of the thesis consists of the development of a new DH paradigm, namely the “low-temperature district heating” concept, the study of its potential and the investigations of technical options that improve its applicability, in terms of energy performance and economy. This chapter describes what is meant by LTDH, which is built upon the considerations of the previous chapters.

3.1 Description of the Concept

In a historical perspective, the new DH generation, is the 4th generation of the technology development, following the steam-based systems (1st generation), the high-temperature water systems ($T_{\text{supply}} > 100^{\circ}\text{C}$, 2nd generation), and the medium-temperature water systems ($T_{\text{supply}} < 100^{\circ}\text{C}$, 3rd generation).

The first generation of DH systems use steam as heat carrier and was introduced in the USA in the late 19th century; the majority of DH systems established until the second world war used this technology. Steam-based DH is an outdated technology, because of high heat loss, high operating and maintenance costs and safety reasons. The second generation switched to pressurized hot water as the heat carrier and emerged in the third decade of the 20th century, prevailing until the 1970s. The third generation of systems came after and gained a major success in the 1980s; they are the most used systems both in upgrading of existing network and in new projects as well. The energy carrier is still pressurised water, but supply temperatures are lower and they are often combined with the use of the twin pipe system and plastic media pipes, when possible. The new generation of DH systems is characterized by strategies to achieve low energy use. The use of the term “low-energy DH” is linked to the definition of a community energy supply concept which fits the decreased heat demand in new low-energy buildings and in existing buildings that have been undergone energy retrofit: low-energy supply systems for low-energy demand buildings. The heat transferred from a DH network to a building is proportional to the flow of the energy carrier and to the temperature difference between supply and return, and is thus independent of the temperature level of the network: the low-energy DH does not necessary mean LTDH, according to the aforementioned definition. The introduction of low-temperature characteristics is needed to put together energy efficiency at building and network level with heat sources based on low-grade heat (low-exergy) and RE, achieving a long-term, integrated and holistic concept (see Figure 3.1). DH traditionally benefits from the economics of scale of

mass production of heat from central heating plants and as technology that makes use of the thermodynamic inefficiencies related to energy conversion processes, such as electricity production in thermal power plants or industrial processes. Based on the studies [21]-[23], the network supply temperature at 50-55°C and the return temperature at 25-30°C can meet end-user SH and domestic hot water (DHW) demands in central-northern Europe climates, in properly designed in-house installations.



Figure 3.1 The low-temperature district heating concept.

The concept envisages the possibility of increasing the supply temperature in peak load periods during the heating season to limit the dimensions of the distribution pipelines. The temperature level during these periods depends on the climate, availability of energy sources at higher temperature and total economy, and thus depends on the case considered. A typical supply temperature for peak-load periods in the Nordic countries could be 65-75°C; the hypothesis is that the savings in capital investments and operational costs (in terms of heat losses) exceed the higher operational costs derived from the use of higher operating temperatures during peak-load periods. The low distribution supply and return temperatures outside peak-load periods are one of the most distinguished features of the new generation DH systems. The major advantages due to the reduced network temperature level are:

- Reduced network heat loss. A network with decreased temperature and increased insulation can effectively reduce the heat loss along the pipeline. Flexible twin pipes with the return pipe positioned around the isothermal zone can further decrease the total heat loss.
- Reduced pipeline thermal stress. As the supply temperature lowers, the unevenly distributed temperature gradient along the pipeline is decreased. The risk for pipe leakage due to thermal stress is reduced and hence the maintenance costs as well.
- Reduced heat loss in thermal storage units. Thermal storage in a DH system ranges from large seasonal storage tanks to small-scale tanks at the consumers' installation. Lower network temperature will reduce the heat loss in thermal storage tanks.
- Improved power to heat ratio in CHP plants. The profit from a CHP plant greatly depends on the amount of power being generated. This is particularly relevant in a liberalized electricity market. Low network supply and return temperatures allow more power to be extracted from the steam expansion process. For example, 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. The reduction of electricity output can be defined by the z -factor:

$$z = E_{\text{electricity, loss}} / E_{\text{heat, production}} \quad (3.1)$$

Figure 3.2 shows the z -factor calculated for the range of temperatures suitable for DH supply, according to the theory in [24]. The vertical segments refer to the z -factor values that correspond to supply temperatures, T_s equal to or lower than the design supply temperatures, which are respectively 120°C for High-Temperature District Heating (HTDH), 90°C for MTDH and 60°C for LTDH. The following return temperatures, T_r are used: 70°C (HTDH), 40°C (MTDH), 30°C (LTDH). It can be seen how the energy efficiency benefits from lower operating temperatures and that in this case the z -factor is more sensitive to the supply temperature than to the return temperature.

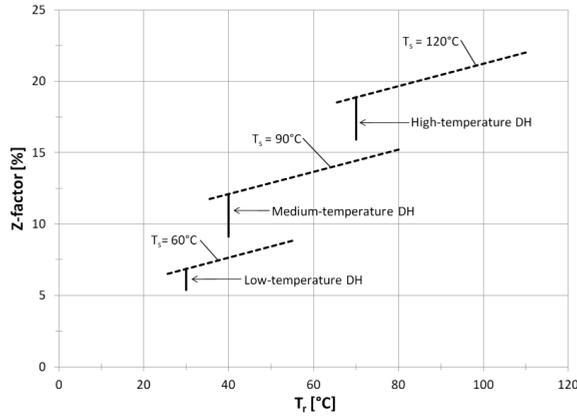


Figure 3.2 z -factor in an extraction-condensing turbine for CHP as function of the DH operating temperatures.

- Improved capability for heat recovery. The low network return temperature makes direct flue gas condensation possible. This is particularly relevant for biomass/waste CHP plants due to the high moisture content in the fuel. Meanwhile, the low network supply temperature allows further exploitation of low-exergy excess heat, either from industrial processes or by heat recovery from cooling processes.

- Increased utilization of RE. Thanks to the low operating temperatures, it is possible to exploit further RE sources and make them competitive with individual-building heat generation technologies. Fluid temperature below 60°C makes geothermal plants more advantageous to satisfy the base load demand; similarly, it increases the efficiency of solar thermal collectors, both in the case of roof applications and large-scale solar thermal fields (see Figure 3.3).

The focus on low operating temperatures targets not only the developments with especially suitable characteristics, but also provides a solution to local energy

planners and the DH utilities for increasing further the market share under the current situation. In Nordic countries, DH is well developed and may cover 80-90% of the heating supply in the designated area [27]. Further market penetration requires the engagement of peripheral urban areas, which are currently supplied through independent heat generation units like natural gas furnaces and oil boilers. The linear heat density in such region is normally quite low (typically between 0.2 and 1 MWh/(m²yr)) and the heat loss would exceed the energy saving due to central DH supply. The consumers in such regions may prefer independent heat generation units for economical reasons.

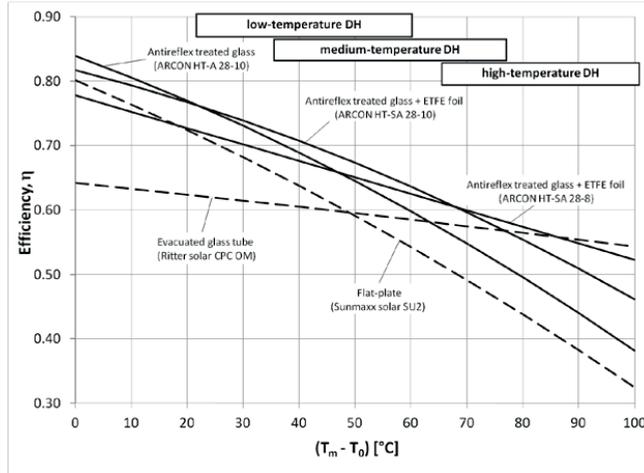


Figure 3.3 Efficiency of solar thermal collectors as function of the difference between the average temperature of the fluid in the collector, T_m and the ambient temperature, T_0 ($G = 1000 \text{ W/m}^2$). — Large-scale solar thermal collectors, source: [25][24]; ---- Small-scale solar thermal collectors, source: [26].

Furthermore, DH market penetration is hindered as there are no obligations to enforce DH connection to low-energy density regions. In this circumstance, LTDH might be one of the most appropriate candidates to help remove these barriers. The idea of designing the new generation of DH is to develop a flexible, smart and secure energy supply, transmission and distribution system with effective integration of energy efficient buildings and energy efficient DH networks. The reduction of network operating temperatures requires the development of proper DHW and SH systems in order to meet the low-temperature requirements and the limited available differential temperature (difference between the supply and the return temperature) in the buildings. The integrated design approach must be implemented during the design process with overall technical, economical and environmental assessment of the buildings, the DH network and energy supply systems based on RE, waste-to-heat and surplus heat.

3.2 Energy-Efficient Buildings

“Energy-efficient buildings” – also called “low-energy buildings” – is a terminology that refers to buildings whose specific energy use is drastically reduced in comparison to the typical energy use in the building stock or to the minimum requirements set by the national building regulation. Therefore, the specific definition depends on a number of factors, e.g. climate, the practice in the construction industry and the building type and use. Moreover, the limits can be set according to primary energy use and/or energy end-use, so the term “low-energy building” should be defined case by case. In the most advanced building codes, the requirements for low-energy building are listed and continuously updated as a consequence of stricter energy policy targets and improvements in building technology. The following paragraph introduces the definition of low-energy buildings valid in Denmark, which is the basis of this thesis when treating energy-efficient buildings.

3.2.1 Danish Building Regulation

Following the Energy Performance of Buildings Directive (EPBD), Denmark introduced in 2006 a new building code with strict energy requirements for total primary energy demand, including SH, DHW and electricity for pumps, ventilation etc.. The requirements were per m^2 of total heated floor area (floor area of the building measured outside the building multiplied by the number of heated floors). Solar heating and solar electricity production by RE is subtracted in the calculations. The requirements were different for residential buildings and hotels, and office, commercial and public buildings. The requirements were also mandatory for large renovations.

The building code was updated in 2008 and 2010. The Building Regulation (BR) 2006 and its update in 2008 categorized the buildings according to their energy use, defining an energy framework which set the minimum requirements and two classes of energy-efficient buildings: the low-energy class 1 and the low-energy class 2. The BR 2010 version and its updates list the formulae for calculating the maximum annual specific primary energy use for SH, DHW, ventilation and lighting in low-energy buildings (lighting is included only in office, commercial and public buildings, whilst is excluded in residential buildings); there are 3 definitions of buildings, setting the minimum energy requirements for standard buildings respectively in 2010, 2015 and 2020. The formulae are listed Table 3.1 in a historical sequence. In the table, E is the maximum specific annual primary energy use in $\text{kWh}/(\text{m}^2\text{yr})$ and A is the heated floor area in m^2 . The primary energy factor assigned to DH is 1, but it is 0.8 for buildings class 2015 and 0.6 for buildings class 2020. The primary energy factor for electricity is 2.5, but it is 1.8 for buildings built according to class 2020.

That gave substantial interest in construction of low-energy houses. Local authorities (municipalities) could decide that in specific developments, houses must belong to low-energy classes. Local authorities could make mandatory that houses must connect to DH or natural gas, except in the case of low-energy houses.

Table 3.1: Formulae for calculating the specific primary energy demands in buildings [kWh/(m²·yr)], according to BR08 and BR10.

BR08, energy framework (minimum requirements in the period 2006-2010)	
Residential and hotels	$E = 70 + 2200/A$
Offices, commercial buildings, schools, institutions	$E = 95 + 1000/A$
<i>BR08, low-energy building classes</i>	
BR08, low-energy building class 1	$E = 35 + 1100/A$
BR08, low-energy building class 2	$E = 50 + 1600/A$
BR10, Building class 2010 (minimum requirements when this thesis is being written, 2012)	
Residential and hotels	$E = 52.5 + 1650/A$
Offices, commercial buildings, schools, institutions:	$E = 71.3 + 1650/A$
<i>BR10, low-energy building classes</i>	
Residential and hotels class 2015	$E = 30 + 1000/A$
Offices, commercial buildings, schools, institutions class 2015	$E = 41 + 1000/A$
BR10, Building class 2020	$E = 20$

3.3 Factor-4 District Heating

The number 4 recurs frequently in the low-energy DH concept, for various reasons:

- The new concept can be described as the 4th generation of DH, in a historical perspective.
- The concept fits with the needs of energy-efficient buildings, whose SH demand is, as rule of thumb, approximately 4 times lower than in the existing building stock.
- The network design and the operational temperatures are set in order to cut the heat loss by a factor 4, in comparison to traditional HTDH/MTDH networks.

3.4 Long-Term Perspective

According to the national energy policy in Denmark, the building total energy use will drop approximately 25% of the current level by the 2060, while the RE share will increase from 20% to 100% in the meantime [28]. These facts prove that the political will to implement the measures to achieve a low-carbon society is present, together with an ambitious long-term goal. The backbone of the herein presented studies consists of the conviction that such a long-term goal will be effectively reached only if energy-savings and RE supply are holistically integrated. First, this means that long-term investments in technologies not strategically optimized towards the final goal should be avoided; for example this might be the case of the possible extensive use of biomass for heating purposes: if this is at the moment the most economic RE resource, on the other hand it is necessary to consider the increased use of biomass for the transportation sector and food-related issues, which will be urgent topics in the next years. An additional example deals with the fact that LTDH systems might be helpful to avoid putting critical pressure on the power sector, by decreasing the future need for electricity for heating. Secondly, it relies on the belief that the energy supply side, such as DH utilities and power utilities, and entities implementing energy conservation measures, although acting in a market economy, are together part of the same solution, not mere competitors: policy makers should therefore ensure their reciprocal collaboration.

The thesis deals with research aiming at developing the future generation of DH, because such systems seem to be very promising concepts to help solve the global issues connected with the need for climate mitigation policies, increasing urbanization and the security of energy supply. DH is a community energy system that prioritises by definition the “community point of view”, instead of the “single-building point of view” and therefore, in the best cases, considers the many implications to the local, regional or even national energy system. This fact stresses the role of DH technology towards energy-efficient, sustainable and smart communities and is directly linked with the international research of the “IEA-ECBCS Annex 51: energy efficient communities” and of the IEA-DHC|CHP Programme. The fact that Denmark is a mature DH country with a well developed DH infrastructure, where state-of-the-art systems have been built over the last 4 decades, has facilitated the choice of DH as a focus research area, both for the opportunities of interacting with the best available knowledge and for the chance to demonstrate in practice the recommendations derived from the scientific research.

3.5 The Relevance of Low-Temperature District Heating

DH uses a heat carrier transporting energy from centralized heat sources to residential, commercial or industrial consumers. It is traditionally considered a low-grade energy system, often a secondary result of electricity production processes in CHP plants. That is the reason why the common approach often has focused on the production and supply point of views and only afterwards on the final users. The low-temperature concept switches the perspective, putting into focus the comfort requirements of the end-users and, starting from those, tries to find the best economical way to satisfy the heat demand through efficient distribution networks and supply systems based on RE, waste-to-energy and surplus heat. Therefore, the new approach starts from the accomplishment of heating demand and thermal comfort requirements in suitable in-house substations, goes back in designing efficient and reliable networks and finally considers environment-friendly heat production units.

3.5.1 Danish Perspective

The challenges and opportunities the DH sector faces in Denmark were first described at the beginning of the new millennium, when solutions to extend the distribution network to target low heat density areas in a cost-efficient way were brought forward. Since then, research projects have developed and tested new concepts regarding the installations in low-energy buildings and the network operation. Moreover, an ongoing project is testing the potential for applying the LTDH concept to the existing building stock. The main projects are, in chronological order:

2001-2004: EFP-2001: District heating supply to low-energy areas [29].

2006-2009: EFP-2007: Development and demonstration of low-energy district heating for low energy buildings [15].

2008-2011: EUDP 2008-II: CO₂ reductions in low-energy buildings and communities by implementation of low-temperature district heating systems. Demonstration cases in EnergyFlexHouse and Boligforeningen Ringgården [23].

2011-2014: EUDP 2010-II: Full-scale demonstration of future low-temperature district heating in existing settlements (Fuldskala demonstration af fremtidens lavtemperatur fjernvarme i eksisterende bebyggelser, in Danish). The project is ongoing.

The research work reported in this doctoral thesis is in line with the above-mentioned framework and aims at deepening specific issues.

3.5.2 European Perspective

DH has reached very different levels of success in different European countries and this is reflected in Table 3.2, which reports the classification made in [30].

Table 3.2 Classification of the status of the DH market in Europe. Source: [30]

Status of the DH market	Market share [%]	Examples
Consolidation	50-60	Denmark, Finland, Sweden
Refurbishment	10-50	Croatia, Czech Republic, Lithuania
Expansion	3-15	France, Germany, Italy
New development	<1	Ireland, Spain, United Kingdom

* Share in the total number of buildings.

In “consolidation” countries, DH systems are well established and are an essential part of the energy infrastructure. In “refurbishment” countries, DH has also a high market share, but there is need for refurbishment in order to increase reliability, energy efficiency, and cost-effectiveness. The DH networks were generally established and developed in periods with planned economies. In “expansion countries”, DH is well-established in specific urban contexts; however, the total market share is low, but could grow significantly by expanding the existing systems and establishing new systems. Only a small number of DH schemes appear in “new development” countries, although there is growing interest in the technology. The reasons for such significant differences are only to a certain extent linked to climatic differences and could be explained better by historical and socio-economic factors; in fact the specific heat demands are comparable in Western, Central, Eastern, and Northern Europe, as concluded in [31]. Lower heat demands exist only in the Mediterranean and in the south-eastern countries. Hence, European policy makers have the responsibility and opportunity to fill the gap in the knowledge share among the member countries and create suitable conditions which allow DH to contribute effectively to energy targets. In 2007 the European Council stated that the EU energy goal is to reduce by at least 20% GHG emissions from all primary energy sources by 2020 (compared to 1990 levels), while achieving 20% reduction in primary energy use and a share of 20% RE. The Directives that regulate the transition and that are relevant for the DH sector are: the Directive 2010/31/EC on the energy performance of buildings, the Directive 2009/28/EC on the promotion of RE and the Directive 2004/02/EC on the promotion of cogeneration. In the EcoHeat4EU project [30] it was found that although the national implementation of these political measures is valuable in promoting DH schemes, they do not “reflect the need for their synergetic application at local level”.

An important conclusion is that there are a number of measures that can support the effective implementation of DH in Europe; some of them are listed in Table 3.3 and

comprise a mix of economical interventions, regulations and policy tools that could support DH and remove critical barriers.

Table 3.3 List of the policy measures supporting the effective implementation of DH in Europe. Source: [30].

	<i>Support Measures</i>	<i>Description</i>
Demand	Connection grant	Financial support for connecting to existing distribution network
	Building regulations	Laws and regulations that remove the barriers and provide a framework that facilitates DH implementation
	Financial support	Low interest loans that ease capital intensive investments
Distribution	Heat planning/zoning	Local plans to facilitate or enforce DH implementation
	Investment grant	Funds available for the investment in distribution pipelines
	Tax benefits	Favourable tax conditions for DH schemes
	Financial support	Low interest loans that ease capital intensive investments
Production	Support of CHP	Feed-in tariffs or CHP bonus
	Carbon tax	Tax penalties for fossil-fuels use, proportional to GHG emissions
	Investment grants – energy efficiency	Funds available for the investment in energy-efficient heat generation facilities, as CHP
	Investment grant – renewable energy	Funds available for the investment in low-carbon heat generation facilities
	Waste management	Regulating the strategic treatment and disposal of waste, so that it can feed DH schemes
	Financial support	Low interest loans that ease capital intensive investments
Policy	Planning	National regulations where all the measures are listed and coordinated

Some recommendations which were drawn are particularly interesting for DH and are linked with this thesis:

- The necessity for treating “eco-districts”, e.g. block of buildings, neighbourhoods or city quarters rather than individual low-energy buildings.
- The opportunity for combining DH with low-energy buildings.
- Competencies should be created to allow local governments to carry out the activities related to heat planning.
- Feed-in tariffs for electricity from CHP with biomass as energy source should reward energy recovery for heating purposes.
- Waste management should be regulated by national plans and waste should contribute to RE targets.
- Support DH networks that exploit RE that are “future proof”, in terms of heat source shortage and development of future prices.

- Assess the cost-effectiveness of supporting community energy solutions compared to building-based systems using RE sources and define the boundaries between them.

The measures necessary to undertake the paradigm shift are in the context of the necessary GHG emission reductions according to the IPCC recommendations, in order to keep the climate change below 2°C during the 21st century. Besides climate protection, deep reductions in GHG emissions have the potential to deliver great benefits in the form of savings on fossil fuel imports, strengthening energy security, improvements in air quality and public health and stimulating technological innovation, sustainable economic growth, job creation. In line with that, the EU Climate Commission roadmap [32] gives ranges for emissions reductions for 2030 and 2050 for key sectors, see Figure 3.4. The roadmap states that “shifting energy consumption towards low carbon electricity (including heat pumps and storage heaters) and renewable energy (e.g. solar heating, biogas, biomass), also provided through district heating systems, would help to protect consumers against rising fossil fuel prices and bring significant health benefits”. Therefore, DH is clearly defined as part of the solution towards a fossil-fuel-free energy sector.

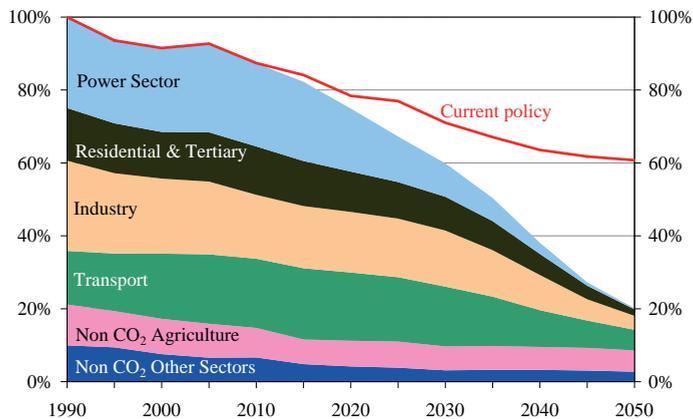


Figure 3.4 GHG emissions trend in the EU towards an 80% domestic reduction (100% = 1990). Source: [32].

3.5.3 International Perspective

The IEA Programme of research, development, and demonstration on District Heating and Cooling, including the integration of Combined Heat and Power (IEA-DHC/CHP) was established in 1983. At present time 9 countries participate in its activities, representing different geographical areas: Europe (Denmark, Finland, the Netherlands, Norway, Sweden and The United Kingdom), North America (Canada and the United States of America) and Asia (Republic of Korea). The agreement deals with joint research activities on the design, performance and operation of heat plants, distribution systems and consumer installations. As reported in [33], “the agreement is

dedicated to helping to make district heating and cooling and combined heat and power powerful tools for energy conservation and the reduction of environmental impacts of supplying heat”, and it has been the platform for international research activities in the field over the last three decades. Figure 3.5 groups the most recent completed research projects in 3 main technological subjects, namely “energy sources”, “networks” and “end-users”, together with the projects that integrated 2 or more areas and the projects that dealt with policy-related matters, e.g. showing the benefits of DHC and/or the political measures that encourage or that are necessary to implement successfully community energy systems.

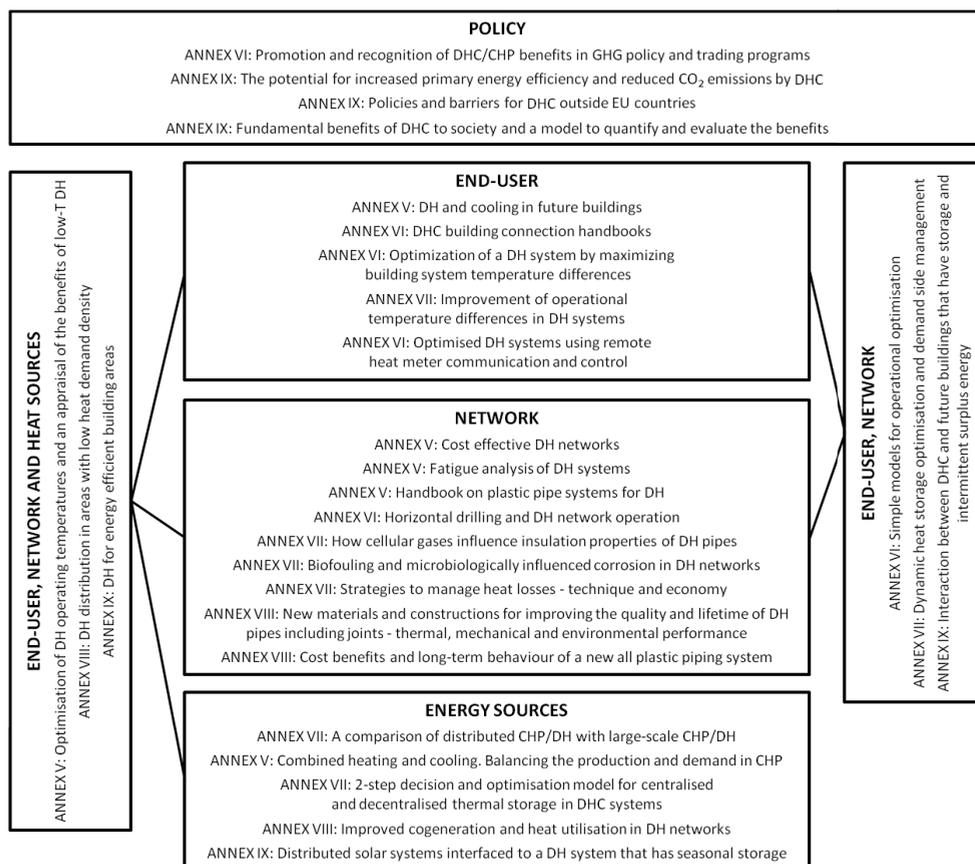


Figure 3.5 Organization of the IEA-DHC research projects over the period 1996-2011 (Annex V-Annex IX), according to their focus subjects.

This provides a holistic framework and historical overview of the development of community energy systems, first focusing on the use of CHP and network design, continuing with the improvement of the network operation and modelling, towards an approach more focused on the end-user side and non-conventional heat sources. In some recent works it was recognized the importance of combining an environmental-

friendly supply system with energy conservation measures, as in the projects “Annex VIII: DH distribution in areas with low heat demand density” and “Annex IX: DH for energy efficient building areas”. This is useful not only for expansion in mature DH countries, but also as a new paradigm for energy sustainability in the heating of buildings. In 2012, the project “Annex X: towards 4th generation district heating: experiences with and potential of low-temperature district heating” started. The research plan shares some common contents with this thesis and that demonstrates the relevance of the issue.

This doctoral thesis and the IEA-DHC/CHP share the same philosophy about the research methodology, that is the integration of optimal technical solutions at the end-users’ side, at the level of the distribution networks and for the heat sources and the suggestion of policy measures that facilitate their implementation (see Figure 3.6).

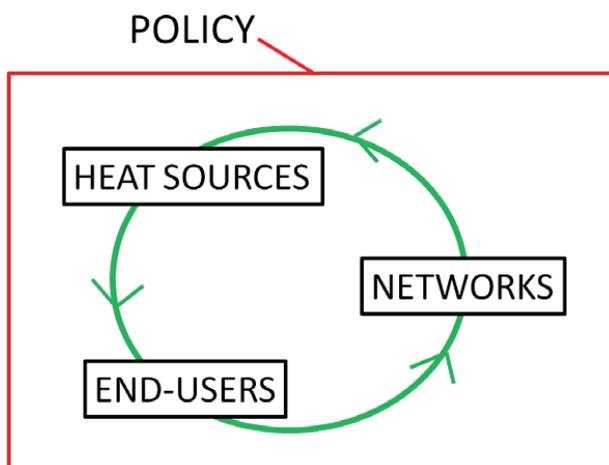


Figure 3.6 Scheme of the framework acting as backbone of R&D projects in district heating.

4 Methodology

Chapter 4 presents the hypotheses which were the basis of the research carried out in this thesis, draws the boundaries between the focus area of the thesis and other relevant aspects of the subject, describes the limitations of the work and lists the methods which were used to perform the studies. The hypotheses derive from the problem statement and the research studies which have been described in the previous chapters. The objective of the thesis was to verify/refute such hypotheses.

4.1 Hypotheses

The research work described in this thesis is based on a series of hypotheses which mainly derive from the content and ideas described in chapters 1, 2 and 3 and represent the object of study. They are summarized by the following statements:

- the issues of climate change, security of energy supply, sustainable development, ecological and health problems connected to fossil fuel exploitation are dramatic problems proven by scientific studies and they challenge science to find long-term solutions.
- The sustainable use of energy relies on the most cost-effective synergy between reduction of energy use and RE deployment.
- The long-term goal is the phase-out of fossil fuels as a primary source of energy in heat and electricity production, industry and in the transportation sector. The heating sector can achieve such a target in a cost-efficient way from the socio-economic perspective earlier than the other sectors, thanks to the optimization of existing technologies.
- Integrated energy planning at the local level, sustained by an effective policy framework, has a fundamental role in defining the path towards energy sustainable communities.
- When treating the building heating sector, DH is a key technology for the sustainable provision of heat for SH and DHW to communities in climates where heating demands are present.
- Innovative design and operation strategies of DH systems, based on low temperature of the heat carrier, can be applied when supplying buildings whose heat demand is dramatically reduced in comparison to the average heat demand of the existing building stock.

- From an engineering perspective, detailed models for the analysis of the steady-state and transient heat transfer in DH pipes are valuable for the design of improved solution and for the study of their energy performance and applicability.
- In countries such as Denmark the DH sector is mature and DH infrastructure is extensively present across the communities. If on one side the target of reducing the heat demand of buildings is an issue to the “business as usual” in the DH sector, on the other it offers the opportunity to make use of the existing networks and adapt and extend them without requiring further heat production capacity, in order to optimally integrate low-grade heat sources and RE in the community and phase-out the use of fossil fuels.
- Countries where the market penetration of DH is low or nil can benefit greatly from the development of new DH systems or expansion of the existing ones, in terms of environmental protection, efficient use of resources and local economy. The process should focus on the application of the best-available knowledge and be consistent with the long-term energy targets and the future trends of the heating demand.
- Boundaries between areas where community energy systems are potentially superior to individual systems based on RE can be defined according to engineering parameters.

4.2 Organization of the Studies

A DH system is here defined as consisting of the heat sources, where the heat is generated or recovered, the network of pipes, through which the heat is distributed by means of the heat carrier fluid and the building installations, which comprise the energy transfer units, the in-house piping and the heat emission system.

The research described in the doctoral thesis focuses on the design, operation and optimization of DH networks that fits the vision of a fossil-fuel free heating sector. Neither the heat sources nor the building installations were part of the main research area as they are currently part of studies carried out by other researchers at the Technical University of Denmark. Nevertheless, it has been inevitable for the sake of the research that reciprocal interactions between both the network and heat sources and the network and the building installations were taken into account.

The structure of the thesis follows the logical order given by the scientific publications that are the core of the thesis itself and are reported in Part II. The main topic and the focus points of each article are summed up in Figure 4.1.

First of all, article I introduces the investigations carried out in the framework of the IEA-ECBCS Annex 51: “*energy efficient communities: case studies and strategic guidance for urban decision makers*” and discusses the strategies that can facilitate

the establishment of successful energy planning in a community. Focus is given to the role of DH, by debating the lessons learnt through the Danish case studies in Lystrup and Aarhus. The information about the two case studies is found in the appendices A and B. The objective of this part of the thesis is to describe by means of examples the socio-political framework and decision processes that help the implementation of sustainable energy projects, and in particular district energy projects.

Next, detailed technical analyses are performed. The investigations in article II deal with the modelling of the thermal transfer in DH pipes, the validation of the models by experimental measures and the study of how to best assess the steady-state heat loss of various DH pipe configurations and materials. The method can be applied in daily engineering studies by pipe manufacturing companies.

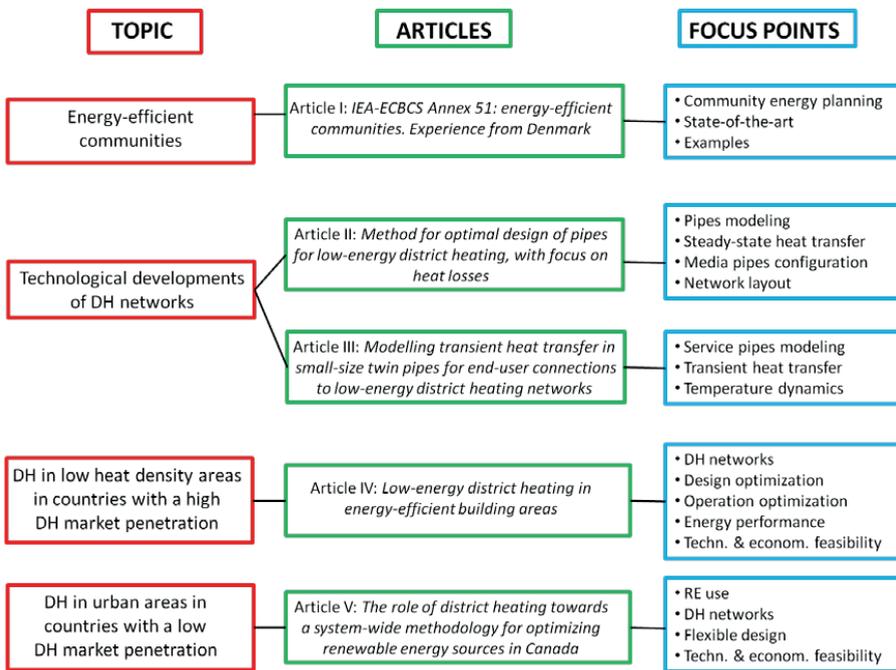


Figure 4.1 Main topic and focus points of the 5 scientific publications.

Article III is linked to article II because it treats DH pipes too, but modelling now the transient heat transfer and specifically the service pipes, which are important elements of LTDH networks, particularly when supplying low-energy density building areas.

In article IV the results of article II and III are applied together with simulations and analyses of low-energy DH networks supplying heat to low heat density areas with energy-efficient buildings, which is a natural application of the 4th generation DH concept in countries with well-established DH systems. The study considers the conditions in Denmark, regarding climate, economy and building construction.

Finally, article V deals with the potential and barriers of implementing DH in countries with a different tradition in the energy field than Denmark and a low market share for DH. Techno-economical feasibility studies for DH networks supplying an urban area in the city of Ottawa, Canada is performed and the impact of lower operating temperatures is assessed, with particular attention to developing the potential for RE-based heat supply.

4.3 Methods

The methodology used in the research work is to gather the results of experimental investigations carried out at the laboratories of the Department of Civil Engineering, Technical University of Denmark, computer-based simulations with the use of commercial software and the development of computer programming codes.

The complete description of the experimental facilities is available in the method chapters of article II and article III, in the PART II of this thesis.

The calculations were made possible by extensive use of state-of-the art software or models created through computer programming. Four families of computer-based tools have been used: software applying the Finite Element Method (FEM) for detailed calculation of differential equations (COMSOL Multiphysics® and ANSYS Fluent®), the programming language MATLAB®, the district energy network simulation software TERMIS®, and the Geographic Information System (GIS) software ArcGIS®.

COMSOL Multiphysics® is a finite element analysis, solver and simulation software package for various physics and engineering applications, especially coupled phenomena, such as thermal and fluid dynamic phenomena. It was the basis for the work documented in the article II and in the article III.

ANSYS Fluent® is simulation tool for computer-aided engineering that contains the physical modelling capabilities needed to model flow, turbulence and heat transfer. The simulations ANSYS Fluent® reported in the article III, PART II were carried out by Senior Researcher Hongwei Li, Technical University of Denmark.

MATLAB® is a numerical computing environment and 4th generation programming language, which allows matrix manipulations, plotting of functions and data, implementation of algorithms. MATLAB is widely used in academic and research institutions as well as industrial enterprises. It was used for article III.

TERMIS® is a district energy network simulation platform for network design, dimensioning and operation. The software can be used for planning purposes and for evaluating the network performances or design alternatives. Its real-time version is in use for network operation in approximately 500 cities in the world in connection with

Supervisory Control And Data Acquisition (SCADA) systems. TERMIS was used in the studies which were reported in articles IV and V.

ArcGIS® is a Geographic Information System (GIS) tool for working with maps and geographic information. It is used to create and use maps, compile geographic data, analyze mapped information and manage geographic information in a database. It was used for article V for mapping building data and energy use data from municipal and energy utility databases.

The description of the service pipe model simulated by an algorithm in the programming language MATLAB® is described in the chapter “methods” of article 3 and the main code is reported in appendix C.

5 Results and Discussion

This chapter describes and explains the results of the scientific content reported in the articles of PART II. The discussion is organized in a successive way, from article I to article V and it is meant to present the results logically and comprehensively. The previous chapters of the thesis explained the purpose of the study, the hypothesis whose truthfulness is the object of investigations and the methodology applied. The starting point is in chapter 5.1, where the experiences developed in the field of community energy planning by some IEA countries are shared and the role of DH is pointed out, starting with existing, past and present case studies and drawing a path towards the use of the best energy planning strategies and tools towards the implementation of energy sustainable communities.

5.1 Community Energy Planning

Article I introduces the subject of the planning of energy-efficient communities, analyses the state-of-the art, discusses critical issues that should be taken into account and point to the role of DH towards a sustainable heat supply.

5.1.1 IEA – ECBCS Annex 51

The article deals with the summary of the Danish preliminary contribution to the project “IEA-ECBCS Annex 51 energy efficient communities: case studies and strategic guidance for urban decision makers”, which is a 4-year collaboration project (2009 – 2012) among 11 countries: Austria, Canada, Denmark, France, Finland, Germany, Japan, Sweden, Switzerland, The Netherlands, USA. The players addressed by the project are energy planners, decision makers on community investments and local administrations. The aim of the Annex 51 is to provide guidelines for the design of long-term energy conservation and GHG mitigation strategies and their continuous optimization at a community level. The term “community” includes neighbourhoods, city quarters, small towns and entire cities, thus defining different approaches, requirements and levels of complexity. The objectives of Annex 51 are:

- to identify management methods that use delegation of responsibilities, marketing and conflict resolution tools, that can support Local Energy Planning (LEP).

- To use an integrated and multidisciplinary approach as a basis for providing tools, guidelines, recommendations, best-practice examples and background material for designers and decision makers.
- To enable communities to set up sustainable and secure energy infrastructure and identify the specific actions necessary to reach ambitious climate and energy goals.
- To transfer experiences among communities and enable them to establish their own local strategy and effective LEP.

The novelty of the approach lies in exploring effective paths that implement energy-efficient, low-carbon technologies in communities at an increased rate and are therefore the basis for creating sustainable communities. The project was structured in 4 subtasks, respectively subtask A, subtask B, subtask C and subtask D.

Subtask A: “*state-of-the-art of energy efficient projects at the scale of neighbourhood*” provided a review of the state-of-the-art of planning methods and existing tools and models for urban energy planning and the relevant instruments for implementation, which are currently used by or are available in the participating countries. It therefore envisaged successful examples for community energy planning projects with reference to energy planning methods and implementation strategies, the review of data acquisition methods and monitoring tools for energy and GHG balances; moreover it analyzed the state-of-the-art urban or local energy system modelling and simulation tools for the design of energy supply systems and energy demand calculation. Finally, after assessing different approaches in the participating countries, it described the requirements of legal framework for urban energy and climate change policies. The summary of part of the Danish contribution to the subtask A is present in the PART II, article I, whereas the full subtask A report is available in [34].

Subtask B: “*case-studies of local energy planning for neighbourhoods or city quarters*” dealt with either energy renovation projects, or new settlements at a neighbourhood/city quarter level. The case studies to be considered in subtask B were energy planning projects, whose essential part of the realization phase took place during the Annex 51 time plan, and implemented innovative technologies and/or planning methods. The key issues in subtask B were the planning and implementation of local energy projects concerning energy-efficiency, energy conservation and use of RE and an evaluation of the experiences made in the implementation of specific technologies and non-technical framework such as organization or implementation processes and lessons learned. The summary of part of the Danish contribution to the subtask B is present in the PART II, article I, whereas the full subtask B report is available in [34]. An additional contribution to subtask B is given by the case study of Lystrup, which is reported in appendix A.

Subtask C: “*case studies of integrated energy planning for cities and implementation strategies*” described methods for holistic long-term energy planning for entire

towns/cities and how to lead the transition process from the specific present situation to a future ambitious vision of energy sustainability.

The case studies within subtask C illustrate methods for a realistic estimate of the energy use and the energy performance of the existing energy systems of whole towns/cities. Secondly, it lists tools for the continuous recording of energy and CO₂ balances at the city scale. In addition to that, it aims at deriving the best combination of measures that will enable the town/city to achieve its long term energy targets. Finally, it uses methods and instruments usable to support urban decision makers in developing and implementing effective long-term energy strategies for the community. The Danish contribution to subtask C is represented by the case study of the city of Aarhus, which is reported in appendix B.

Subtask D: “knowledge transfer and dissemination”. The main purpose of subtask D is to elaborate the means that are necessary to enable decision makers in urban administrations, developers and urban planners to establish and implement a successful local or urban energy strategy. It makes use of the studies and lessons learnt from the other subtasks. The outcome is the preparation of the “*Guidebook to Successful Urban Energy Planning*” and the development of the software “*Energy Concept Adviser for Districts (D-ECA)*” [34].

5.1.2 General Conclusions

The lessons learnt from the Danish case studies and the comparison with the experiences made in other countries lead to some general conclusions on how to organize and structure the planning and implementation process of an energy project. The essential considerations linked to the topic of the thesis are listed herein:

- it is essential that the decision makers define and communicate the energy targets which are then implemented by the municipal instruments such as master plans, bylaws and contracts with the developers. The targets should be based on clear figures defining the "sustainable community", including the GHG emission reduction, the efficient use of energy, the use of RE and the improved socio-economy and quality of life.
- Efficient use of energy, GHG emissions reduction and increased use of RE need to have benchmark targets in urban development projects. The applied indicators should reflect the priorities chosen by the decision makers in their list of objectives for the specific project. Traditionally, either final energy use or primary energy indicators are used for buildings and communities. Both final energy and primary energy ratings must be considered, because evaluating only the end-user energy use does not give the possibility to quantify energy generation from local RE sources and using only primary energy use could lead to sub-optimal situations, where RE is utilized to compensate energy inefficiencies that lead to high final energy use.

- The consistent monitoring of energy production, distribution and use throughout the project phases is an important aspect that provides the necessary inputs to the energy models, helps identify the necessary improvements by comparing the initial targets with the achieved performance and provide insights on the optimization of the operation [35]. Monitoring criteria should relate both to the targets set and to the implementation process itself. It should allow the evaluation of the achievements in several phases during and after the implementation and it can be used as an instrument to guarantee quality control and to check the project success.

- It is important to structure the overall planning framework, so that clear successive phases are identified. Figure 5.1 shows an example of a simplified scheme.

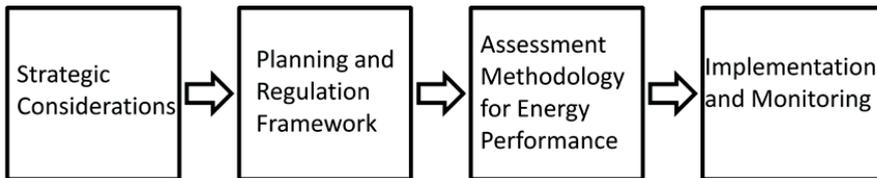


Figure 5.1 Diagram of a proper energy planning process. Derived from [36].

This offers the constant overview of the different tasks and indicates when involvement of different stakeholders is required and/or the level of accuracy of energy models. Besides that, together with suitable monitoring, it assists quality management and control.

- The driving forces and targets not directly related to sustainable energy, such as social protection, mix use of urban areas, increase economic value of a community or its market attractiveness must be included in the overall decision, planning and management process, since synergies or conflicts might arise. The introduction of local RE sources with the active involvement of the people that have an interest in the community is a typical possible synergy, as proven by the case study of Samsø island; a potential conflict might arise for instance when investments in energy conservation and RE cause higher rents that the stakeholders do not consider.

- The success of urban development projects related to energy relies on an effective decision, planning and implementation process that achieves the technical and societal objectives in a way that is quantitatively or qualitatively measurable. Hence, it is essential to set the framework in which the policy or energy concept takes place, the definition of indicators describing the outcome expected and a reference against which the results are measured. During the running time of the development projects there are often changes that influence the plans and goals and might damp the objectives or even jeopardize the partners' commitment and the success of the project. For this reason, it is suggested that contractual agreements are structured to ensure that targets originally set are constantly pursued. At the same time, long-term development contracts demand flexibility of the stakeholders, but in turn ensure that the final outcome remains clear and can be used to justify the investments required.

- Steering groups representing the fundamental stakeholders, such as the politicians, the energy utilities, the housing associations and the developers should be created, to ensure that the success of the project is as much as possible independent from the capacity of individual leaders, but relies instead on a well established process, as stated in [35].

5.1.3 Case Study of a Low-Temperature District Heating Network

The specific considerations and the lessons derived from the Danish case study for the subtask B are listed in this paragraph. The technical details about the project “*low-energy community in Lystrup, Denmark*”, which is one of the first demonstration project of a LTDH network serving a low-energy housing settlement, can be found in appendix A. Additional conclusions are gathered here below:

- the low-energy residential area was originally planned to be connected to the main DH network in Lystrup, according to a traditional layout of the pipeline, based on a pair of single pipes (supply and return) and common design operating temperatures in Denmark ($T_{supply}=80^{\circ}\text{C}$ and $T_{return}=40^{\circ}\text{C}$). Before the implementation of the energy supply system, the plan was changed in order to implement the LTDH concept, since the site was assessed as a suitable location to test the technical and economical feasibility. This decision brought more investment capital to upgrade the initial project and enhanced both the economic and environmental sustainability of the project in the long-term perspective (30 years). The flexibility of the decision makers – mainly the board of the housing association – and their readiness to take the chance was decisive for the success of the project. This is a successful example of how a flexible decision process is desirable, despite the need for clearly defined targets.
- The recognition of the existence of a market in Denmark for sustainable, energy-efficient and environmentally-friendly houses was an additional motivation for starting the project, from the housing association point of view. In fact, the completed dwellings were fully occupied by tenants faster than in other newly established areas, despite the housing sector crisis in the same period.
- The people involved in the project agree in saying that the “neighbourhood approach” is more profitable and achieves better results than the “local approach”. A better socio-economy is possible, if the energy plan is done for the community as a whole instead of considering local plans for the single housing units.
- The subsidies from the EU and the Danish Energy Agency had a central role in the overall financial feasibility of the project. The project could not have been realized to the same extent without those capital resources, due to the risks involved for private investors in applying solutions that aren't standard.
- The project is among the first of this type, thus the lack of experience was a barrier at the beginning. The obstacle was removed by relying on qualified expertise groups in each sector, such as top architectural firms for designing the buildings, building

components producers from abroad for supplying cost-effective solutions, and a DH R&D group for implementing the innovative solutions.

- The pay-back time of the new generation of DH systems implemented at the site is between 20 and 30 years. The low value of the return on investment was certainly seen a barrier, but it was not decisive for the project. The sustainability targets had the priority, once the financial resources were found and the economical figures reasonable. The board of the housing association claimed to be aware that they need to gain experience, in order to compete in a market where the requirements become stricter and stricter.

5.1.4 Municipal Heat Plan for a Carbon-Neutral Heating Sector

This paragraph summarizes the lessons learnt from the Danish case study for the subtask C. The description of the case study “*municipal energy plan towards a carbon-neutral city in the city of Aarhus, Denmark*” can be found in the appendix B. The main statements that can be made are:

- two main planning processes were articulated through the comparison of the case study of Aarhus and the case studies in the other countries: forecasting energy planning and backcasting energy planning.

The first approach consists of phases, where starting from the definition of the potential within a specific time horizon, successive steps (energy projects) are implemented and as consequence a certain result is achieved; the long-term outcome can deviate more or less from the originally desired target, depending on the accuracy of the plan and on the success of the projects.

Forecasting is based on putting into practice the existing best-practices and foreseeing what can be achieved. In this way, the future situation is predicted based on scenario trends.

In the backcasting approach the target is clearly set and the policies and measures that will connect the future goal to the present situation are then defined backwards; in such a process the focus is on the discussion of the optimal actions that will assure the achievement of the final target. The forecasting approach has the advantage that it can be based on a series of clearly defined actions, whose result has an impact that is generally quantifiable and occurs in the short-term. Its main limit is that there might be a weak link between short-term objectives and the long-term target and the pattern towards the end-goal can thus deviate significantly from the optimal one.

The main disadvantages of the backcasting approach is that it can encounter barriers that could stop or slow down the process, since some stakeholders would prefer to engage in projects with a clear, short-term result rather than implementing measures whose effect will fully appear only when approaching the completion of the whole plan. An ideal planning process consists therefore of a mixture of the two aforementioned concepts. For example, the plan for action is first designed following a backcasting approach. Nevertheless, each phase is broken down to smaller projects,

which offer short-term results and can be individually assessed, so that forecasts can be made and used to evaluate if the measures taken are actually leading to the desired target, and in an optimized way.

- The heat plan for the municipal DH system must seek to be consistent with the overall municipal climate plan and with the national climate plan too, so that policies and energy measures at different levels are sustaining each other. In the example of Aarhus, even if the full conversion of the heating supply to RE sources is assessed to be possible in the next two decades, there are issues connected to the use of biomass as primary source of carbon-neutral heat because of the possible competition in the biomass market in the near future. It is important that the use of biomass for heating purposes is considered as a transition technology to be superseded by intensive energy savings and alternative long-term technologies, such as geothermal energy, solar thermal, heat recovery from thermodynamic processes and efficient-use of surplus electricity from wind power generation.

- A “climate partnership” is a framework for creating concrete cooperation and preparing binding agreements between business entities, knowledge institutions and public bodies. Climate partnerships facilitate the collaboration between companies and knowledge institutions on concrete development projects and new use of existing solutions. They focus on creating business growth and company results, which are important to achieve the commitment of the private sector. In Aarhus, the first part of a climate partnership agreement obliged companies to reduce their internal energy demand and it was followed by a second part that committed the companies to participate in innovative projects to develop new concepts and products that can create green growth in the community. Simultaneously, the local government committed to create the necessary framework for actors’ cooperation, including e.g. to influence the legislative and infrastructural framework that is needed for the development of commercial climate solutions. Moreover, the municipality of Aarhus acted as stimulator in pushing the whole community to get involved in climate-related projects, by taking the lead in projects financed by the State within the energy focus areas.

- Aarhus developed a tool to monitor and map its total CO₂ emission. In this way, it was possible to obtain awareness of where the city needs to focus its attention and the opportunity to estimate the impact of specific measures.

- After setting the targets and preparing concrete plans of action the local government must lead the process of converting governmental-driven and local-authority-driven urban planning into a climate partnership with the private sectors and the citizens. In practice the municipal authority is acting as a front-runner and tries to fully exploit its role, being the main promoter of climate-related projects, but trying also to involve the private sectors and all the citizens, starting in the case of Aarhus, from its own employees.

- The example of energy planning in Aarhus, although still to be fully implemented, demonstrates that capital investments towards a long-term ambitious climate target

can be financed by normal municipal budgets, without extraordinary State subsidies. On one hand, this is made possible by the relatively high municipal taxes, the consequent level of financing resources and the leading role that municipalities have in Denmark, but on the other hand it shows that sustainable energy planning can effectively be part of city master planning.

5.2 Modelling of the Heat Transfer in District Heating Pipes

Articles II and III aim at providing science-based knowledge for the development of improved solutions for the DH networks; hence they focus on DH pipeline modelling and performance simulation. Article II considers the detailed steady-state modelling and analysis of heat losses in pre-insulated DH pipes, whereas article III focuses on the modelling and computation of the transient heat transfer and temperature dynamics in small-size DH service pipes. In general terms, they provide models and tools for assessing the energy performance of new pipe geometries, materials or system configurations. The models were validated against experimental measurements.

5.2.1 Steady-State Heat Transfer

Table 5.1 lists the standards that describe the calculations of the heat transfer in DH pipes and the thermal properties of pipe materials. Calculation of heat loss and insulation properties, such as the thermal transmittance, U and thermal conductivity, λ_i is relatively simple for single pipes, where the geometry consists of concentric circles: formulae can be derived directly from Fourier's heat transfer theory [37]. The geometry of twin pipes (see Figure 5.2) or, in the most general case, DH pipes with at least two media pipes embedded in the same insulation is more complex, and simple analytical calculations cannot be performed. Although the standard for flexible twin pipe systems EN 15632-1:2009 introduces the definition of radial thermal resistance, R_{TPS} , and thermal conductivity, λ_{TPS} , the standard basis for calculating both R_{TPS} and λ_{TPS} has been shown to be flawed because formulae are not dimensionally correct and, in the case of λ_{TPS} , even not accurate [38].

The study [38] suggested the corrections to be made, so that the formulae become dimensionally correct and give results closer to experimental results. The conclusion is that a common, accurate and wide-spread methodology to evaluate the thermal properties of twin pipes does not exist and therefore needs to be developed.

Table 5.1 List of standards for calculations and measurements of thermal properties and heat transfer in DH pipes. Derived from [38].

	Parameter	Straight Pipes	Flexible Pipes
Single Pipe System	λ_i	EN 253	EN 12667
	λ_{SPS}	-	EN 15632-1
	U	-	EN 15632-1
Twin Pipe System	λ_i	EN 253	EN 12667
	λ_{TPS}	-	EN 15632-1
	U	EN 15698	-
	U_{TPS}	-	EN 15632-1

The use of pre-insulated DH twin pipes is predicted to prevail in the coming years, thanks to the improved thermal performance and the savings in the civil works connected to the laying of the pipes into the ground, and this makes the study of the heat transfer in twin pipes relevant.

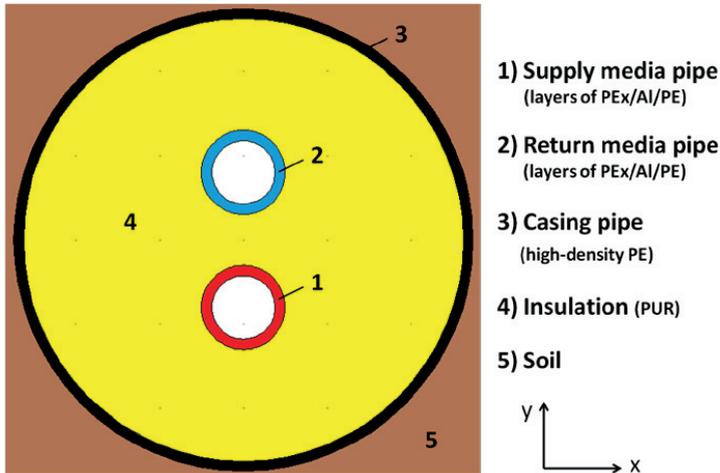


Figure 5.2 Geometry and materials of a flexible, pre-insulated, twin pipe. Example: Aluflex 20-20/110, cross-section x - y .

The standard EN 15632-1:2009 indicates that the thermal conductivity of the insulation material, λ_i , should be found by measurements according to the EN 12667:2001, which is based on measurements on samples of insulation material taken from pipe manufactures. Since the thermal conductivity of a material depends on the temperature, there is the need to define the function $\lambda_i = f(T)$, where T is the temperature of the insulation at a specific point, which in a cross section of the pipe in the plane x - y can be defined by its coordinates (x, y) (see Figure 5.2); therefore λ_i is not constant across the insulation domain, but varies from higher values, for example in the central zone of the pipe, between the two media pipes, and lower values, for

example in the outer regions near the casing pipe. This approach is theoretically the most accurate to evaluate the heat transfer between the pipes and between the pipes and the outer environment (air or soil), but it is difficult to measure $\lambda_i = f(T)$ with accuracy.

The practice in Denmark is to perform measurements of total heat loss, media pipe temperatures and casing pipe temperatures in ambient air for a number of set heat carrier temperatures and compares the values with FEM simulations [38]. The temperature of the heat carrier inside the supply and return media pipes is generally kept the same, to obtain the most symmetrical thermal conditions. The value of thermal conductivity of the insulation, which is considered constant inside the whole insulation domain, is found by trials, so that it fits the experimental data. This approach has the advantages of being linked to the products, can be thus used for certification and is accurate in predicting the total heat loss. Nevertheless, the calculation of the heat transfer inside the DH pipe is less accurate, because of the assumption of constant thermal conductivity of the insulation across the pipe section. This methodology results in the definition of λ_i as function of a specific insulation average temperature, T_{avg} . A linear expression for $\lambda_i = f(T_{avg})$ has the following form:

$$\lambda_i = a \cdot T_{avg} + b \quad (5.1)$$

where a and b are constants.

Given:

T_1 : supply temperature; T_2 : return temperature;

T_0 : ambient temperature;

d_1 : outer diameter of the supply media pipe;

d_2 : outer diameter of the return media pipe;

d_c : outer diameter of the casing pipe;

the average temperature of the insulation, T_{avg} , has in the literature been defined in different ways, among those:

1) According to the standard EN 15632-1:2009:

$$T_{avg} = \frac{\frac{(T_1+T_2)}{2}+T_0}{2} = \frac{(T_1+T_2)}{4} + \frac{T_0}{2} \quad (5.2)$$

2) According to the definition in [38]:

$$T_{avg} = \frac{(T_1+T_2)}{2} - T_0 \quad (5.3)$$

3) According to L. E. Pedersen's definition [38]:

$$T_{avg} = \frac{(T_1 \cdot d_1 + T_2 \cdot d_2 + T_0 \cdot d_c)}{d_1 + d_2 + d_c} \quad (5.4)$$

4) More accurate, but also more complex calculation of the average temperature of the insulation, T_{avg} , is possible with the application of the multipole method [40] or FEM simulations and following the definition:

$$T_{avg} = \frac{\int T \cdot dA}{A} \quad (5.5)$$

where T is the temperature in the insulation, varying with the coordinates (x, y) in the insulation domain and A is the cross section area of the insulation. The value of T_{avg} is calculated numerically. When modelling and designing DH pipes geometries it would be ideal to have as input datum the relation $\lambda_i = f(T)$, as characteristic of the specific insulation material used in the manufacturing of the twin pipe, so that such relation could be applied to model the conductive heat transfer in the insulation domain. Unfortunately, such relations that follow the first aforementioned method do not exist at present time, to the author knowledge. The approach used in article II was to consider a specific linear relation of the type $\lambda_i(T_{avg}) = a \cdot T_{avg} + b$, where a and b were constants and T_{avg} was defined according to EN 15632-1; the formula had been taken from the best available data [15], and then applied to the whole insulation domain, i.e. considering λ_i as function of the temperature T in the specific position (x, y) of the insulation. This is equivalent to assume that: $\lambda_i(T) = a \cdot T(x, y) + b$. It is useful to consider $\lambda_i = f(T)$ when designing the pipe geometry, rather than a unique value of λ_i for the whole insulation (as in $\lambda_i = f(T_{avg})$), because the proposed methodology takes into account that in the region of the insulation at higher temperature the conductive heat transfer is facilitated in comparison to the regions at lower temperature.

The consideration above demonstrates the lack of knowledge and agreement in the definition of the thermal properties of twin pipes; however, with such products foreseen to increase their importance in the future market, there is a need to determine common calculation methods, which are on one hand sufficiently accurate, and on the other can be standardized and used for certification of products. The general conclusion of article II is that it is recommended to use FEM models and simulation both when a high degree of detail is valuable, such as when designing new pipe geometries and systems and when developing improved calculation procedures for adapting the existing theory.

The first recommendation is further treated in article II, which shows a methodology of how to make use of FEM analysis for designing DH twin pipes and evaluate new pipe system concepts. The latter subject will be treated in a future research project³.

³ Project financed by the Dansk Fjernvarme F&U-konto in 2012 for the period March-December 2012: "Forbedring af test og beregningsmetoder af varmeledningsevnen i twinrør" ("Improvement of test and calculation methods of the thermal conductivity in twin pipes", in Danish). Results will be available at www.fjernvarmen.dk

5.2.2 Transient Heat Transfer

The focus of article III is the modelling and computation of the transient heat transfer in service pipes, which are important elements of LTDH networks, particularly when supplying low heat density building areas. The code modelling the transient heat transfer was proven to be accurate, since it gave results that well represented the outlet temperature profile measured in the experiments, with deviations of less than 0.5°C; moreover it is in good accordance with the detailed, finite-volume simulations, both when there is a step change in the inlet temperature and when there is a sinusoidal inlet temperature profile. The model was used to propose an integrated solution consisting of service pipe, a Heat Exchanger (HE) unit with a booster pump, and the in-house service pipelines which satisfies the requirement for supply of DHW within 10 s and achieves heat savings greater than 200 kWh_{th}/yr with an additional electricity use of approximately 58 kWh_{el}. This means that the proposed solution is reasonable from the energy point of view, because it gives a reduction of primary energy use of ~12% (the primary energy factor is 0.8 for DH and 2.5 for electricity).

The model can be applied to study transient, coupled fluid-thermal phenomena in service pipes. This paragraph describes an example of application. The heat demand in buildings decreases outside the heating season because the final users need heat only in connection with DHW use; the demand of DHW is particularly discontinuous and it is generally needed for less than 1 h/day in typical single-family dwellings. The lack of heat load would cause the undesirable cooling of the network to temperatures that would become insufficient to assure the prompt provision of heat when DHW preparation is required, if proper control strategies are not implemented.

That is the reason why control valves are installed at the end-users' energy-transfer units and/or at suitable locations in the network: their purpose is to direct ("bypass") a relatively low water flow from the supply media pipe to the return media pipe, so that the heat carrier temperature along the network is maintained inside the required range of operation. The effect of the bypass is a certain flow achieved during low heat load periods leading to a minimum supply temperature in the network. This operation, although necessary, is a cause of heat loss and is particularly critical in case of low-energy demand building areas. The heat losses due to the bypass operation can exceed the heat demand of low-energy buildings outside the heating season; moreover, the fact that in low-energy buildings the total duration of the periods with SH demand is generally shorter than for traditional buildings, accentuates the importance of an optimal bypass operation. Most bypass controls are operated by a thermostat and they are defined by the set-point temperature, $T_{bypass, set}$ and the amplitude of the "dead band", ΔT_{DB} , which also defines:

$$\text{- the "top temperature": } T_{bypass, top} = T_{bypass, set} + \Delta T_{DB}/2 \quad (5.6)$$

$$\text{- the "bottom temperature": } T_{bypass, bottom} = T_{bypass, set} - \Delta T_{DB}/2. \quad (5.7)$$

The control ensures that the temperature is kept inside the range of operation set by the dead band. The investigations herein deal with the comparison of the energy performance of two theoretical bypass operations. The first is the ideal situation where a time-constant and continuous bypass flow is kept through the service pipe in order to maintain $T_{bypass, set}$ at the service pipe outlet, where the bypass control is assumed to be located. The second one is the case of a perfectly “intermittent” bypass operation: the bypass during the intermittent operating mode is modelled as an ideal control that is acting like an on/off switch. When the temperature at the outlet of the service pipe reaches a specific value, $T_{bypass, top}$, the bypass flow instantaneously stops; the pipe is now in the “stand-by” mode, meaning that there is no flow in the media pipe and the water gradually cools down; after a certain time, that in the examples is either 15 min, 30 min or 60 min, the temperature at the service pipe outlet has decreased to the value of $T_{bypass, bottom}$, and the bypass flow instantaneously develops again.

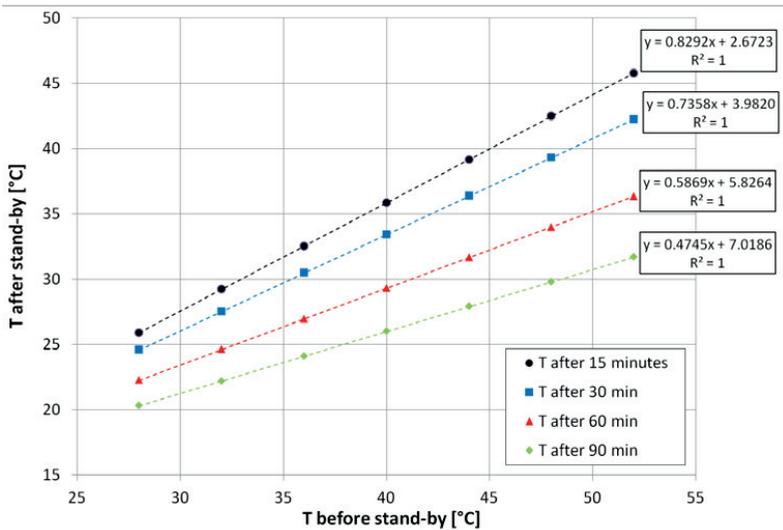


Figure 5.3 Examples of cooling-off curves of the heat carrier, derived by 2-D transient heat transfer simulations in COMSOL Multiphysics. Service pipe: Alx. 20-20/110. At $\tau=0$ s: $T_{soil}= 8^{\circ}C$, $T_{PUR}= 15^{\circ}C$, $T_{return}= 25^{\circ}C$.

A cycle of “intermittent bypass” consists of a period with water flow from the main distribution line to the service supply pipe outlet – the “bypass mode” period – and a period when there is no flow and the water inside the media pipe cools down, the “stand-by” period; after that, another cycle starts, in a process that can be modelled as periodical. The bypass period was modelled by the code developed in the article III (see appendix C), whereas the cooling of the water during the stand-by period was evaluated by regression curves derived by 2-D transient heat transfer simulations in COMSOL Multiphysics, see Figure 5.3. Given a 2-D cross section of the service pipe a specific supply water temperature and certain boundary conditions, it is possible to

calculate the transient temperature field in the pipe, indeed (see Figure 5.4). The model of the DH pipes in the heat transfer simulations were built according to the methodology explained in the article II.

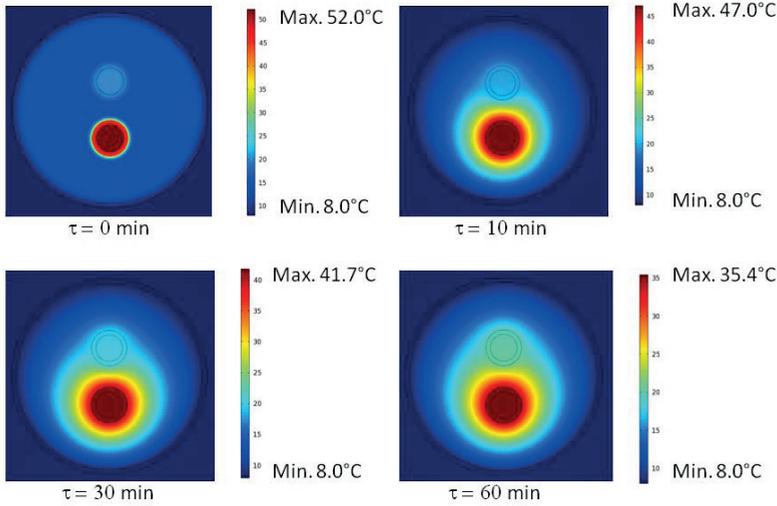


Figure 5.4 Cooling of the water in the supply media pipe of the service pipe during the stand-by period. Example: service pipe: Alx. 20-20/110. At $\tau=0$ s: $T_{soil}=8^{\circ}\text{C}$, $T_{PUR}=15^{\circ}\text{C}$, $T_{supply}=52^{\circ}\text{C}$, $T_{return}=25^{\circ}\text{C}$.

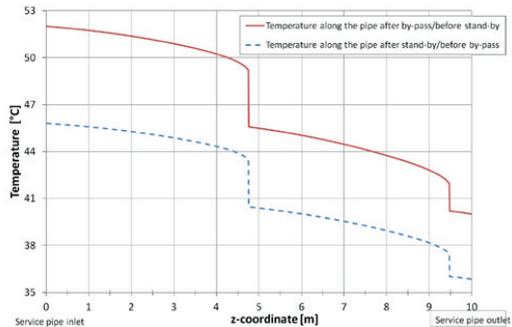
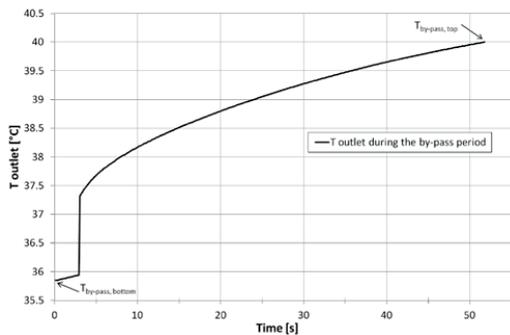
The current status of development of the code can handle only constant bypass water flows, whilst time-dependent inlet temperature profiles can be modelled. In real cases the bypass valve is thermostatically controlled and therefore the flow is time-dependent. This does not affect the use of the code to study the dynamics in service pipes, which is the purpose it has been developed for.

This approach was applied to the service pipe type Aluflex 20-20/110 from the manufacturing company Logstor. It is a typical product for connection of single-family buildings equipped with a DH HE unit. The reference pipe was 10-meter long; $T_{bypass, top}$ was set to 40°C and $T_{bypass, bottom}$ was set equal to the temperature at the service pipe outlet after either 15, 30 or 60 minutes of stand-by period. For the intermittent bypass case, various water flows were applied, defining either laminar flows or transient/turbulent flows. Figure 5.5 shows three examples. On the left side the service pipe temperature outlet vs. the time is plotted during the bypass period; on the right side the figure shows the heat carrier temperature along the z -direction of the pipe at the instant after the bypass flow has stopped/before the stand-by period begins.

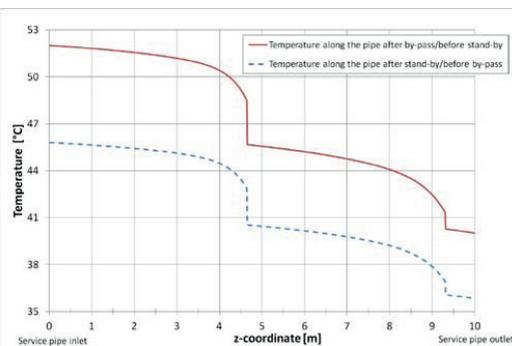
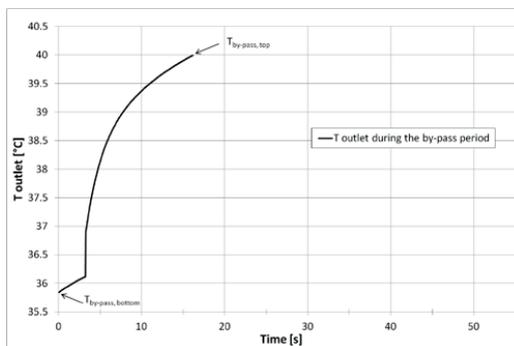
Different values of bypass flows and bypass set temperatures lead to different heat carrier temperatures profiles along the service pipes and consequently to different energy loss, being the boundary conditions the same. Figure 5.6 groups the results of

the simulations, taking a six-month period, i.e. a realistic duration of the bypass operation during a year.

a) Reynolds number, $Re = 2100$



b) $Re = 6700$



c) $Re = 13300$

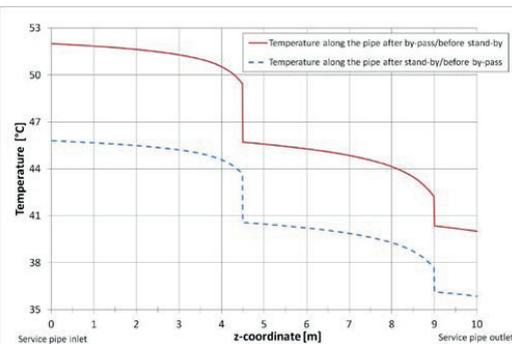
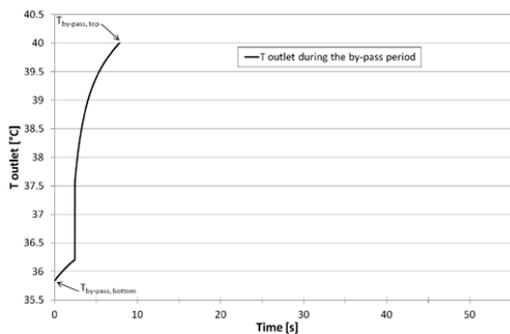


Figure 5.5 Intermittent bypass operation. Left: bypass period, outlet temperature vs. time. Right: stand-by period, heat carrier temperature vs. the longitudinalz-coordinate. Bypass flow: a) 0.96 kg/min; b) 3.0 kg/min; c) 6.0 kg/min.

In case of intermittent bypass, it is possible to see how higher $T_{bypass, bottom}$, due to shorter stand-by periods for the same $T_{bypass, top}$, brings along higher energy use, which is caused by higher time-averaged temperature levels of the heat carrier in the service pipe. At the other end, the more frequent use of the bypass ensures the faster provision of DHW at a specific temperature and thus enhances the users' comfort and reduces the use of potable water.

There are no significant differences in the energy use connected to fluid dynamics considerations for the laminar regime vs. the transient/turbulent regime; the horizontal dashed lines indicate the average energy use in the intermittent bypass zone.

The continuous flow that keeps the same average temperature at the service pipe outlet as in the case of intermittent bypass was calculated according to [41], being the supply temperature at the service pipe inlet the same in the two cases. The most important conclusion is that the continuous bypass operation saves heat equivalent to up more than one third of the heat use for the intermittent bypass.

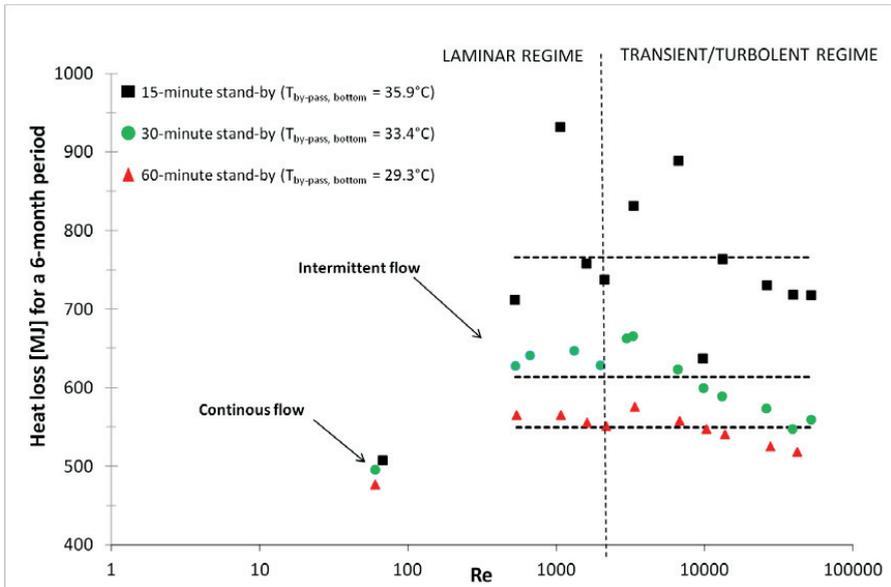


Figure 5.6 Heat loss from the service pipe for a 6-month operation of the bypass. Service pipe: Aluflex twin pipe 20-20/110, $L = 10$ m; $T_{bypass, top} = 40^{\circ}\text{C}$

It might be interesting to combine the use of the continuous bypass concept to a successive, additional heat extraction, thanks to the use of the bypass water in floor heating in rooms with a desirable level of indoor temperature even outside the normal

heating season, as in the case of bathroom floor heating in buildings situated in Nordic climate regions. The study of such possibilities is left to future work.

It has to be underlined that the continuous bypass has additional advantages as well as the ones explained above. In fact, as the lower time-averaged temperature of the heat carrier in the supply media pipe guarantees heat loss reduction from the service pipe in comparison to the intermittent bypass case, the heat loss from the return media pipe similarly decreases. This is also the case for the main distribution pipes, and leads to the conclusion that the continuous bypass optimizes the operation of the whole network outside the heating season.

5.3 Design and Optimization of Fourth Generation District Heating Networks

Chapter 5.2 has treated the modelling of the energy performance of the main items constituting the DH networks, i.e. DH pipes. When targeting the improvement of the design practice for DH networks, it is natural that the second step of the study should try to go beyond the traditional paradigm, propose concepts that could enhance the energy performance and the total economy, evaluate them and finally optimize them, so that they fit the requirements of the decreased heat demand and of supply systems based on low-grade sources and RE. Therefore, chapter 5.3 deals with the development of LTDH networks. The first part – section 5.3.1 – refers to the results of the article IV and the opportunities and limitations that LTDH offers when targeting energy-efficient building areas in mature DH countries, specifically Denmark. The next sub-chapter – 5.3.2 – is linked to article V and describes the role that DH has when integrating large shares of RE into the supply of heat to a community and considers the potential for application in Canada, which is a country where the DH sector has not reached a significant market share.

5.3.1 District Heating for Low-Energy Buildings in Denmark

End-use energy savings and the expansion of DH are key-measures to make the Danish heat supply sector more sustainable, as described in chapter 2. Efficient heat supply systems based on RE sources are an important element of future energy systems that do not depend on fossil fuels, since they improve the overall fuel efficiency of the system [42]. A number of studies have investigated the feasibility and impacts of heat demand reduction measures at the level of individual buildings in DH networks [43]–[45], have analysed the optimisation of DH control at the demand side [46] and have looked into the future potential, profitability and possible strategies for DH in different geographical contexts [47]–[54].

Back in the early 1990s, the feasibility of combining DH and energy-efficient new houses was mentioned as a strategy to contribute to fuel consumption reduction goals, through the joint implementation of heat demand reduction and cogeneration, but the option was assessed to not be cost-effective, given fossil fuel prices at that time [55]. The scenario and conclusions change dramatically when heat derived from fossil-fuels is not anymore contemplated as a future option and optimal network design and operation are assured, as in article IV. Article IV investigates the potential for applying the 4th generation DH to low-energy areas in countries with an extensive existing DH infrastructure, such as Denmark, quantifying the technical and economical feasibility of such systems and suggesting strategies for optimizing DH network design and operation. It deals with the analyses of the annual energy performance of a low-energy network for low-energy houses in Denmark. The article demonstrates the feasibility of LTDH systems supplying energy-efficient buildings and the advantages they could deliver; it then proposes concepts improved from the engineering point of view. It thus moves the discussion from technical matters to how the stakeholders, i.e. the local authority, the building owners and energy utilities can be motivated to invest in long-term cost-effective heat savings and sustainable heat supply: this is suggested to be studied in future works, with the involvement of both engineering and social sciences.

From the results of article IV one can infer that it is technically and economically feasible to extend the DH network to suburban areas with newly-built, energy-efficient buildings. At least two factors are decisive for the success of such strategy. The first one deals with the design of proper systems that are energy-efficient, optimal network dimensioning and low-temperature operation being among the most important issues to be addressed. The second one refers to the existence of major distribution networks at a relatively short distance from the target group of buildings; at the same time, it is desirable that such a main network should have spare load capacity, so that new investments are kept to a minimum. In Danish conditions, the existence of DH networks is already extensive and spare load capacity is likely to be present in many systems, due to past design practice. In addition to that, if the desired level of reduction of the heat demand in the building stock is achieved, extra load capacity will be created and could be used for network expansion.

The results of article IV support the conclusions of the “Heat Plan Denmark” [16]: it is reasonable from the socio-economical point of view to extend the DH supply to areas currently equipped with individual heat supply systems – natural gas boilers, oil boilers and wood stoves – and to connect adjacent areas heated by natural gas to the existing networks, bringing the DH share in the national heat demand from 50% to 70%. It is recommended that the process is guided by local, public authorities supported by national regulations, in a way that in Denmark could resemble the methodology deployed in the past when applying the Heat Supply Act [56]. It is suggested that zoning of the heat supply, drawing the boundaries between community energy systems and individual solutions, should be re-drawn, including new developments with low-energy buildings, which are at present excluded from the

obligation to connect to DH networks. Local authorities have the responsibility to synchronize heat conservation measures with the investments necessary to fully convert the heat supply system to RE.

Moreover, the results underline that the tariff structure and the way that DH projects are financed are critical aspects. In Denmark, the tariffs to the final customers supplied by DH are set according to actual, average costs in the current supply system, including the costs for heat production and the amortization of the investments. The tariffs are set to have a fixed element, based on heated floor area or peak heat load and a variable part based on actual heat usage. This follows the fact that DH distribution companies are not-for-profit entities in Denmark that are obliged to supply heat to the citizens with the best socio-economy. This practice can become a barrier, when converting the energy system to the new paradigm that is based on energy conservation and RE, because it hinders the long-term investments needed to guide the transition. This was pointed out in [20], where the authors stated that “in a long-term perspective, where the goals are an economical strategic optimization of demand and supply activities, the price should be set according to the long term total costs per extra heat unit supplied by a future supply system. Already to-day, the tariffs should be set according to the price of the future renewable energy based system”.

In practice, tariffs should be based on marginal costs and not on average costs. In the article IV it is mentioned that a typical current value for the variable part of the tariff in the capital region of Denmark in 2011 was approximately 6.9 c€/kWh, based on average costs from several heat sources. If the tariff was based on marginal costs, such value could be assumed to nearly double [20] and once the fixed part of the tariff is added, the final levelized cost of heat would be 15-20 c€/kWh. The new tariff could match the future cost of RE-based heat supply system and eliminate the conflict between the right price at the present time, and the right price for the future system.

The additional advantages of the proposed tariff structure are: first, the sensitive higher heat costs for existing customers would stimulate the efforts towards the implementation of energy renovation measures according to the desired level; secondly, the price would be at the same level as the one suggested in article IV for low-energy buildings supplied by DH, avoiding conflicts in establishing separate tariffs for new developments and existing buildings. The disadvantages are that a larger risk in the capital investment is given to the project developer – generally a public authority – because of the required new tariff structure solely based on heat usage and the risk of the existing customers’ dissatisfaction, due to increases in the heat bill. Nonetheless, those are the costs the society should withstand to implement the ambitious goals set by the national energy targets according to the concept described in this thesis, where a strong role is given to the DH sector.

These considerations are subjected to the uncertainty of future price developments, which are unknown, and should be used more as a suggestion for further studies than for making final conclusions. What can be concluded is that the focal point should be the comparison of the presented scenario based on the strong role of DH and the alternative of a scenario where energy reduction measures are combined with

individual heating solutions, which in Denmark would be principally based on electricity. The assessment of the best solution should be based on total future costs, avoiding the distortions of short-term analyses that would cause either the choice of sub-optimal systems or the failure to meet energy targets.

5.3.2 Integration of Renewable Energy via District Heating in Canada

Article V applies the lessons learnt from the previous articles to a different context than article IV: the investigation of the role of DH towards sustainable energy supply in a country with low DH market penetration such as Canada. The suggestion is the one of adapting the 4th-generation DH concept to the specific requirements of countries other than Nordic countries in Europe.

In 2009 the primary energy use in the Canadian residential and commercial/institutional building sectors was respectively 1422 PJ and 1184 PJ [57], which in total corresponded to approximately 31% of the total country primary energy use. Natural gas and electricity were the dominant energy inputs to the building sector, providing 87% of the final energy demand. Three basic considerations can be made by observing Figure 5.7.

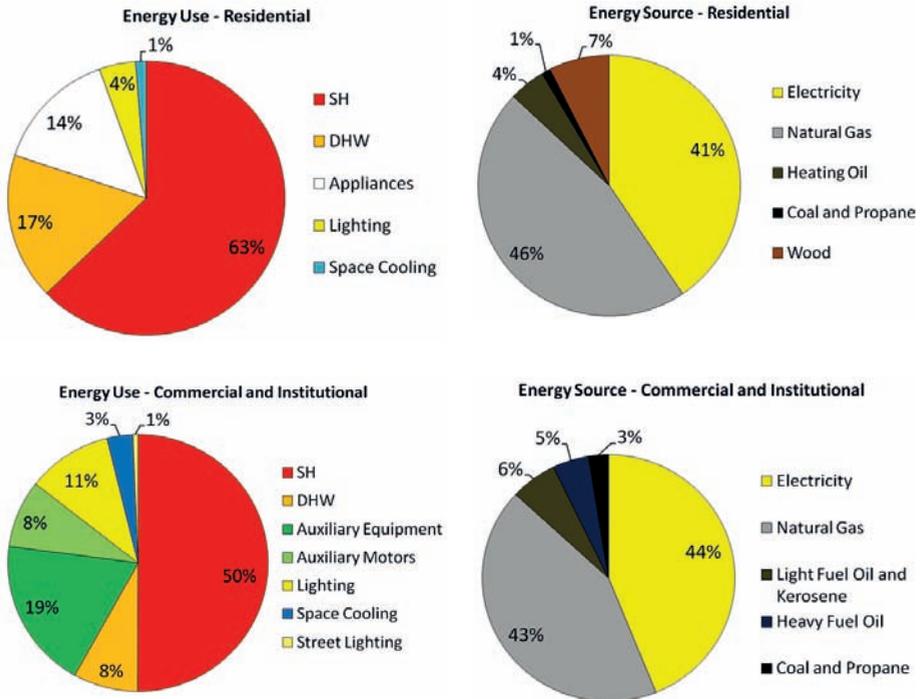


Figure 5.7 Energy use by typology and by source in Canadian buildings in 2009. Derived from [57].

First of all, SH and DHW were responsible together for 80% of the final energy use in residential buildings and 58% in commercial/institutional buildings, and that demonstrates that the heat demand is significant in Canadian communities; that is due to a combination of factors, among those the cold climate, the high expectations of thermal comfort and a historically low energy price which has limited the effort in the construction of energy-efficient buildings and responsible attitudes towards energy usage.

Second, the high use of electricity for heating purposes, especially in the residential sector; if this practice is questionable from the energy/exergy efficiency point of view, it has partly been motivated by the extensive availability of hydro power which has provided a cheap, reliable and clean source of energy. Nevertheless, it should be taken into account that the conditions vary greatly among the 10 Provinces and 3 Territories and that the Provinces of Ontario, Alberta, British Columbia and Quebec account for most of the energy use in Canada and are responsible for nearly 80% of Canada’s total electricity production.

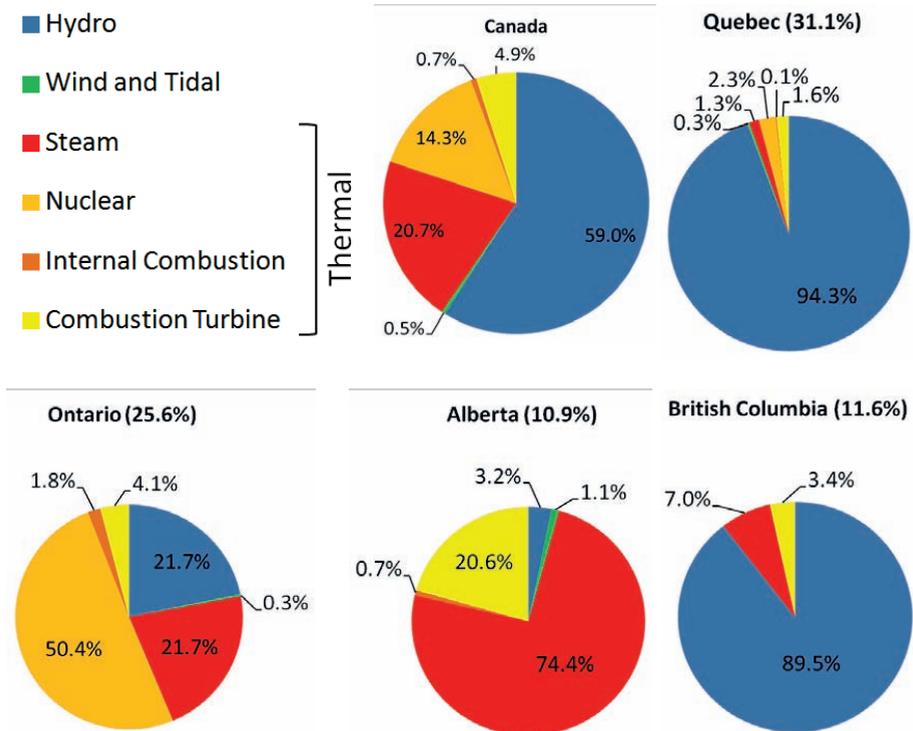


Figure 5.8 Electricity production by energy source in Canada as a whole and in the main Provinces in 2007. The percentage between brackets indicates the share of the national production, which was equivalent to 2223 PJ. Derived from [57].

Figure 5.8 shows that the share of hydro power for electricity generation is close to or even greater than 90% in Quebec and British Columbia; it is reasonable to think that such Provinces could benefit from a energy policy based on energy savings and electrical smart grids, including the heating sector. On the contrary, Ontario and Alberta rely to a great extent on thermal power plants – based either on fossil fuels or nuclear energy – and they could benefit from an energy policy based on energy savings and the development of DH. Hence, strategic local master planning that includes DH and energy savings in the building sector has the potential to decrease the dependency on fossil fuels of many communities across Canada; such measures should consider both traditional concepts related to DH, such as cogeneration in thermal power plant, but also the deployment of local low-grade heat sources and RE.

Third, from what has been stated before it is possible to conclude that DH in Canada must compete in the short term with individual heating based on natural gas.

The considerations made above formed the basis for the scenarios developed in the case studies of article V.

The main conclusions of article V can be summarized by the following points:

- The areas in the case studies with linear heat density greater than 3 MWh/(m²·yr) can economically be supplied by DH, because they are already competitive with the natural gas supply alternative and offer the opportunity of implementing the use of RE and low-grade heat sources.
- The areas in the case studies with linear heat density below 1.5 MWh/(m²·yr) are considered not economically feasible given the current situation of the energy market in Canada, but could be considered for future network extensions together with design and planning concepts that can enhance the profitability of DH supply to those areas.
- MTDH networks can be implemented according to current heating loads while enabling flexibility to provide energy needs in the future; the networks can be low-temperature operated, without any major changes in the network, after energy saving initiatives and conversion of building installations have been widely implemented in the buildings. The design of systems that meet both the present needs and the future conditions allows the investments to be made in an efficient, effective and consistent way.
- The leadership in the local authorities and the involvement of investors in the building sectors are critical to the success of DH projects. It is necessary to decide on medium-long term energy goals, choose the areas which have potential for being supplied by DH, prepare energy plans and coordinate public/private investments, so that installations in the buildings in those areas become “district-energy ready”.

dwelling controls the opening of an automatic valve that allows hot water to flow from the DH loop through the HE in the air-handler unit. A fan blows air across the hot coil, heating the air and distributing it in high volume, low velocity ductwork, similarly to conventional systems. The heat recovery ventilator exhausts warm, moist, stale air from within the home's kitchens and bathrooms to the outside, and preheats cool, fresh incoming air. The system has been in operation since 2007.

5.3.3 Suggestions for Future Research

The research content of this thesis demonstrated that LTDH is a promising technology for energy sustainable communities. This section points at some subjects that could be part of future research aiming at improving the understanding of the physical phenomena involved, optimizing the technology, refining the design and operation of LTDH schemes and widening the geographical applicability. References are made to research projects that have been recently launched or are going to start and deal with some of the proposed topics.

- It is recommended to use FEM models and simulations when developing improved calculation procedures for the heat transfer in DH pipes. The subject will be treated in a recently founded research project (see chapter 5.3.2.), whose aim is to improve the accuracy of the multipole method when predicting temperature distribution in the insulation material of twin pipes by means of calibration with data derived by experimental measurements and FEM simulations.
- The necessity to maintain a certain bypass flow outside the heating season causes heat losses that are especially critical in the case of supply to energy-efficient buildings that already have a low heat demand; moreover, the longer duration of the non-heating season in low-energy buildings than for traditional buildings, accentuates the importance of improving the bypass operation. One possibility outside the heating season could be to use a continuous, low flow (in the magnitude of few L/h) to supply the radiant floor heating circuits of bathrooms, with a direct DH/SH connection; in the best case scenario the concept could increase the thermal comfort in bathrooms thanks to the warmer floor temperature without causing overheating problems, have the same functionality of the traditional bypass, provide a better cooling of the DH return water and have reasonable investment costs and very low to nil additional operational costs. The concept is being investigated at Technical University of Denmark.
- Article IV demonstrated that LTDH for low-energy buildings in countries with a mature DH sector can be advantageous. The requirements, advantages and limits of applying the concept to the existing building stock define a new focus area.
- The barriers and opportunities to implement the LTDH concept in other European countries – where the EPBD defines strict rules for the building primary energy use – will be investigated in [33].

- There is the need to quantify the technical and economical efforts that are needed to introduce DH in Canadian communities, for different building types and for different operating temperatures of the DH system. In parallel, the impact of network operating temperatures on the costs and performance of heat supply technologies based on RE and low-grade heat should be evaluated. After that, the results of article V or similar studies can be integrated and eventually offer the complete overview of costs/benefits of DH systems and the comparison to the alternatives. The applicability to the USA market of the study of the DH potential in typical Canadian urban areas could be assessed as well.
- The practicability of LTDH should also be assessed for China and other fast developing countries where master planning of large urban areas or entire cities are booming.

6 Conclusions

This chapter gathers the main conclusions of the research work described in this thesis. The conclusions are divided accordingly to three main topics – community energy planning, modelling of the heat transfer in district heating pipes and design and optimization of fourth generation district heating networks.

6.1 Community Energy Planning

Benchmark targets are fundamental in community energy projects and should consider both final energy use and primary energy use. Decision makers must define clear energy targets which are then implemented by the municipal instruments such as master plans, bylaws and contracts with the developers. The consistent monitoring of energy production, distribution and use throughout implementation phases is an important aspect that provides the necessary inputs to the energy models, helps implement the necessary improvements by comparing initial targets with achieved performance and provide insights on the optimization of the operation. It is also essential to structure the overall planning framework, so that clear successive phases are identified. This offers the constant overview of the different tasks and suggests the quantity and quality of involvement required by different stakeholders and the level of accuracy of energy models. The driving forces and targets not directly related to sustainable energy, such as social protection, mixed use of urban areas, increase economic value of a community or its market attractiveness must be included in the overall decision, planning and management process, since synergies or conflicts might arise.

The analyses of the case studies suggests that the opportunities for DH implementation and development should be considered during the preparation of community energy plans, as DH is an essential infrastructure of future, sustainable energy systems in many countries. Energy policy should aim at organizing and facilitating the synergy between energy conservation measures and supply of heat based on renewable energy and overcome the traditional competition between the two sectors. The case study in Lystrup demonstrated the technical and economical feasibility of LTDH applied to low-energy buildings and proved that the heat loss in the network can be maintained below 15-20% of the total delivered heat. The example of energy planning in Aarhus demonstrates that capital investments towards a long-term ambitious climate target are possible and suggested that a mixture of backcasting and forecasting is the ideal approach to local energy planning: the targets must be

clearly set and the measures that will connect the future goal to the present situation can be defined backwards, but each phase must be broken down to smaller projects, which offer short-term results and can be individually assessed.

6.2 Modelling of the Heat Transfer in District Heating Pipes

6.2.1 Steady-State Heat Transfer

FEM models can be used as a tool for developing and optimizing pipeline systems serving the next generation of low-energy DH networks. The reliability of the FEM model to calculate steady-state heat loss in DH pipes was validated by means of experimental data and by comparison with analytical formulae and data from the literature. The calculation method takes into account the temperature-dependency of the thermal conductivity of the insulation and enhances the accuracy of the heat transfer calculation for pipes embedded in the same insulation. The application of the method showed that the asymmetrical insulation of twin pipes could lead to 4%-8% lower heat loss from the supply media pipe: consequently, the temperature drop of the supply water decreases, a fact that is relevant for low-temperature applications. At the same time, the heat loss from the return pipe can be kept negligible. With regard to the double pipe system, it is possible to cut heat losses by 6-12% if an optimal design of double pipes is used instead of twin pipes, at no additional costs. Finally, an optimized triple pipe solution was shown, which is suitable for low-energy applications with substations equipped with a HE for instantaneous preparation of DHW.

6.2.2 Transient Heat Transfer

The code modelling the transient heat transfer is proven to be accurate, since it gives results that well represented the outlet temperature profile measured in the experiments, with deviations of less than 0.5°C, and it is in good accordance with the detailed, finite-volume simulations, both when there is a step change in the inlet temperature and when there is a sinusoidal inlet temperature profile. The limitation of the code is that it can currently handle only time-constant water flows. The model was used to propose an integrated solution consisting of service pipe, HE unit with a booster pump, and the in-house service pipelines which satisfies the requirement for supply of DHW within 10 s and achieves heat savings greater than 200 kWh_{th}/yr with an additional electricity use of approximately 58 kWh_{el}. From the primary energy point of view, the improvements could be seen as marginal (approximately 10%, considering primary energy factors for district heating and electricity of respectively

0.8 and 2.5, as in the Danish Building Regulation 2010). Nevertheless, the additional investment in the booster pump could be made reasonable by considerations on the improvement of the comfort and by the development of pumps designed especially for this purpose and with higher energy efficiencies. The model can also be applied to study transient, coupled fluid-thermal phenomena in service pipes, for instance when analyzing the impact of different bypass operation strategies. It was calculated that the heat losses in service pipes with a “continuous bypass” operation are up to 35% lower than in case of “intermittent bypass”, without considering the additional benefits at the level of the distribution network.

6.3 Design and Optimization of Fourth Generation District Heating Networks

6.3.1 District Heating for Low-Energy Buildings in Denmark

The users’ attitude in controlling the indoor environment can lead to 50% greater heating demand than expected according to reference values in the standard calculation of energy demand patterns in energy-efficient buildings. The decisive involvement of the final users is crucial, since energy savings are the prerequisite for a fossil-fuel-free heating sector.

Next, we showed that low-energy DH systems are competitive solutions, when assessing cost-effective and reliable solutions for supplying the heating demand of energy-efficient building areas. The expected linear heat density can be used as the representative value for feasibility studies of DH networks. Low-energy DH networks are capable of supplying heat in a cost-effective and environmentally friendly way in areas with a linear heat density as low as 0.20 MWh/(m yr). Furthermore, such systems are robust and can ensure the security of supply to each customer, even when energy use patterns differ from expectations.

The levelized cost of energy of low-energy DH supply is competitive with the GSHP-based scenario. The cost of heat for the end-user is between 13.9 and 19.3 c€/kWh (excl. VAT) for Low-Energy “Class 2015” detached houses and Low-Energy Class 1 terraced houses. This is approximately 20% lower than the corresponding energy unit cost for GSHP. The energy costs for DH energy supply account for 18-28% of the total costs, while the investment costs represent 63-72% of the overall expenditure. Five different possible network designs were evaluated with the aim of finding the optimal solution, with regard to economic and energy efficiency issues. The importance of low supply and return temperatures and their effect on the energy efficiency of the DH network was demonstrated. The designs based on low-temperature operation are superior to the design based on low-flow operation. The total primary energy use in the most energy-efficient design is 14.3% lower than the

primary energy use for standard recently designed networks, the distribution heat losses are halved and the investment costs for pipe purchasing and laying are reduced by 3.4%. The increase of the electricity use for pumping is to some extent not significant, because its share in the total primary energy demand is at most approximately 2%.

6.3.2 Integration of Renewable Energy via District Heating in Canada

The price of heating by natural gas in Canada is among the lowest in OECD countries, the reasons being the relatively large fuel availability inside the country territory and a relatively low taxation on fossil fuel deployment. DH would become more attractive if all socio-economic aspects were considered, including environmental and health protection, local economic development, efficient-use of energy resources; in particular, LTDH has the capability of including a larger amount of RE and waste or recovered heat, in a way that might be at only a marginal cost for the end-users and should therefore be considered as a future option. The leadership in the local authorities and the involvement of investors in the building sectors are critical to the success of DH projects. It is necessary to make decisions on medium-long term energy goals, choose the areas which have potential for being supplied by DH, prepare energy plans and coordinate the public/private investments, so that the installations in the buildings in those areas become “district-energy ready”.

MTDH networks can be implemented according to current heating loads while enabling flexibility to provide energy needs in the future; the networks can be low-temperature operated, without any major changes in the network, after energy saving initiatives and conversion of building installations have been widely implemented in the buildings.

The areas in the case studies with linear heat density greater than 3 MWh/(m²yr) can be supplied by DH, because they are already competitive with the natural gas supply alternative and offer the opportunity of implementing the use of RE and low-grade heat sources. However, the areas with linear heat density below 1.5 MWh/(m²yr) are considered not economically feasible with the current situation of the energy market in Canada.

References

NOTE: The links to internet websites were last accessed on 30th March 2012.

- [1] IPCC Fourth Assessment Report: Climate Change 2007 (AR4), Synthesis Report. IPCC; 2007. Available at www.ipcc.ch
- [2] IPCC Fourth Assessment Report: Climate Change 2007 (AR4), the Physical Science Basis. IPCC; 2007. Available at www.ipcc.ch
- [3] IPCC Special Report on Emission Scenarios. IPCC; 2000. Available at www.ipcc.ch
- [4] J. Hansen, M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson et al. "Target atmospheric CO₂: where should humanity aim?" The Open Atmospheric Science Journal, vol. 2, pp. 217-231, 2008.
- [5] H. D. Matthews and K. Caldeira, "Stabilizing climate requires near-zero emissions," Geophysical Research Letters, vol. 35, no. 4, 2008.
- [6] IPCC Fourth Assessment Report: Climate Change 2007 (AR4), Mitigation of Climate Change. IPCC; 2007. Available at www.ipcc.ch
- [7] Y. Kaya, K. Yokobori. Environment, energy, and economy: strategies for sustainability. United Nations University Press, 1997, Tokyo, Japan.
- [8] World Urbanization Prospects, the 2009 Revision .United Nations, Department of Economic and Social Affairs, Population Division, New York, 2010.
- [9] 2010 Survey of Energy Resources. World Energy Council, 2010.
- [10] The World Factbook. Central Intelligence Agency, 2011. Available at www.cia.gov
- [11] Uppsala Conflict Data Program, University of Uppsala, Department of Peace and Conflict Research, 2011. www.ucdp.uu.se
- [12] Benchmarking statistik 2010/2011 ("Benchmarking statistics 2010/2011, in Danish). Dansk Fjernvarme; 2011. Available at www.fjernvarmen.dk
- [13] Udviklingstendenser i dansk fjernvarme - Aarsstatistik 2010 ("Trends in the Danish district heating", in Danish). Dansk Fjernvarme; 2011. Available at www.fjernvarmen.dk
- [14] Benchmarking statistik 2009/2010 ("Benchmarking statistics 2009/2010, in Danish). Dansk Fjernvarme; 2010. Available at www.fjernvarmen.dk
- [15] EFP 2007: udvikling og demonstration af lavenergifjernvarme til lavenergibyggeri (Final report 2007: development and demonstration of low energy district heating for low energy buildings, in Danish); Energystyrelsen, 2009.
- [16] Varmeplan Danmark ("Heat Plan Denmark", in Danish). Rambøll Denmark A/S and Aalborg University; 2008. Available at www.vbn.aau.dk
- [17] Varmeplan Danmark 2010 ("Heat Plan Denmark 2010", in Danish). Rambøll Denmark A/S and Aalborg University; 2010. Available at www.vbn.aau.dk
- [18] Our Future Energy. The Danish Government; November 2011. Available at www.ens.dk

- [19] The IDA Climate Plan 2050: Main Report. IDA; 2009. Available at www.ida.dk
- [20] Coherent Energy and Environmental System Analysis. Aalborg University, 2011. ISBN 978-87-91404-15-3. Available at www.ceesa.dk
- [21] P.K. Olsen et al. Low-temperature district heating system for low-energy buildings. Presented at the 11th International Symposium on District Heating and Cooling, Reykjavik, Iceland, 2008.
- [22] O. Paulsen. Consumer unit for low energy district heating net. Presented at the 11th International Symposium on District Heating and Cooling, Reykjavik, Iceland, 2008.
- [23] CO₂-reductions in low-energy buildings and communities by implementing low-temperature district heating systems. Demonstration cases in energyflexhouse and boligforeningen Ringgården. Danish Energy Agency, 2011.
- [24] Winkens HP. Economic outgoing temperatures in DH supply. Fjernvarme International yearbook; 1988.
- [25] www.arcon.dk
- [26] www.builditsolar.com
- [27] H. Lund, B.V. Mathiesen. Energy system analysis of 100% renewable energy systems – the case of Denmark in years 2030 and 2050. Energy 2009; 34(5):524–31.
- [28] H. Lund, B. Moller, B. V. Mathiesen, A. Dyrelund. The role of district heating in future RE systems. Energy, 35, pp. 1381-1390, 2010.
- [29] EFP-2001: Fjernvarmeforsyning af lavenergiområder (District heating supply to low-energy area, in Danish). Energistyrelsen, Journal nr. 1373/01-0035, 2004.
- [30] Ecoheat4EU. Executive summary report, 2011. Available at www.ecoheat4eu.eu
- [31] EcoHeatCool. The European Heat market. Final report of Work package 1, 2006. Available at www.euroheat.org
- [32] A roadmap for moving towards a competitive low carbon economy in 2050, European Commission, 2011. Available at www.ec.europa.eu/clima.
- [33] www.iea-dhc.org
- [34] www.annex51.org
- [35] A. Koch, J.C. Kersting. IEA-ECBCS Annex 51, Subtask A. Description of the state-of-the-art of energy efficient projects on the scale of neighbourhood, 2011. Available at www.annex51.org
- [36] M.B. Quitzau, B. Hoffmann, M. Elle, P. Munthe-Kaas, J. Lilliendahl-Larsen. Municipalities as promoters of energy efficient buildings - Idea catalogue for proactive planning practices. Available at www.class1.dk
- [37] Arpacı VS. Conduction heat transfer. Addison-Wesley Publishing Company, Scranton, Pa., 1968.
- [38] Fastlæggelse af varmeledningsevne og varmetab for fleksible twinrør. Project nr. 2009-03, Dansk Fjernvarme 2009. Available at www.fjernvarmen.dk
- [39] Bøhm B. On transient heat losses from buried district heating pipes. Int. J. Energy Res 2000; 24: 1311-34.
- [40] Claesson J, Bennet J, Hellström G. Multipole method to compute the conductive heat flows to and between pipes in a cylinder. Lund: Department of Building Technology and Mathematical Physics; 1987.
- [41] Software Termis 2.10. Help menu-Models and Formulae-Temperature; 7-Technologies, 2012.

- [42] Sperling K, Möller B. End-use energy savings and district heating expansion in a local renewable energy system – A short-term perspective. *Applied Energy* 2012;92:831–42.
- [43] Joelsson A, Gustavsson L. District heating and energy efficiency in detached houses of differing size and construction. *Appl Energy* 2009;86:126–34.
- [44] Difs K, Bennstam M, Trygg L, Nordenstam L. Energy conservation measures in buildings heated by district heating – a local energy system perspective. *Energy* 2010;35:3194–203.
- [45] Gustavsson L, Dodoa A, Truong NL, Danielski I. Primary energy implications of end-use energy efficiency measures in district heated buildings. *Energy Build* 2011;43:38–48.
- [46] Gustafsson J, Delsing J, van Deventer J. Improved district heating substation efficiency with a new control strategy. *Appl Energy* 2010;87:1996–2004.
- [47] Thyholt M, Hestnes AG. Heat supply to low-energy buildings in district heating areas. Analyses of CO₂ emissions and electricity supply security. *Energy Build* 2008;40:131–9.
- [48] Difs K, Danestig M, Trygg L. Increased use of district heating in industrial processes – impacts on heat load duration. *Appl Energy* 2009;86:2327–34.
- [49] Lygnerud K, Peltola-Ojala P. Factors impacting district heating companies’ decision to provide small house customers with heat. *Appl Energy* 2010;87:185–90.
- [50] Amiri S, Moshfegh B. Possibilities and consequences of deregulation of the European electricity market for connection of heat sparse areas to district heating systems. *Appl Energy* 2010;87:2401–10.
- [51] Möller B, Lund H. Conversion of individual natural gas to district heating: geographical studies of supply costs and consequences for the Danish energy system. *Appl Energy* 2010;87:1846–57.
- [52] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. *Appl Energy* 2011;88:568–76.
- [53] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. *Energy* 2010;35:1381–90.
- [54] Østergaard PA, Lund H, Hvelplund F, Möller B, Mathiesen BV, Remmen A, et al. Energy vision for Aalborg Municipality 2050 [Energivision for Aalborg Kommune 2050]. Aalborg, Denmark: Aalborg University; 2010.
- [55] Giljiamse W, Boonstra ME. Energy efficiency in new houses. Heat demand reduction versus cogeneration. *Energy Build* 1995;23:49–62.
- [56] www.ens.dk
- [57] Energy Efficiency Trends Analysis Tables. National Energy Use Database, Office of Energy Efficiency Statistics and Analysis, Natural Resources Canada. www.oee.nrcan.gc.ca
- [58] www.dlsc.ca

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PART II

Scientific Articles

Abstracts of the Scientific Articles

Article I

Dalla Rosa, Alessandro; Svendsen, Svend. *IEA-ECBCS Annex 51: energy-efficient communities: experience from Denmark*. Presented at: World Renewable Energy Conference, Linköping, Sweden, 2011.

Abstract

The paper describes the Danish contribution to the IEA-ECBCS Annex 51: “energy efficient communities”. We present three case studies, two from Annex subtask A (state-of-the-art review) and one from subtask B (ongoing projects). The first case study is “Samsoe: a renewable energy island”. The community achieved a net 100% share of renewable energy in its total energy use, relying on available technical solutions, but finding new ways of organizing, financing and ownerships. The second project is “Concerto class I: Stenloese Syd”. The buildings in the settlement are low-energy buildings class I (Building Regulation 2008). The project partners envisaged the implementation of selected key energy-supply technologies and building components and carried out an evaluation of user preferences to give suggestions to designers and constructors of low-energy houses. The third case study (Subtask B) is: “low-energy neighbourhood in Lystrup, Denmark”. The project integrates sustainable solutions both for the building sector and the energy supply side, which in the case consists on a low-temperature district heating network. The analysis of the successful/unsuccessful factors in the projects contributes to develop the instruments that are needed to prepare local energy and climate change strategies and supports the planning and implementation of energy-efficient communities.

Article II

Dalla Rosa, Alessandro; Li, Hongwei; Svendsen, Svend. *Method for optimal design of pipes for low-energy district heating, with focus on heat losses*. *Energy* 2011; 36 (5):2407-18.

Abstract

The synergy between highly energy-efficient buildings and low-energy district heating (DH) systems is a promising concept for the optimal integration of energy-saving policies and energy supply systems based on renewable energy (RE). Network transmission and distribution heat loss is one of the key factors in the optimal design of low-energy DH systems. Various pipe configurations are considered in this paper: flexible pre-insulated twin pipes with symmetrical or asymmetrical insulation, double pipes, and triple pipes. These technologies represent potential energy-efficient and cost-effective solutions for DH networks in low-heat density areas. We start with a review of theories and methods for steady-state heat loss calculation. Next, the article shows how detailed calculations with 2D-modeling of pipes can be carried out by means of computer software based on the finite-element method (FEM). The model was validated by comparison with experimental measurements, analytical formulae, and data from the literature. We took into account the influence of the temperature-dependent conductivity coefficient of polyurethane insulation foam, which enabled us to achieve a high degree of accuracy. We also showed the influence of the soil temperature throughout the year. Finally, the article describes proposals for the optimal design of pipes for low-energy applications and presents methods for decreasing heat losses.

Article III

Dalla Rosa, Alessandro; Li, Hongwei; Svendsen, Svend. *Modelling transient heat transfer in small-size twin pipes for end-user connections to low-energy district heating networks*. Accepted in the ISI Journal Heat Transfer Engineering, February 2012. Available online since 06-08-2012.

Abstract

The low-energy district heating concept has the potential of increasing the energy and exergy efficiencies of heat supply systems and of exploiting renewable energy, provided technical solutions for its wide application can be developed and implemented. This paper investigates the dynamic behaviour of district heating branch pipes in low-temperature operation (supply temperature 50-55°C and return temperature 20-25°C). We looked at state-of-the-art district heating branch pipes, suitable for the connection of a typical single-family house to a substation equipped with a heat exchanger for domestic hot water preparation. Experimental measurements of the supply temperature profiles at the outlet of the pipe, i.e. at the inlet to the substation, were compared with detailed simulations based on the finite volume (FV) method. A programming code was developed to model these profiles, and this was validated against experimental measurements and compared to the results of an analytical formula and the FV simulations. The model proved accurate, since it gives results that well represent the outlet temperature profiles measured in the experiments and calculated in the FV simulations, both where there was a step change of the inlet temperature and where there was a sinusoidal inlet temperature profile. The model could be used for the development of improved substation concepts and enhanced control strategies.

Article IV

Dalla Rosa, Alessandro; Christensen, Jørgen Erik. *Low-energy district heating in energy-efficient building areas*. Energy 2011; 36: 6890-99.

Abstract

This paper presents an innovative low-energy district heating (DH) concept based on low-temperature operation. The decreased heating demand from low-energy buildings affects the cost-effectiveness of traditionally-designed DH systems, so we carried out a case study of the annual energy performance of a low-energy network for low-energy houses in Denmark. We took into account the effect of human behaviour on energy demand, the effect of the number of buildings connected to the network, a socio-economic comparison with ground source heat pumps, and opportunities for the optimization of the network design, and operational temperature and pressure. In the north-European climate, we found that human behaviour can lead to 50% higher heating demand and 60% higher heating power than those anticipated in the reference values in the standard calculations for energy demand patterns in energy-efficient buildings. This considerable impact of human behaviour should clearly be included in energy simulations. We also showed that low-energy DH systems are robust systems that ensure security of supply for each customer in a cost-effective and environmentally friendly way in areas with linear heat density down to 0.20 MWh/(m²yr), and that the levelized cost of energy in low-energy DH supply is competitive with a scenario based on ground source heat pumps. The investment costs represent up to three quarters of the overall expenditure, over a time horizon of 30 years; so, the implementation of an energy system that fully relies on renewable energy needs substantial capital investment, but in the long term this is sustainable from the environmental and socio-economic points of view. Having demonstrated the value of the low-energy DH concept, we evaluated various possible designs with the aim of finding the optimal solution with regard to economic and energy efficiency

issues. Here we showed the advantage of low supply and return temperatures, their effect on energy efficiency and that a DH design that relies on low-temperature operation is superior to a design based on low-flow operation. The total primary energy use in the best design was 14.3% lower than the primary energy use for standard, recently designed networks, and distribution heat losses were halved. Moreover, the exploitation of the entire available pressure by means of careful network design decreased the average pipe size required, which slightly lowers the investment costs for purchasing and laying the pipelines in the ground. This low-temperature DH concept fits the vision of the future energy-sustainable society.

Article V

Dalla Rosa, Alessandro; Boulter, Raymond; Church, Ken; Svendsen, Svend. *The role of district heating towards a system-wide methodology for optimizing renewable energy sources in Canada: a case study*. Energy 2012; 45: 960-974.

Abstract

This paper discusses the opportunities and challenges of implementing District Heating (DH) systems in Canada. The structure follows a methodology that community energy planners can follow when assessing the potential for DH implementation. We selected as case study an urban area in the capital city of Ottawa; a technical-economical analysis was then carried out, with focus on the DH network design and operation. First, we proved that the characteristic of the site and the heat price have a decisive role on the choice of the pipeline system. In urban areas, the twin pipe system is superior to the single pipe system. Secondly, the medium-temperature DH had better energy performance than high-temperature DH, 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 pumping energy and additional capital investment, which is 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 DH should be taken into consideration, thanks to the capability of including larger share of renewable energy and excess heat, at an only marginal cost for the end-user. Next, the simulation shows that medium temperature DH can be implemented to supply present heating loads and in the future - when energy saving initiatives are widely implemented in the buildings - be low-temperature operated. This planning strategy in the case study decreased the capital investment by 12% and heat losses by 17%. The modelled areas having linear heat densities greater than 3 MWh/(m²yr) could justifiably be supplied by DH, because results indicate competitiveness with the natural gas supply. Areas with linear heat density below 1.5 MWh/(m²yr) are considered not practically feasible with the current situation of the energy market in Canada, but should be considered for future network extensions. The paper discusses critical issues and quantifies the performance of design concepts for DH supply to those areas. A general conclusion is that DH can be widely implemented in urban areas in Canada with reasonable economy, which must be quantified in the specific case and would assure the long-term energy sustainability. The process should begin with the areas with the highest possible linear heat density and thermal effectiveness, with the implementation of medium-temperature DH 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. DH is a fundamental energy infrastructure and is part of the solution for sustainable energy planning in Canadian communities.

ARTICLE

I

IEA-ECBCS Annex 51: energy efficient communities. Experience from Denmark

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Abstract: The paper describes the Danish contribution to the IEA-ECBCS Annex 51: “energy efficient communities”. We present three case studies, two from Annex subtask A (state-of-the-art review) and one from subtask B (ongoing projects). The first case study is “Samsøe: a renewable energy island”. In a ten-year period, the community achieved a net 100% share of renewable energy in its total energy use, relying on available technical solutions, but finding new ways of organizing, financing and owning. The second project is “Concerto class I: Stenløse Syd”. The buildings in the settlement are low-energy buildings class I (Building Regulation 2008). The project envisaged the implementation of selected key energy-supply technologies and building components and carried out an evaluation of user preferences to give suggestions to designers and constructors of low-energy houses. The third case study is: “low-energy neighborhood in Lystrup, Denmark”. The project integrates sustainable solutions both for the building sector and the energy supply side, which in the case consists on a low-temperature district heating network. The analysis of the successful/unsuccessful factors in the projects contributes to develop the instruments that are needed to prepare local energy and climate change strategies and supports the planning and implementation of energy-efficient communities.

Keywords: energy efficiency, urban planning, renewable energy, district heating

1. Introduction

The main objective of the IEA-ECBCS Annex 51: “energy efficient communities” is the design of integrated long-term energy conservation and greenhouse gas (GHG) mitigation strategies within a community, with optimal exploitation of renewable energy (RE) [1]. A holistic approach is used, comprehending generation, supply, transport and use of energy. Annex 51 explores effective paths that implement technical innovations in communities with an increased rate, enabling communities to set up sustainable energy structures and identify the specific actions necessary to reach ambitious goals. We consider both short-term and long-term plans, and their economic feasibility. Furthermore, we prepared recommendations, best-practice examples and background material for designers and decision makers.

2. Methodology

The title of subtask A is “existing organizational models, implementation instruments and planning tools for local administrations and developers – a state-of-the-art review”. Each participating country describes the national legislative and economic framework for urban energy and climate change policies and prepared a review of data acquisition methods and tools for monitoring municipal energy and GHG balances. Next, we consider local energy system modeling and simulation tools and their combination with conventional planning tools for the design of energy supply systems and demand calculation. Finally, we discuss successful examples of community energy planning projects within the participating countries. The focus is on methods and planning principle, implementation strategies and the final comparison and evaluation of approaches in different countries.

In subtask B, “case studies on energy planning and implementation strategies for neighborhoods, quarters or municipal areas”, we describe methods to characterize the actual state of a project in terms of energy and GHG performance. We investigate scenarios and planning alternatives arisen during the case study timeframe, and we report cost structures and

cost/benefit analyses. The process organization, the role of the decision makers and the implementation strategy are put into focus. Finally, we report R&D issues, methods and tools used by the decision makers and the results achieved, with regard to GHG targets and economic feasibility.

3. Results and Discussion

3.1. Samsø: a renewable energy island

In 1997 Samsø island (114 km², 4124 inhabitant in 2010) won a competition, announced by the Danish Ministry of Energy. It dealt with the choice of a local community with the most feasible plan for the transition to energy self-sufficiency with exploitation of RE.

3.1.1. Objectives and milestones

The objective was to study what share of RE a well-defined area could achieve using available technology, and without extraordinary state subsidies. The master plan described the available resources and how the transition could be made, with descriptions of both technical and organizational figures. Reduced energy consumption in all sectors, i.e., heating, electricity and transportation was an essential requirement. The degree of local participation was another top priority for the project: the business community, local authorities and local organizations had to support the proposed master plan to give it credibility. It was expected to envisage new ways of organizing, financing and owning the sub-projects proposed.

Table 1: Comparison between energy and economical figures in Samsø, period 1997-2005.

Energy and economical figures	Master Plan (1997)	Achieved (2005)
Share of renewable energy [%]	100	99.7
Degree of energy self-sufficiency [%]	100	35
Share of district heating [%]	65	43
Heat use [TJ/year]	140 (+ 0%*)	155 (+10%*)
Electricity use (no for heat) [TJ/year]	70.0 (-12%*)	77.3 (-3%*)
Onshore wind turbines [TJ/year]	86	100
Offshore wind turbines [TJ/year]	260	285
CO ₂ emissions [tons/year]	-14000	-15000
Private investment [€10 ⁶]	78.7	53.3
Public subsidies [€10 ⁶]	9.3	4.0
Private investment [€/inhabitant]	20000	13500
Public subsidies [€/inhabitant]	2300	1000

*Reference year: 1997

3.1.2. Energy conservation

Campaigns were made concerning energy savings, among those the "pensioner project". The Danish Energy Authority granted funds (50% of the investment, max. 3250 EUR) to pensioners for energy saving renovations in their private houses. Informative letters were sent to the 444 pensioner families of Samsø and a free visit by an energy adviser was offered. 43% of the families made use of it. Local business increased its turnover by 1.1 million EUR. Nevertheless, the total energy use (electricity, heat and transport) increased by 4% in the period 1997-2005, from 305.4 TJ to 318.6 TJ, mainly due to an increased heat demand (+10%, partly because of a cold winter in 2005) and energy use for transportation (+ 7%).

3.1.3. Energy supply

The municipal council guaranteed the mortgage loans that financed the district heating (DH) plants, whose fuel (straw and wood chips) is produced by local farmers. Buildings built in

areas with existing or planned DH were compelled to connect to the system, while the houses that complied at least with the low-energy class 2 standard (Building Regulation 98, [2]) were exempt. Outside DH areas, the actual planning process began when 70% of consumers using regular oil furnaces or boilers had signed up for the conversion to DH. The energy utilities introduced a new financial model, who was an exception to normal practice. The consumer paid a connection fee of around 10 EUR, if registered before the establishment of the network, while the fee increased up to 5000 EUR afterwards. This method guaranteed a high degree of connection and aimed at encouraging end-users' energy savings, due to higher energy supply costs. The production increased from 39.6 TJ in 1997 to 82.4 TJ in 2005 [3]; at the same time, the expansion of the existing networks caused the distribution heat losses to increase from 19.9% to 24.2% of the delivered energy. The main figures about the DH systems are shown in Table 2. A cooperatively owned regional utility, NRGi, own and operates two DH systems; another system is owned by a local commercial operator, while the consumers themselves own and finance the last system.

Table 2: District heating in Samsø (2005).

Location	Nordby/Mårup	Tranebjerg	Ballen/Brundby	Onsbjerg
Ownership	NRGi*	NRGi*	Consumer-owned	Private
Consumers	178	400	240	76
Investment costs [€*10⁶]	2.7	3.5	2.2	1.1
Subsidy [€*10⁶]	1.2	-	0.3	0.4
Peak power [MW]	1.6	3.0	1.6	0.8
Energy [MWh/year]	n.a.	9500	3300	1500
Solar collector area [m²]	2500	-	-	-
Solar storage tank [m³]	800	-	-	-
Year of establishment	2002	1993	2005	2002
Resources	Biomass/ solar	Biomass	Biomass	Biomass
Fuel consumption [tons/year]	1250	n.a.	1200	600
Fixed fee [€/(consumer*year)]	344	362	345	350
Price [€/MW]	92	104	90	90
Connection fee* [€]	3350	3350	6000	6000
Connection fee* [€/m_{pipe}]	150	150	-	-

* Only for customers who connect after the establishment of the DH network

Individual solutions were applied in areas not reached by DH networks: 860 solar thermal systems, 35 heat pumps and 120 biomass-based units were installed [4]. To cover the electricity demand, 11 onshore wind turbines were installed, with a total peak capacity of 9 MW_{el}. An offshore wind turbines park was dimensioned with a capacity of 23 MW_{el}, corresponding to the difference between the actual energy use in the transport sector and the energy savings to be realized in the master plan. Five of the 10 off-shore wind turbines are owned by the municipality of Samsø. The proceeds from the windmills are reinvested in future energy projects as Danish law does not allow local municipalities to earn money by generating energy. Three of the off-shore turbines are privately owned by local farmers. Nine offshore wind turbines are owned privately by small groups of farmers and two are owned by local cooperatives with up to 1500 shareholders [5]. Spreading the ownership improved citizenship acceptance for the construction of the wind turbines. Electricity production prices are regulated by law and include a ten-year fixed price agreement which is the same for all the wind turbines on the island. The agreement stipulates a guaranteed price of about 0.08 EUR for the first 12000 full-load running hours and afterward about 0.06 EUR, until the ten year period expires.

3.1.4. Analysis

The strengths, weaknesses, opportunities, and threats (SWOT) analysis is shown in Table 3.

Table 3: SWOT analysis for the Samsø case study.

	Helpful	Harmful
Internal origin	<p><i>Strength</i></p> <ul style="list-style-type: none"> - Political support - Internal energy market - Local coordination - Local ownership - Organizational structure - Local resources - Challenging jobs 	<p><i>Weakness</i></p> <ul style="list-style-type: none"> - Minor energy savings - No cogeneration - Municipality administration - Uncertainty of energy prices - Training and education - Protests against placement of wind generators and DH plants
External origin	<p><i>Opportunity</i></p> <ul style="list-style-type: none"> - External investments - EU incentives - Lower tax for electricity from RE - Creation of new employment opportunities - El. contracts avoid price fluctuations - Positive effect on tourism 	<p><i>Threat</i></p> <ul style="list-style-type: none"> - Removal of subsidies by new government - Immaturity of electric car technology - Lack of suppliers and companies for maintenance

3.2. Concerto class I: Stenløse Syd

The project Class1 began in 2007, after the municipality of Egedal decided to strengthen the energy requirements for a new settlement to be erected in the municipality [6]. The project is part of the “EU Concerto initiative project” [7]. During the years 2007-2011 a total of 442 dwellings were or are designed and constructed with a heating demand corresponding to the Danish "low-energy class I". This means that the energy consumption will be 50% below the energy frame set by the Danish Building Regulation (DBR 08). The energy frame is calculated with the following formula, where A is the heated floor area:

$$\text{Energy frame} = 70 + 2200/A \text{ in kWh/m}^2/\text{year} \quad (1)$$

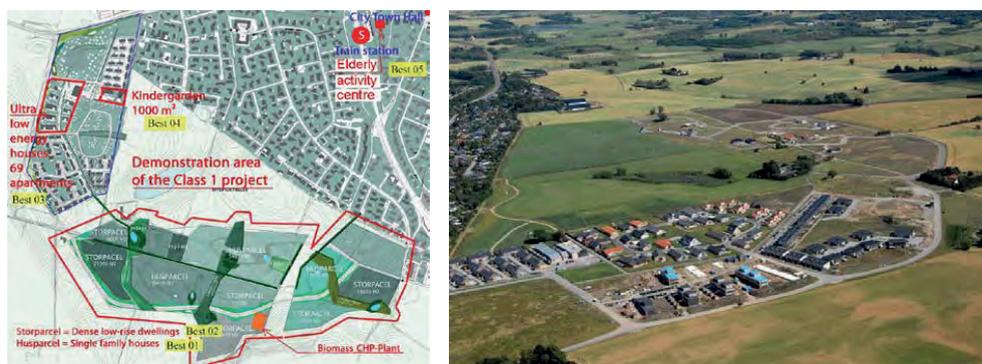


Figure 1: Site area (left) and status of the settlement in 2010 (right).

During the first year of the project, the municipality itself has constructed a kindergarten in compliance with the above restrictions and a social housing association has completed an ultra low-energy house project (heating demand of 15 kWh/(m2.year)) – comprising 65

dwelling. Besides, the constructions of the elderly centre and 13 single family houses have commenced. The Class 1 project focuses on selected key technologies and building components: slab and foundation insulation, window frames, mechanical ventilation with heat-recovery combined with heat-pumps, biomass-CHP, heat distribution for local DH and user-friendly building energy management systems.

3.2.1. Evaluation of user preferences and legislative analysis

One part of the demonstration activities deals with the evaluation of the user preferences to improve target future buyers/builders of low-energy houses. The methodology was determined and the initial interviews were carried out. The final report is available in [6]. Proactive attempts have been identified and documented to understand legislative and planning means in the process of promoting sustainable community projects [8].

3.2.2. Key-product development

Industrial partners have made progress in developing new and/or improved products suitable to low-energy buildings: a low energy window, whose production costs were reduced by 30% by process changes and machinery investment and a ventilation unit with heat recovery and integrated heat pump for low-energy houses. Moreover the low-rise, dense building sites will be supplied by a local low-temperature DH network. During the summer period the bio-mass CHP plant will be closed down and the solar heating systems will deliver the heat for domestic hot water (DHW).

Table 4: SWOT analysis for the Stenløse Syd case study.

	Helpful	Harmful
Internal origin	<p><i>Strength</i></p> <ul style="list-style-type: none"> - Integration of different sectors - Comparison of strategies in the different participating countries 	<p><i>Weakness</i></p> <ul style="list-style-type: none"> - No obligatory monitoring concept implemented in all the sub-projects
External origin	<p><i>Opportunities</i></p> <ul style="list-style-type: none"> - Mix of energy savings and renewable energy policies, R&D and dissemination activities - Intelligent management and monitoring of water and energy consumption 	<p><i>Threats</i></p> <ul style="list-style-type: none"> - Coordination of many partners

3.3. Low-energy neighborhood in Lystrup

The project deals with the realization and evaluation of a sustainable housing area in Lystrup, Aarhus. The residential area B was completed in “Lærkehaven” in May 2008 and represented the first step towards the vision of a sustainable housing development, with a total of 122 low-energy buildings. The residential area C was completed in early 2010. The last stage (residential area A) will be finalized in 2011. The main characteristics of each area are [9]:

A: 32 two-storey family houses according to the German Passive House Standard.

B: 33 two storey houses (Danish low-energy class I) and 17 single-storey houses (Danish low-energy class 2), LED lighting, phase change materials (PCM), common solar cell facility.

C: 40 residences (Danish low-energy class I, expected energy demand of 30 kWh/m², total heated floor area: 4115 m²), connected to a low-energy DH network.

In the paper, we focus on the area C. The project integrates sustainable solutions in the end-user side (building sector) and in the energy supply side (DH network). The former deals with finding cost-effective solutions for the construction of low-energy buildings and at the same time promoting high architectural quality and comfort; the latter refers to the demonstration of

the technical and economical feasibility of DH applied to areas with low heat demand densities and to the testing of two heating unit designs with focus on return temperature.

3.3.1. The low-energy and low-exergy district heating system

The project is among the first in the world, where a low-temperature DH network is applied. The DH network (total trench length: ~800 m) was designed according to low-temperature operation in the supply pipe (55°C) and in the return pipe (25°C). The application of the low-exergy concept to the DH technology aims at three main targets. The first one is to guarantee comfort, with regards to delivery of DHW and to space heating requirements, by exploiting low-grade energy sources and RE. The second objective is to match the exergy demand of such applications with the necessary exergy available in the supply system, by making the temperature levels of the supply and the demand closer to each other. Finally, it aims at reducing the heat loss in the distribution network, so that the total profitability is ensured from the socio-economic point of view. The main design concepts are:

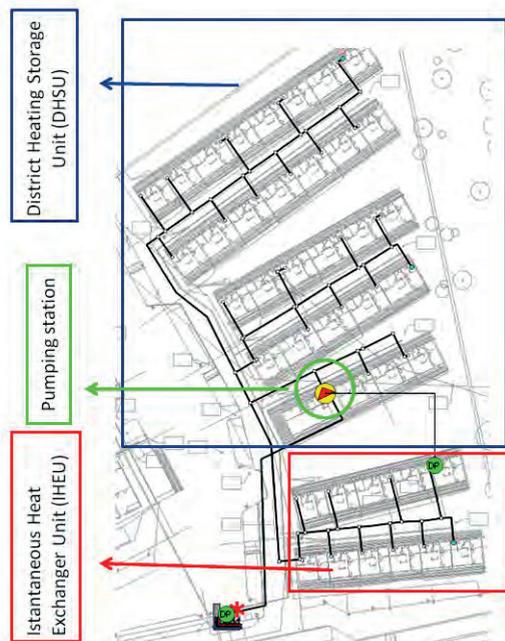
- Low-size media pipes. This is achieved by allowing a high pressure gradient in the branch pipes connected to the unit with instantaneous DHW preparation or by installing units with storage of DH water. The latter one consists on a heat exchanger coupled to a water storage tank on the primary side, which ensures low continuous water flow from the DH network and therefore media pipes of lower size in the distribution lines.

- Low-operational temperatures: down to 50-55°C in the supply line and 20-25°C in the return line.

- Twin pipes are used. Furthermore flexible plastic pipes replace steel pipes, wherever it is possible. This leads both to lower investment costs for the civil works connected to the laying of the pipeline and to lower total heat loss.

- Installation of a circulation pump. The pump ensures an increase of the available differential pressure in the network and it compensates for the choice of small-diameter media pipes.

Figure 2: Sketch of the DH network with the location of the meters (adapted from [10]).



Two types of DH substations are installed: 30 Instantaneous Heat Exchanger Unit (IHEU) and 11 District Heating Storage Unit (DHSU). This former utilizes a heat exchanger between the primary side (DH loop) and the secondary side (DHW loop) for instantaneous production of DHW, while there is a direct system for space heating. The unit is equipped with an external by-pass, meaning that the by-pass water does not flow through the heat exchanger. The latter includes a storage tank and a heat exchanger. Heat is stored with DH fluid as medium. The DHW is produced by a heat exchanger, supplied from the tank. A flow switch detects a water flow and starts the pump. There is no need for by-pass flow in this type of unit. The DHSU are all placed on the same street line so that it is possible to measure both the performance of

the unit itself and the implications at street level. The total investment cost for the whole network, including the substations, lies between 350000 € and 400000 €.

3.3.2. Analysis

We highlight here the main findings, with regards to the planning process.

- The project took profit of the extensive collaboration among different partners: the housing association, industrial partners, architectural and engineering consultants, research institutions and governmental agencies.

- The international architectural competition and the import of prefabricated building envelopes from abroad succeeded to ensure high standards and reasonable economy.

- To some extent, the Danish building construction tradition has been a barrier for planning the community as a whole, more than as a collection of individual building units. In fact, the tendency in the sector, related to low-energy buildings, is to provide solutions based upon individual energy supply systems, mainly heat pumps, and the building types are often not developed with a friendly interface to DH systems. On one hand, this means that standard and reliable offers for low-energy buildings already exist; on the other hand, it could hinder the chance of implementing a sustainable and holistic vision that gathers both the end-user' side and the energy supply side.

- A conflict between different goals arose during the planning and implementation process. A target pertained to the high expectations about reaching the “climate goal”, which for Denmark is defined by the political will of developing an energy system based on 100% RE by 2050 and it is translated to action at national, regional and local level. Another objective was connected to the need of finding solutions that can lead the process in a cost-effective way. The conflict was critical at least in two phases: during the definition of the budget for the construction of the low-energy buildings in the residential area A, and during the planning of the energy supply system for the residential area C. In the first case, the maximum allowed budget was constrained by the requirements of the social housing in Denmark, whose requirements limit the economical burden for the tenants. The implementation phase was then delayed and the construction started only when it was decided to exceed the maximum budget. In the preliminary plan for the energy supply system for the residential area B, the planners chose a traditional DH network based on a pair of single pipes, directly connected to the main network in Lystrup ($T_{\text{supply}} = 80^{\circ}\text{C}$ and $T_{\text{return}} = 40^{\circ}\text{C}$). The cost-effectiveness of such network was questioned, so that individual solutions, such as heat pumps were considered as alternative. The final decision was taken when an external R&D project took over the planning responsibility, bringing along also more capital to be invested. The final outcome was successful, since it was demonstrated not only that the low-temperature DH concept is applicable to low-energy buildings, but also that the total long-term economy (30 years) improved in comparison to the original design solutions.

- The recognition of the existence of a market in Denmark in relation to sustainable, energy-efficient and environmental-friendly houses was an additional motivation for starting the project, from the housing association point of view. In fact, the completed dwellings were fully occupied by tenants faster than in other newly established areas, despite the housing sector suffered a crisis in that period.

4. Conclusions

We conclude by summing up the main findings, which will be extensively discussed in the final report of IEA-ECBCS Annex 51. The case study of Samsø demonstrates how a community can base its whole energy system on RE, without extraordinary external subsidies. The process towards such communities benefits from local participation and local ownership. Taking the results from the experience in Samsø and simply transferring it to a national level,

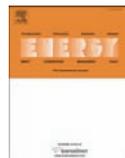
the transition towards a fully RE-based nation would cost about 90 billion EUR, giving savings for 8 billion EUR/year and a pay-back time of about 11 years (considering 2005 figures). Although these data are encouraging, the Danish average energy use per inhabitant is 25% higher than in Samsø, while the potential biomass per inhabitant is one third. Moreover, the potential of wind energy is lower in the rest of the country. Therefore, substantial energy conservation efforts are needed to achieve the goal of 100% share of RE in the country as a whole. Such issue is central in the project in Stenløse Syd, where proactive attempts have been identified and documented to understand legislative and planning means in the process of promoting sustainable low-energy community projects [8]. With regard to energy planning, the “neighborhood approach” is more profitable and can achieve better results than the “local approach”, as demonstrated by the project in Lystrup. The best social-economy is obtained only if the energy plan is done for the community as a whole, instead of considering local plans for the single housing units. Moreover, the combination of energy saving policies in the building sector and an energy efficient supply system based on RE, such as a low-temperature DH network, is seen as a promising concept for achieving ambitious climate goals.

References

- [1] www.annex51.org (2010).
- [2] www.ebst.dk (2010)
- [3] PlanEnergy and Samsø Energy Academy, Samsø – a renewable energy island, 10 years of development and evaluation, 2007.
- [4] J.P. Nielsen, J. Jantzen, Summary of work 2005-2008, Samsø Energy Agency, 2009.
- [5] www.energiakademiet.dk (2010).
- [6] www.class1.dk (2010).
- [7] www.concertoplus.eu (2010).
- [8] L. Castellazzi, M. Citterio, and others, National guidelines for residential buildings presented as grid of applicability in participating countries, Concerto Class 1 project, Work Package 4, Deliverable 22, 2009.
- [9] www.bf-ringgaarden.dk (2010).
- [10] Ledningsdimensionering og konceptuelt layout (“Pipe dimensioning and conceptual design”), COWI A/S, 2009.

ARTICLE

II



Method for optimal design of pipes for low-energy district heating, with focus on heat losses

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ABSTRACT

The synergy between highly energy-efficient buildings and low-energy district heating (DH) systems is a promising concept for the optimal integration of energy-saving policies and energy supply systems based on renewable energy (RE). Network transmission and distribution heat loss is one of the key factors in the optimal design of low-energy DH systems. Various pipe configurations are considered in this paper: flexible pre-insulated twin pipes with symmetrical or asymmetrical insulation, double pipes, and triple pipes. These technologies represent potential energy-efficient and cost-effective solutions for DH networks in low-heat density areas. We start with a review of theories and methods for steady-state heat loss calculation. Next, the article shows how detailed calculations with 2D-modeling of pipes can be carried out by means of computer software based on the finite element method (FEM). The model was validated by comparison with experimental measurements, analytical formulas, and data from the literature. We took into account the influence of the temperature-dependent conductivity coefficient of polyurethane insulation foam, which enabled us to achieve a high degree of accuracy. We also showed the influence of the soil temperature throughout the year. Finally, the article describes proposals for the optimal design of pipes for low-energy applications and presents methods for decreasing heat losses.

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1. Introduction

District heating (DH) will have a central role in the future energy system based on renewable energy (RE) [1–3]. For that, the DH industry should re-think the way district energy is produced and distributed to end-users [4,5], since policy on energy conservation poses stringent requirements in the building energy sector. Future buildings with a high performance envelope will lead to reduced space-heating loads and therefore to a lower required distribution temperature for heating. The introduction of low-energy DH networks is an appropriate and natural solution to enhance energy and exergy efficiencies. Low-energy DH networks applied to low-energy buildings represent a technology that matches the benefit of an environmentally friendly energy supply sector and the advantages of energy-saving policies on the part of the end-users. From the energy supply point of view, the application of low-energy DH offers many advantages: higher energy output in biomass-based and waste-based energy plants; higher energy output from available medium-temperature (60–100 °C) water flows of geothermal

heat or industrial residual heat; higher output capacity from connected solar heat collectors; higher power-to-heat ratios in combined heat and power (CHP) plants; increased performance of water-based heat storage, etc. Network transmission and distribution heat losses represent a key factor in the design of low-energy DH systems, because they play a critical role in the system's cost-effectiveness. The industry could meet the requirements of higher insulation to reduce heat losses and thus save operational costs; however, this option would increase investment and installation costs. Alternatively, the design principles for DH networks could turn toward the use of media pipes with smaller nominal diameters and reduced heat losses, but with a higher permissible specific pressure drop. Moreover, lower all-year-round supply and return temperatures constitute an effective option for reducing heat losses [6]. These principles have a considerable potential for heat supply to low-energy buildings, as explained in [7], and they are investigated in this paper. To conduct a comprehensive heat loss analysis, a number of variables need to be taken into account. These variables can be divided into 4 categories. The first group is represented by the operational data, mainly supply, return and outdoor air temperatures, and climatic data. The second group includes the heat conductivity of the insulating material and the soil; the third and fourth categories deal, respectively, with the geometry of pipes

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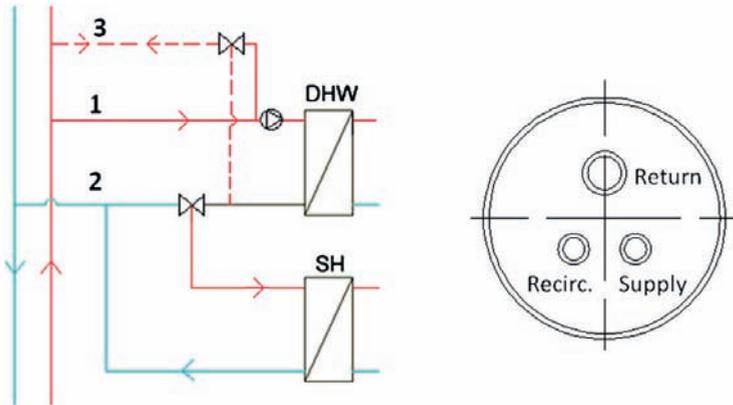


Fig. 1. Left: sketch of a user connection with HEXs: twin pipe connection with/without booster pump (1–2) and triple pipe connection (1–2–3). 1: supply 2: return 3: supply/recirculation. Right: Cross-section of a triple pipe configuration.

and pipelines (pipe diameter, thickness of the insulating layer, laying depth, pipe distance, etc.) and the arrangement of the pipes (twin pipes with vertical or horizontal placement of media pipes, double pipe, symmetrical/asymmetrical insulation of twin pipes, triple pipes, etc.). The total length of branch pipes can be significant in proportion to the total length of the network, above all in areas with a low-energy demand density. Moreover, the temperatures in the critical service lines affect the temperature level in the whole network, so that heat loss and temperature decay in building-connected pipes are decisive for the overall performance of the system. In this paper particular focus is given to pipes for service connections (branch pipes).

1.1. DH pipes for house connection

Alternative design concepts must be considered in branch pipes from street lines to consumers' substations: a pair of single pipes, twin pipes or triple pipes. In twin or triple pipes the media pipes are placed in the same insulation jacket. The choice of the house

connection type depends mainly on the length of the branch pipe, the supply and the return temperatures, the building heating load and the type of substation. This last is decisive with regard to energy performance and thermal comfort. Substations are typically divided into three types, depending on the way they prepare and provide domestic hot water (DHW): units with instantaneous preparation of DHW in a (heat exchanger) HEX, units with a DHW storage tank where the tank is in the secondary-loop, and consumer units with a DH water tank where the tank is placed in the primary loop. This paper considers branch pipe solutions for the concept of a consumer unit with HEX and no storage tank. Two possible configurations of user connection to the distribution line are shown in Fig. 1. A simple and cost-effective configuration is composed of the control system and two heat exchangers (HEXs) for, respectively, space heating (SH) and DHW. The main disadvantage of this type of substation unit is that only rather short lengths of service pipe can usually be applied; otherwise it would not be possible to ensure the required DHW temperature at tapping points in the required time, due to the unsatisfactory transportation

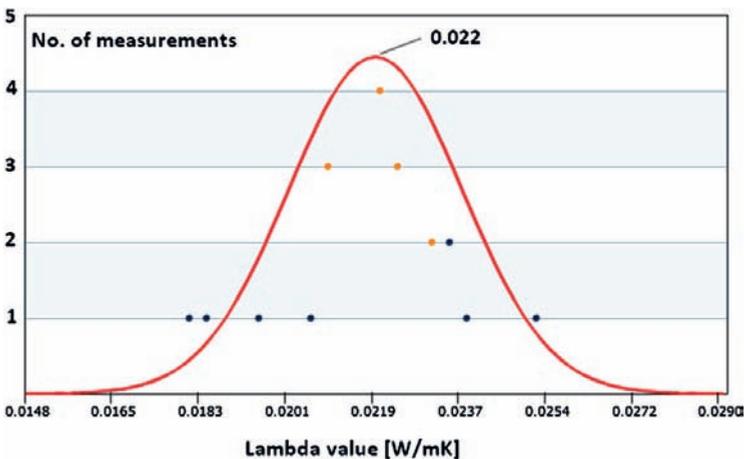


Fig. 2. Distribution of lambda-values. Measurements in 20 flexible pipes. Source: [14].

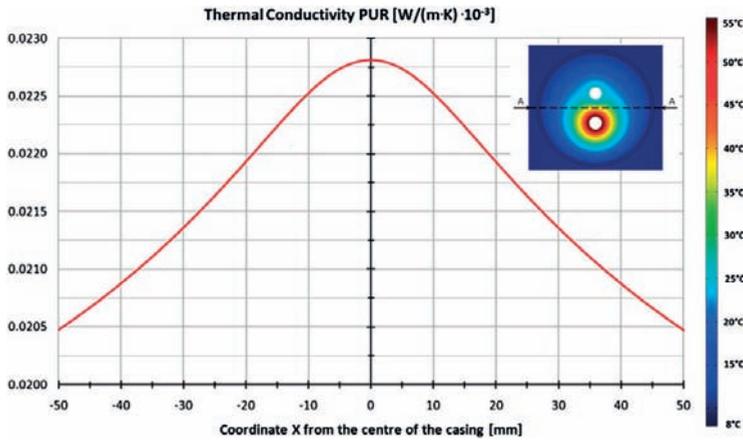


Fig. 3. Thermal conductivity in the insulation, pipe cross-section A–A. Pipe: Aluflex 16–16/110. Temperatures supply/return/ground 55/25/8 °C.

time. We therefore propose a modified unit equipped with a booster pump, which ensures a quicker response to DHW demand, although a non-perfect cooling of DH water occurs when tapping of DHW starts. The concept is based on twin pipes and a substation with instantaneous production of DHW in a HEX, and it is a simple and cost-effective solution, if certain conditions are respected. The first requirement is that the control method gives priority to DHW preparation over SH; the second condition is that the SH load during summer, to keep a high level of comfort in bathrooms for example, has to guarantee a sufficient cooling of the return water. As a result media pipes with inner diameters as small as 10 mm can be applied in the primary loop and the water return temperature can be kept sufficiently low, even in summer conditions. The triple pipe system is applicable in three different operational modes. The first one (Mode I) occurs in the case of DHW demand, when pipe 1 and pipe 3 both act as water supply pipes; the second operational mode (Mode II) is activated when an idle water flow is supplied by pipe 1 and pipe 3 acts as recirculation line to the supply distribution line, while the return line (pipe 2) is not active: this is often the case when there is no demand for SH: a small amount of water circulates in the DHW HEX, keeping the loop warm to satisfy the instantaneous preparation of DHW in the required time. This system avoids an undesirable heating of the water in the return distribution line. The third operational mode (Mode III) occurs during the heating season, when there is only demand for SH and no tapping of DHW: pipe 1 and pipe 2 operate as a traditional supply–return system, while there is no water flow in pipe 3. The different modes can be summarized as follows:

- Mode I: DHW tapping, pipes 1 (supply), 2 (return), and 3 (additional supply) active.
- Mode II: supply-to-supply recirculation, pipes 1 (supply) and 3 (recirculation) active; pipe 2 not active.
- Mode III: SH demand, pipes 1 (supply) and 2 (return) active; pipe 3 not active.

2. Methods

In this section, we present methods for evaluating steady-state heat losses in DH buried pipes, with reference to the present state of the technology in the DH sector. Furthermore, key-points and critical aspects are discussed, such as the temperature-dependency

of the thermal conductivity of the insulation, and the temperature field of the soil around the DH pipes. Next, we describe the FEM model and the assumptions the model is based on. Finally, we propose improvements in the methodology of calculating steady-state heat losses, with particular focus on low-temperature and medium-temperature applications. Low-temperature DH systems are defined as networks where fluids at a temperature below 50 °C are used, while a medium-temperature DH system is defined as using fluids at temperatures no higher than 70 °C [8,9].

2.1. Theory of steady-state heat loss in buried pipes

There are analytical methods [10] and explicit solutions for the most common cases [11] for calculating steady-state heat losses in DH buried pipes. A complete review of the available literature about steady-state heat losses in DH pipes was carried out in [12]. Steady-state heat losses from pre-insulated buried pipes are generally treated by use of the following equation [12], which is valid for each pipe-*i*:

$$q_i = \sum_{j=1}^n U_{ij} \cdot (T_j - T_0) \tag{1}$$

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, which is the most common application in the DH sector, the heat losses can be calculated for the supply pipe and the return pipe, respectively, as follows:

Supply pipe:

$$q_1 = U_{11} \cdot (T_1 - T_0) + U_{12} \cdot (T_2 - T_0) \\ = (U_{11} + U_{12}) \cdot (T_1 - T_0) + U_{12} \cdot (T_2 - T_1) \tag{2}$$

Table 1
Thermal properties of materials.

Material	Soil	polyethylene (PE)	PUR	Crosslinked Polyethylene (PEX)	Steel
λ [W/(m·K)]	1.6	0.43	0.023–0.024	0.38	76
ρ [kg/m ³]	1600	940	60	938	8930
C_p [J/(kg·K)]	2000	1800	1500	550	480

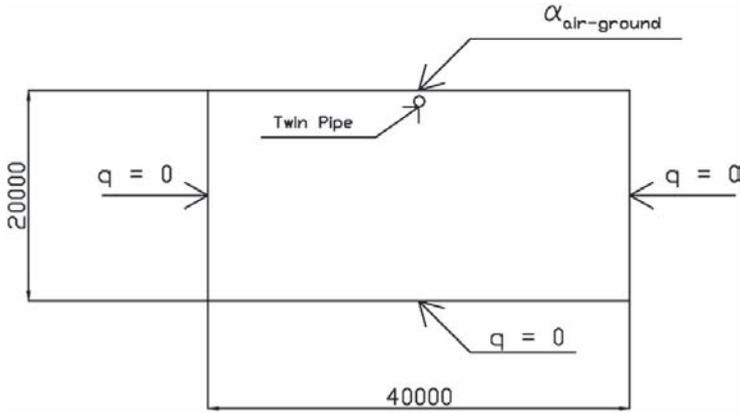


Fig. 4. Sketch of the rectangular model of the ground, with boundary conditions. Dimensions are in [mm].

Return pipe:

$$q_1 = U_{22} \cdot (T_2 - T_0) + U_{21} \cdot (T_1 - T_0) = (U_{22} + U_{21}) \cdot (T_2 - T_0) + U_{21} \cdot (T_1 - T_2) \quad (3)$$

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

Equations (2) and (3) show how the heat transfer from each pipe can be treated as the linear superimposition of two heat fluxes, with the first one describing the heat transfer between the pipe and the ground, and the second one representing the heat transfer between the supply pipe and the return pipe. The equations can also be re-arranged in the following way:

Supply pipe:

$$q_1 = \left[U_{11} + U_{12} \cdot \frac{(T_2 - T_0)}{(T_1 - T_0)} \right] \cdot (T_1 - T_0) = U_1 \cdot (T_1 - T_0) \quad (4)$$

Return pipe:

$$q_2 = \left[U_{22} + U_{21} \cdot \frac{(T_1 - T_0)}{(T_2 - T_0)} \right] \cdot (T_2 - T_0) = U_2 \cdot (T_2 - T_0) \quad (5)$$

Equations (4) and (5) show how the heat transfer from each pipe can be calculated by using only one linear thermal coefficient, which is a function of the temperature in this case. This is the methodology used by some network simulation programs, which usually consider only one temperature difference and one linear thermal coefficient for each line: U_1 for the supply line, and U_2 for the return line. The U -value based approach is convenient and gives acceptable results from the engineering point of view. However, U -values are dependent both on temperature and time. While the time-dependency due to the ageing of the foam can be restrained by introducing effective diffusion barriers, this is not true for the temperature-dependency. It is common practice to evaluate the steady-state heat loss by applying a thermal-conductivity value that is constant and corresponds to a hypothesized mean

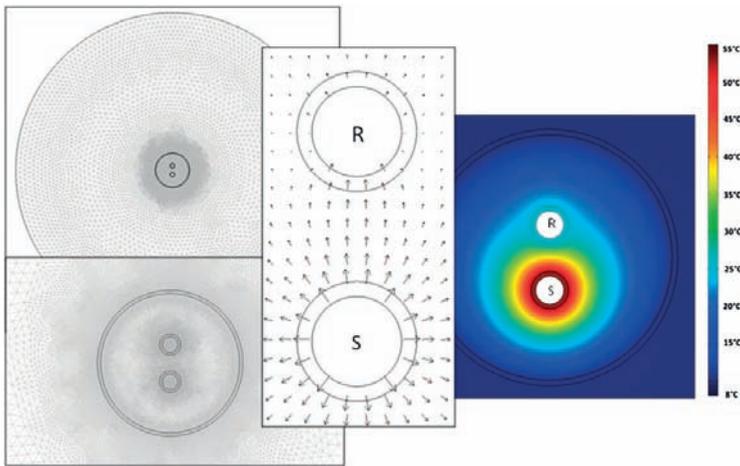


Fig. 5. Mesh model of a pre-insulated twin pipe buried in the ground (left); Heat flux between the media pipes (middle) and temperature field in Aluflex twin pipe 16–16/110 (right); temperature supply/return/ground: 55/25/8 °C.

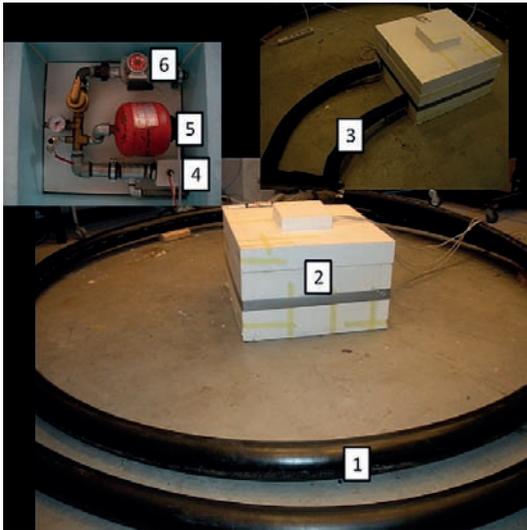


Fig. 6. Experimental set-up: 1: Aluflex twin pipe coil; 2: insulated box; 3: connection pipes; 4: electric heater; 5: expansion vessel; 6: pump.

temperature of the insulation. However, we need models based, for example, on the finite-element method (FEM) when complex geometries or a high degree of detail are required.

2.2. Temperature-dependent thermal conductivity of insulation foam

Considering a life cycle assessment of a DH system, the main impact on the environment is represented by heat losses [13]. It is therefore necessary to enhance the product performance by acting on the thermal properties of the insulation. The thermal conductivity of the insulation material in pre-insulated DH pipes is usually given as at a temperature of 50 °C. The value of the thermal conductivity is based on a mean value from measurements of multiple testing samples. The tests are carried out during the production process or by authorized laboratories. Fig. 2 shows an example.

The lambda-coefficients were chosen in accordance with the available data [14]; the lambda-value at 50 °C for straight pipes, axial continuous production was set to 0.024 W/(mK) and for flexible pipes to 0.023 W/(mK). But it would be better to take into account the temperature-dependency of the thermal conductivity

of the insulation foam. The calculations in this paper used the following expression, unless otherwise stated. It is derived from experimental data [15]:

$$\lambda(T) = 0.0196734 + 8.0747308 \cdot 10^{-5} \cdot T \text{ [W/(mK)]} \quad (6)$$

where λ is the insulation thermal conductivity as a function of the local temperature T . The temperature gradient in the insulation foam in the radial direction is often higher than 10 °C/cm, meaning that the local thermal conductivity of the material varies remarkably. In Fig. 3 an example is shown, where a twin pipe type Aluflex 16–16/110 was considered (the outer diameter of supply and return pipes is 16 mm and the outer diameter of the casing is 110 mm). In the example, the thermal conductivity varies more than 10% from the prescribed mean value. This affects the magnitude of the heat transfer, especially if more than one pipe is placed in the same insulation. Hence it is relevant to make available a tool that is capable of taking into account the variations in thermal conductivity in the insulation volume.

2.3. Temperature field in the soil around the pipe

The overall heat transfer resistance between the DH water and the environment is mainly composed of the thermal resistance of the insulation and the thermal resistance of the soil; compared to these two factors, the thermal resistance of the pipe wall and the convective resistance at the surface water-pipe are in practice negligible. The thermal resistance of the insulation foam always has the greatest share in the overall insulation effect. The contribution of the soil is smaller on small-sized pipes than on large-sized pipes. The heat conductivity coefficient of the soil is the main parameter affecting the thermal resistance of the soil itself, and its value is often unknown in practice. In fact, it may range between 0.5 W/(mK) in the case of dry sand, and 2.5 W/(mK) in the case of wet clay soil. It is common to apply a mean heat conductivity coefficient of the soil, when more detailed data are not available. In the calculations we chose a value of 1.6 W/(mK).

The soil temperature affects heat losses from DH buried pipes. The soil layer around the pipes slightly warms up. The evaluation of the temperature field in the soil is a prerequisite for creating a realistic model for heat loss calculation. FEM simulations were carried out and temperature conditions were evaluated over a 10-year period, in the soil around a typical DH branch pipe, suitable for low-temperature applications. Results are available in Section 3.1.

The heat transfer coefficient at the ground surface was assumed to be 14.6 W/(m²K), including convection and radiation [16]; we set the outdoor air temperature during the year in accordance with the harmonic function valid for the Danish climate [17]:

$$T_{\text{air}} = 8.0 + 8.5 \cdot \sin(2\pi \cdot M/12) \quad (7)$$

where T_{air} is the outdoor air temperature and M is the monthly average outdoor air temperature.

Pure heat conduction was assumed, so that combined heat and moisture transfer was disregarded. The material properties were homogeneous, and phase changes, i.e. freezing and thawing, were not considered. Table 1 lists the material properties, used as input values also for the following models; a sketch of the slab-model, where the boundary conditions are described, can be seen in Fig. 4.

2.4. FEM model

In this paper, we address the question of how to create a simple yet detailed FEM model for steady-state heat loss calculations. All the models were created in the commercial software Comsol Multiphysics. A rectangle representing a semi-infinite soil domain

Table 2
Data about the set-up and the instruments.

Item	Description
Aluflex Twin Pipe 14–14/110	Length: 16.1 m; water content: ~1.3 L
Aluflex Twin Pipe 20–20/110	Length: 14.8 m; water content: ~2.6 L
Pump	Variable-speed pump, type MC12 from Biral Electronics
Heater	Electrical heater, manually controlled by a voltage converter
Thermocouples	5 thermocouples, type T. Accuracy: ± 1.0 °C or 0.75%
Wattmeter	Kamstrup A/S Wattmeter, accuracy class 2 (IEC/EN 62053-21)
Data logger	Hewlett Packard 34970A data acquisition/switch unit

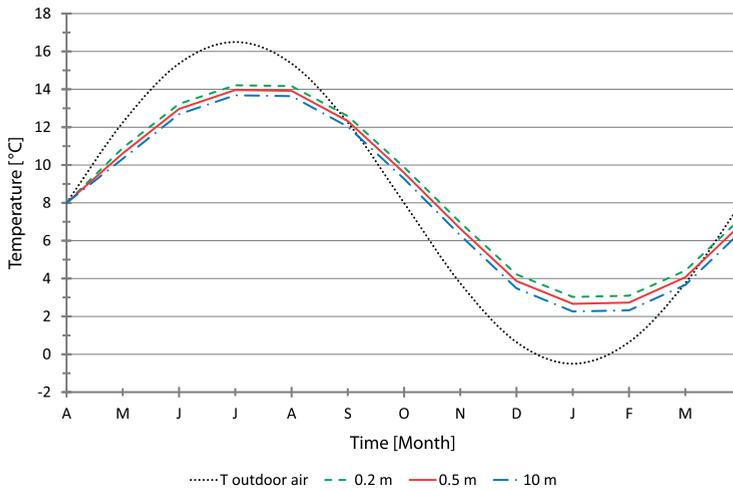


Fig. 7. All-year temperature profiles of the outdoor air and of the ground at depth equal to 0.5 m with 3 horizontal distances from the centre of the casing.

(width: 10–20 m, height: 20–40 m) is the most often used geometry to model the ground in heat loss calculations [18,19]. We used a finite, circular soil domain instead. Its diameter is 0.5 m, equal to the distance between the soil surface and the centre of the casing pipe. Calculations in Section 3.2 show that the simplification introduced hardly affects the accuracy of the results. The mesh model and an example of the temperature field in the small-size twin pipe type Aluflex 16–16/11 (outer diameters in [mm] of respectively supply pipe, return pipe, and casing) are shown in Fig. 5.

In the case of a pair of single pipes, arranging the supply pipe below the return pipe (piggy-back laying) does not lead to considerably lower heat losses compared to an arrangement where the supply pipe is laid above the return pipe. In Ref. [6], where FEM simulations were performed, it was stated that the deviation of the lineal thermal coefficient for media pipes size from DN 50 to DN 400 between the piggy-back laying and the traditional system is less than 1%. The same conclusion can be stated for twin pipes; this is confirmed by calculations with the multipole method in Ref. [20] for two examples of twin pipe (DN 20 and DN 80) and in Ref. [12]. For twin pipes of even smaller size, such as in branch connections, the heat losses occurring in the case of vertical layout are only slightly less than the losses occurring on horizontally arranged pipes. This result is shown with an example in Section 3.2.

2.5. Experimental set-up

An experimental facility was designed and constructed to validate the FEM model. The set-up consisted of a 15-m long Aluflex

Table 3

Heat loss for various placements of the media pipes and various models of the ground. Supply/return/ground temperatures: 55/25/8 °C.

Ground model	Media pipes layout	Heat loss [W/m]		
		Supply	Return	Total
A ^a	Vertical	3.79	-0.17	3.62
A	Horizontal	3.80	-0.18	3.62
B ^b	Vertical	3.84	-0.18	3.66

^a A: Semi-infinite, rectangular (width × depth: 40 m × 20 m)

^b B: Finite, circular (diameter: 0.5 m)

twin pipe coil, two connection pipes and an insulated box, which contained a variable-speed pump, an electrical heater and an expansion vessel (see Fig. 6).

The supply media pipe was connected to the box at the two edges of the pipe coil, hence creating a hydraulic circuit. The box and the two connection pipes were insulated with, respectively, polystyrene (0.3 m) and polyurethane (0.05 m). The whole set-up was placed in ambient temperature. A constant water flow, corresponding to the minimum pumping power (7 W), circulated in the supply media pipe, while the return media pipe was kept in still ambient air. The hydraulic pressure of the system was set to 2 bar. A wattmeter measured the total input power, composed by the sum of pumping and heating power, which were kept constant until steady-state conditions occurred. It was assumed that the steady-state was reached when the water temperature increased less than 0.2 °C/h, during two consecutive hours of measurement. Five thermocouples type T measured the ambient air temperature, the water temperature at the inlet/outlet of the supply media pipe and the surface temperature of the casing pipe at the axial distance of 0.3 m from the inlet and the outlet. The process took between 10 h and 14 h per measurement. Temperature data were taken for 5 min at intervals of 5 s, when steady-state conditions were reached. Technical information about the set-up and the instruments are listed in Table 2.

The total heat loss of the circuit, i.e. twin pipe, insulated box and connection pipes, were measured in such a way for 4 different values of input power (step 1). Next, we modified the set-up. The twin pipe was by-passed and the two connection pipes were joined together, so that the heat loss of such circuit was evaluated for 6

Table 4

Computational time and heat losses for successive mesh refinements. Aluflex twin 16–16/110.

Mesh elements	Time [s]	Heat loss [W/m]		
		Supply	Return	Total
I) 4418	0.52	3.7171	-0.2390	3.4781
II) 17672	2.02	3.7370	-0.2397	3.4973
III) 70688	9.81	3.7477	-0.2399	3.5078
IV) 233056	24.95	3.7512	-0.2400	3.5112

Table 5
Heat losses calculated with three different methods.

Pipe type	Method	Heat loss [W/m]		
		Supply	Return	Total
Aluflex 16–16 Series 2	$\lambda = 0.023, T = 50\text{ }^\circ\text{C}$	3.84	-0.17	3.68
	$\lambda = \text{const., mean } T$	3.55	-0.15	3.40
	$\lambda = f(T)$	3.75	-0.24	3.51
Steel DN65 Series 2	$\lambda = 0.024, T = 50\text{ }^\circ\text{C}$	7.91	-0.14	7.78
	$\lambda = \text{const., mean } T$	7.10	-0.11	6.98
	$\lambda = f(T)$	7.41	-0.28	7.13

different values of input power. Hence, we were able to calculate a linear regression equation that gives the heat loss of such configuration as function of the water temperature (step 2). Finally, we calculated the heat loss of the twin pipe at specific water temperatures, as difference between the total heat loss, which was measured in step 1, and the heat loss of the box and connection pipes, which was calculated by means of the regression equation in step 2. The accuracy of the measurements was calculated to be $\pm 4\%$ of the measured values, considering the accuracy of the wattmeter and the thermocouples. Next step consisted in utilizing the measured average water temperature and the ambient air temperature as input to the FEM model. A convective heat transfer coefficient of $4\text{ W}/(\text{m}^2\text{K})$ was assumed between ambient air and casing pipe. Section 3.3 presents the comparison between the heat loss measured during the experiments and the calculated ones from simulations, for two sizes of twin pipes: Aluflex 14–14/110 and Aluflex 20–20/110.

3. Results and discussion

In this section, we discuss the influence of the soil temperature on heat losses and what are reasonable boundary conditions around DH pipes; next, the FEM model is validated; finally we apply the method to show the potential for energy-saving in the case of asymmetrical insulation of twin pipes, double pipes, and triple pipes. The fundamental idea of low-temperature DH networks is that such systems can meet the energy and comfort requirements in low-energy buildings without increasing the amount of insulation around the pipes and therefore in a cost-effective way. We explained that with an example, where we considered two pipe types: the first, a typical medium-size distribution steel twin pipe (DN65, insulation series 2), and the second, a typical plastic branch

Table 6
Heat losses from Aluflex twin pipes, series 2.

Supply/Return/ Ground [$^\circ\text{C}$]	Size [mm]	Total heat loss [W/m]		Difference [%]
		Analytical formula	FEM ($\lambda = 0.023$)	
50/20/8	14–14	2.82	2.82	0.3
	16–16	3.11	3.09	0.6
	20–20	3.66	3.65	0.2
	26–26	4.01	4.05	0.9
55/20/8	14–14	3.09	3.08	0.2
	16–16	3.40	3.38	0.6
	20–20	4.00	3.99	0.2
	26–26	4.39	4.43	0.8
55/25/8	14–14	3.35	3.34	0.2
	16–16	3.68	3.68	0.1
	20–20	4.34	4.33	0.1
	26–26	4.76	4.80	0.8
60/30/8	14–14	3.87	3.86	0.2
	16–16	4.26	4.24	0.5
	20–20	5.01	5.01	0.2
	26–26	5.51	5.55	0.7

Table 7
Experiments in Aluflex twin pipe 14–14/110.

Average temperature [$^\circ\text{C}$]		T_{air} [$^\circ\text{C}$]	Average DT water-air [$^\circ\text{C}$]	Heat Loss [W/m]		
Water	Casing [$^\circ\text{C}$]			Calculated	Measured	[%]
49.2	23.8	22.2	27.0	1.88	2.00	-6.0
58.3	24.4	22	36.3	2.56	2.72	-5.7
66.8	24.9	21.6	45.2	3.24	3.37	-3.9
74.2	25.4	21.7	52.5	3.81	3.99	-4.6

pipe (Aluflex 16–16, insulation series 2). We compared the heat losses in the case of normal operational temperature (supply: $85\text{ }^\circ\text{C}$, return: $50\text{ }^\circ\text{C}$) and in the case of low-temperature operation (supply: $55\text{ }^\circ\text{C}$, return: $25\text{ }^\circ\text{C}$). Calculations proved that, to achieve the same heat loss, the distribution pipe and the branch pipe in the first case need, respectively, 3 and 11 times more insulation than in the second case.

3.1. Temperature field in the soil

The temperature conditions in the soil around a typical twin pipe Aluflex 16–16/110 were evaluated over a 10-year period. The geometry used is shown in Fig. 7. This was necessary in order to obtain realistic boundary conditions and implement them in the FEM model. Fig. 7 shows the all-year-round temperature profiles of the outdoor air and of the ground at a depth equal to 0.5 m from the ground surface, at three horizontal distances from the centre of the casing, during the first year of operation. No notable differences in the yearly profile were noticed in longer periods of time.

We found that in state-of-the-art well-insulated twin pipes (insulation series 2 or 3) a certain amount of soil is slightly heated up by the warm twin pipe; nevertheless, the level of such heating can be neglected because its effect is not noticeable in comparison to the fact that the uncertainties about the thermal properties of the soil usually have a bigger impact. Considering annual average temperatures, the magnitude of the soil heating is about $1.0\text{ }^\circ\text{C}$ for distances of around 0.2–0.3 m from the centre of the casing, and less than $0.5\text{ }^\circ\text{C}$ by 0.5 m. The increase of the annual average temperature due to the influence of the DH pipe was considered in comparison to the undisturbed temperature of the ground at a distance of 10 m from the centre of the casing.

3.2. FEM model

We started from the geometric model of the pre-insulated Aluflex twin pipe type 16–16/110 and we calculated the heat losses for vertical or horizontal placement of the media pipes inside the casing, which was embedded either in a rectangular or a circular model of the ground. The same calculations were repeated for other twin pipe sizes up to DN 32, and for other medium pipe materials, i.e. steel and copper. The results confirmed that the vertical placement of the media pipes inside the insulation barely affected

Table 8
Experiments in Aluflex twin pipe 20–20/110.

Average temperature [$^\circ\text{C}$]		T_{air} [$^\circ\text{C}$]	Average DT water-air [$^\circ\text{C}$]	Heat loss [W/m]		
Water	Casing [$^\circ\text{C}$]			Calculated	Measured	[%]
51.5	24.6	23	28.5	2.48	2.62	-5.4
68.6	25.7	23.3	45.3	3.97	4.13	-3.9
76.4	26.4	24.1	52.3	4.74	5.03	-5.7
58.8	25.0	23.6	35.2	3.10	3.30	-6.1

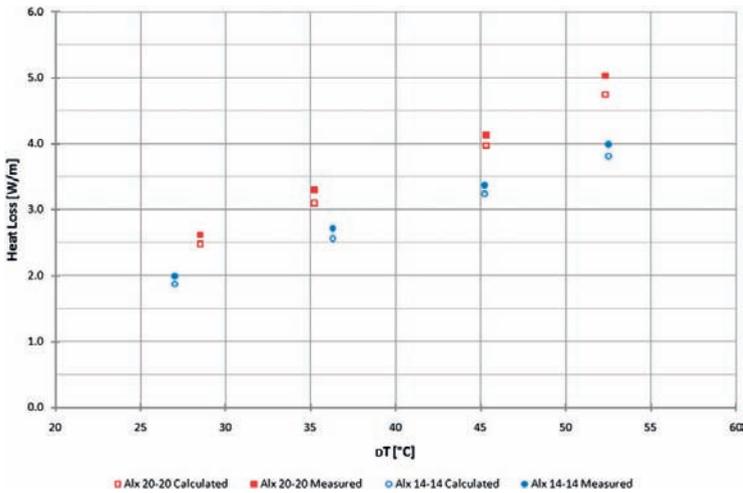


Fig. 8. Experimental and calculated heat losses. Aluflex twin pipe 14–14/110 and Aluflex twin pipe 20–20/110.

the heat transfer, because the difference between the two configurations was less than 2% (see Table 3).

There is little difference between the results obtained with the use of the finite, circular computational domain and those with the semi-infinite rectangular computational domain. Moreover, the finite, circular computational domain has the advantage that it saves computational time and allows a better refinement of the mesh. Table 4 shows that fast heat loss calculations can be made, starting from the pre-defined mesh and after two successive mesh refinements. Simulations were performed with a CPU type Intel Core Duo, 2.53 GHz, 2.98 GB of RAM. Heat losses are traditionally calculated considering a constant thermal conductivity of the insulation. It might be the certified value at 50 °C or the value that corresponds to the assumed mean temperature of the insulation. Instead, the model proposed takes into account the temperature-

dependency of the thermal conductivity of the insulation, assuming that the material is homogenous. This method guarantees a high degree of detail in the evaluation of the heat transfer and it is more accurate. In fact, the method considered for assessing the thermal conductivity of the insulation has an influence on the heat loss calculation. Table 5 illustrates this for two reference pipes and for the three methods mentioned above.

The model proposed has a circular computational domain for the ground and it is capable of taking into account the temperature-dependency of the thermal conductivity of the insulation. It was validated by comparing the results from FEM simulation with the analytical calculation for pre-insulated pipes embedded in the ground [12]. The lambda-value of the insulation was set to 0.023 W/(mK) because the analytical formula can only be used in the case of constant thermal conductivity.

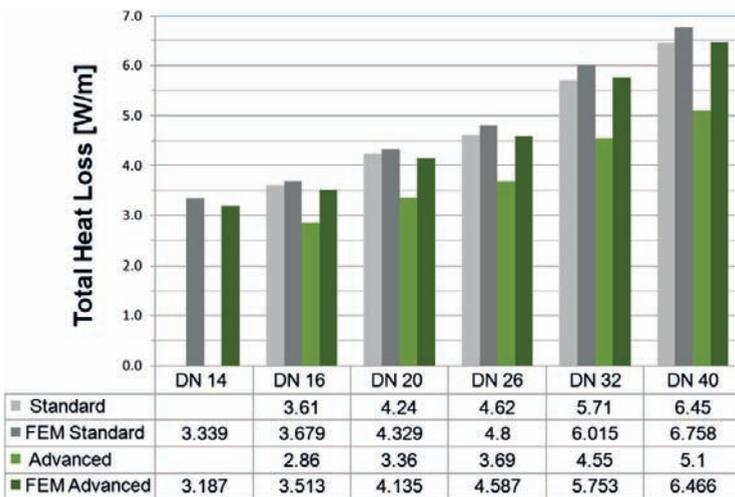


Fig. 9. Comparison of 4 different approaches for steady-state heat loss calculation. Aluflex twin pipe series 2, supply/return/ground temperatures: 55/25/8 °C.

Table 9

Comparison between asymmetrical and symmetrical insulation in twin pipes. The centre of the casing is the origin of the Cartesian system (x; y).

Pipe data		Coordinates (x; y) [mm]		Heat loss [W/m]			asymm.-symm. [%]	
Size (DN)	Material	Supply	Return	Supply	Return	Total	Supply	Total
14	Aluflex	(0; 0)	(0; 27)	3.24	0.01	3.25	-7.6	2.0
16		(0; 0)	(0; 28)	3.56	-0.01	3.55	-5.1	1.1
20		(0; 0)	(0; 30)	4.16	-0.04	4.12	-4.2	-0.3
26		(0; 0)	(0; 36)	4.67	0.00	4.67	-5.1	1.9
32		(0; -16)	(0; 28)	5.54	0.00	5.54	-5.8	-2.5
50	Steel	(0; -25)	(0; 55)	5.69	-0.03	5.66	-7.7	-2.4
65		(0; -36)	(0; 60)	6.70	-0.02	6.68	-7.8	-3.2

Table 6 lists the results for four different sizes of Aluflex twin pipes and for selected sets of supply, return and ground temperatures. The pipes selected are suitable for use as branch pipes in low-energy demand areas. There is a good agreement between the two methods, the deviation being less than 1%. Further calculations were carried out for the steel and copper twin pipe series: they show analogous results.

3.3. Experimental validation

The results from the experiments described in Section 2.5 are reported in Table 7 and in Table 8, respectively for the Aluflex twin pipe 14–14/110 and the Aluflex twin pipe 20–20/110. In the same tables the values of total heat loss, calculated by means of the FEM model are listed too. All the results are gathered in Fig. 8, where it is possible to see the almost-linear correlation between the heat loss and the temperature difference between the water and the ambient air.

The heat losses from the simulations are between 3.9% and 6.0% lower than the measured values, in the case of the Aluflex twin pipe 14–14/110 and between 3.9% and 6.1%, in the case of the Aluflex twin pipe 20–20/110. Such values are higher than the accuracy of

the measurements ($\pm 4\%$), but they are still inside the range of uncertainty the heat loss can be assessed with. In fact, even in pipes of the same material and size, the thermal conductivity of the insulation can vary up to 8–10% of the statistical mean value (see Fig. 2, for example). This does not affect the utility of the software-based calculations of the heat loss, since the length of the DH networks allows average values to be considered. Therefore the agreement between the experimental results and the values calculated with the FEM model is acceptable.

3.4. Steady-state heat loss in commercial pipes

Fig. 9 collects the values of total heat loss for the Aluflex twin pipe category; four different approaches are reported. The term “standard” is used when the effect of the temperature on the thermal properties of the insulation is ignored and the thermal conductivity of the polyurethane (PUR) foam is therefore constant. This is in accordance with Ref. [21]. The term “advanced” is used when the calculation method takes into account the fact that the thermal conductivity of the insulation depends on the temperature. Based on the temperatures calculated for a number of points in the cross-section of the insulation, the program calculates an average temperature for the material; the lambda-value of the insulation is then calculated as a function of this temperature. An average temperature of the ground is similarly calculated. The calculation is repeated until the mean temperature difference for the insulation material, pipe shell, and surrounding soil is less than $0.005\text{ }^{\circ}\text{C}$ for two consecutive calculations. The “standard” and “advanced” models have been reported in Ref. [14]. In the “FEM advanced” model, we directly implemented Equation (1) in the insulation domain. The results indicate that, in the case of low-temperature operation, lower total heat losses are calculated if the temperature-dependency of the insulation lambda-value is taken into account. Moreover the heat transfer among the media pipes in twin or triple pipes can be properly evaluated in this case, since the correlation between temperature and thermal conductivity is locally defined in the whole insulation domain.

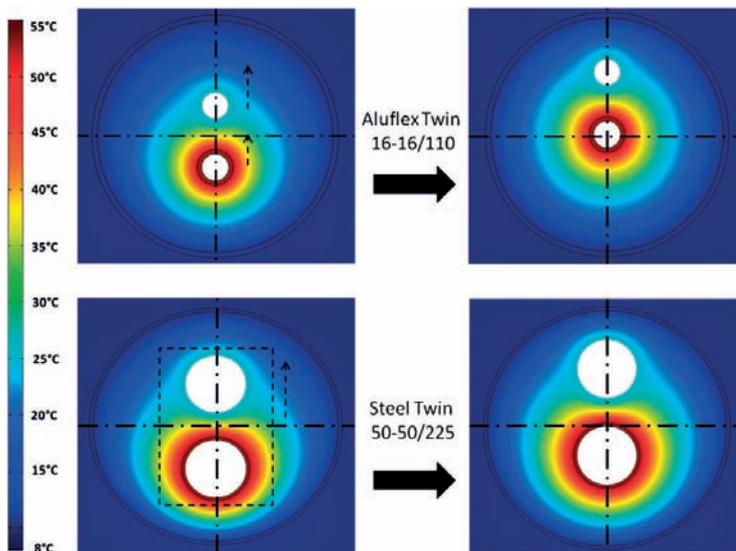


Fig. 10. Proposed modification in DH pipe design. Top: Aluflex Twin 16–16/110. Bottom: Steel Twin 50–50/225.

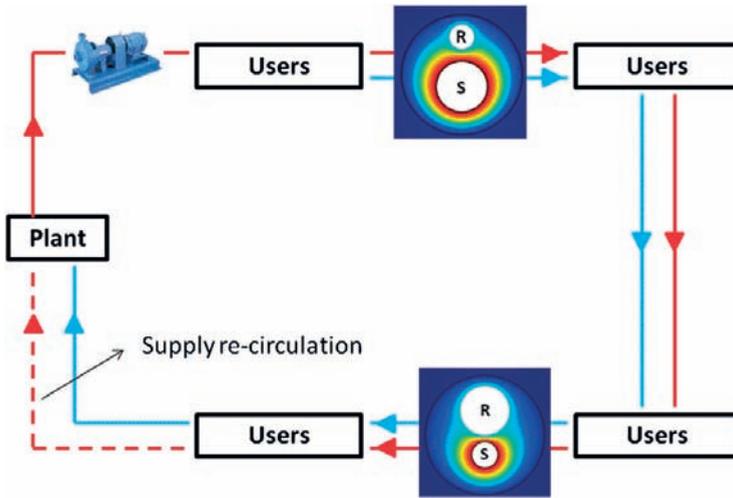


Fig. 11. Sketch of the possible application of the double pipe concept in a simple district heating network.

3.5. Asymmetrical insulation in twin pipes

The expression “asymmetrical insulation” means that the media pipes are placed in the insulation in a way that the distance between the centre of the supply pipe and the centre of the casing pipe is different from the distance between the centre of the return pipe and the centre of the casing pipe. The results show that such asymmetrical insulation of twin pipes makes improvements possible (see Table 9). We proved that a better design leads to lower heat losses from the supply pipe (leading to a lower temperature drop); next, the heat loss from the return pipe can be close to zero, maintaining isothermal conditions in the return line. If commercially available casing sizes are used, we suggest two design strategies depending on the size of the pipes (see Fig. 10). For small pipe sizes (Aluflex: \leq DN 26, steel: \leq DN 50), the best design is to place the supply pipe in the centre of the casing, assuring the best possible insulation for the supply pipe. This strategy guarantees also the lowest temperature drop in the supply line, which is a critical figure in low-temperature applications. The return pipe is placed at a vertical distance from the supply pipe such that the total heat transfer from the return pipe boundaries is null, thus the distance between the media pipes is not necessarily the same as in the symmetrical case. For larger sizes (Aluflex: \geq DN 26, steel: \geq DN 50), the best design is achieved by “moving up” the media pipe layout and at the same time keeping the same distance between the media pipes as in the symmetrical case. In fact, it is not possible to apply the first design concept for big media pipe sizes imbedded in standard insulation casings, due to space restrictions.

3.6. Double pipes

A double pipe consists of a pair of media pipes of dissimilar size, co-insulated in the same casing. This is a further development of the twin pipe concept. A sketch of a possible application of the double pipe concept is shown in Fig. 11.

These measures make it possible to reduce network heat loss, in the case of operation during low heating load periods. The SH demand in summer is low, except for the energy requirement in bathroom heating. According to the energy balance, the reduced heating load requires a lower network flow rate as long as the

designed building temperature drop is maintained. However, the lower network flow rate will increase the supply water temperature drop along the pipeline due to heat loss. As a consequence, the supply temperature at the end-user may decrease below the minimum requirement. This problem is particularly relevant for the low-energy DH system with an already low supply temperature. This design is based on the fact that the supply line also acts as the recirculation line during low heating load periods; this means that a by-pass at the critical consumers is not necessary and the energy loss due to the mixing of supply water into the return line is avoided. Furthermore, the water flow in the return line has the same direction as in the supply line (clockwise in the example), so that the smallest size for the return pipes is expected to correspond to the biggest size for the supply size, and vice versa. This results in lower local pressure differences between supply and return lines and savings in operational costs due to lower heat losses. This is shown in Table 10, by means of two examples: the first one refers to a small-to-medium-size distribution network, the second one to a larger one, capable of supplying four times more energy than the smaller one. We considered an optimal placement of the media pipes in the case of double pipes, and therefore asymmetrical insulation. The same total amount of insulation is used in both the

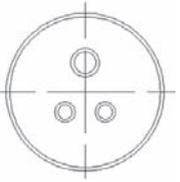
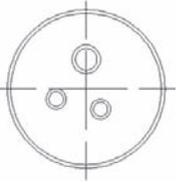
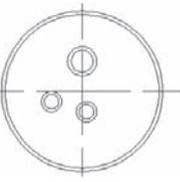
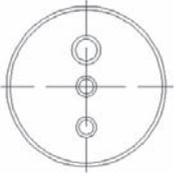
Table 10

Left: comparison between a distribution network based on twin pipes (DN40–40 and DN80–80) with a distribution network based on double pipes (DN40–80 and DN80–40). Right: comparison between a distribution network based on twin pipes (DN100–100 and DN200–200) with a distribution network based on double pipes (DN100–200 and DN200–100). Supply/return/ground temperature: 55/25/8 °C.

Size (DN)	Heat loss [W/m]			Total	[%]
	Supply	Return	Total		
40–40	–6.24	0.04	–6.20	Twin	6.1
80–80	–7.66	0.07	–7.59	–13.79	
40–80	–5.55	0.05	–5.58	Double	11.8
80–40	–7.41	0.05	–7.36	–12.94	
100–100	–7.83	–0.55	–8.39	Twin	11.8
200–200	–8.92	0.24	–8.68	–17.06	
100–200	–6.4	0.08	–6.36	Double	11.8
200–100	–8.07	–0.03	–8.69	–15.05	

Table 11

Placement of media pipes inside the casing for four triple pipe geometries, type Aluflex 14–14–20/110.

Geometry	Coordinates (x, y) [mm]		
	Pipe 1 (Supply)	Pipe 2 (Return)	Pipe 3 (Supply/Recirculation)
A		(14; -14)	(0; 20.5) (-14; -14)
B		(10; -14)	(0; 20.5) (-21; -7)
C		(3; -14)	(0; 20.5) (-21; -7)
D		(0; 0)	(0; 25) (0; -28)

twin-pipe-based distribution network and the double-pipe-based one, so that the investment costs are equal in both cases. Results show that the heat loss can be reduced by 6% by using double pipes instead of twin pipes for the low to medium-size distribution network. Even higher energy savings (around 12%) are possible in the case of the large-size distribution network.

3.7. Triple branch pipes

We assessed the development of an optimized triple pipe solution for low-energy applications using detailed heat transfer models to show its potential use. In this survey, focus was given to choosing media pipe diameters as small as possible. DH manufacturers state that it is not reasonable to consider media pipes whose internal diameters are smaller than 10 mm, due to risk of malfunctioning. So, in the following, the triple pipe geometry is based on modifications of the 14–14/110 twin pipe design which is available in [20]. Four geometrical variations were considered and

Table 12

Steady-state heat losses of triple pipes type Aluflex 14–14–20/110 for 4 geometries and operational modes I, II, III. Temperature supply/recirculation/return/ground: 55/55/25/8 °C.

Operational mode	Geometry	Heat loss [W/m]			
		Pipe 1 (Supply)	Pipe 2 (Return)	Pipe 3	Total
I (DHW tapping)	A	2.67	-0.08	2.67	5.30
	B	2.91	-0.29	2.75	5.38
	C	2.52	-0.22	2.74	5.06
	D	2.46	0.05	2.74	5.24
II (supply-to-supply recirculation)	A	2.67	/	2.67	5.34
	B	2.69	/	2.85	5.55
	C	2.48	/	2.70	5.18
	D	2.49	/	2.75	5.25
III (space heating)	A	3.46	0.48	/	3.95
	B	3.39	0.43	/	3.83
	C	3.41	0.35	/	3.76
	D	3.53	-0.01	/	3.53

the Cartesian coordinates describing the placement of media pipes inside the casing are listed in Table 11. Starting from the configuration A, which was suggested in [20] we assessed other three possible configurations, where the main supply pipe is moved step by step toward the centre of the casing pipe and thus to the core of the insulation, while the recirculation pipe is placed first in a position between the supply pipe and the return pipe (geometries B and C) and then below the supply pipe (geometry D).

The results of the FEM simulations are listed in Table 12 for the four geometries and the three operational modes (I, II, III), described in 1.1. Since Mode II occurs in the case of no demand of SH and thus outside the heating season, simulations were additionally performed with a more realistic temperature of the ground during that period (14 °C), considering Danish weather (see Table 13). This gives also an insight into the effect of ground temperature throughout the year.

We conclude that there is no “absolute best” design for the service triple pipe, but it depends on the operational mode that is chosen as critical. In fact the results reported in Table 12 and Table 13 shows that geometry C gives the lowest total heat loss for operational modes I and II, while geometry D has the best thermal performance for operational mode III and for operational mode II, if a temperature of the soil of 14 °C is considered. It has to be underlined that, in operational mode III, geometry D shows no heating of return water: this is a desirable situation; however it has a slightly higher heat loss from the supply pipe than the other geometries. It has been shown that usually operational mode I occurs for less than 1 h/day [21]. Moreover, the temperature drop in the supply pipe to the DHW HEX is critical in low-temperature applications, so that it is strongly recommended that the heat loss from this media pipe should be minimized. Considering all this and the fact that mode III is the most likely during the heating season and mode II is the most likely outside heating season, the conclusion is that geometry D is preferable.

Table 13

Steady-state heat losses of triple pipes type Aluflex 14–14–20/110 for 4 geometries and operational mode II. Temperature supply/recirculation/return/ground: 55/55/25/14 °C.

Operational Mode	Geometry	Heat loss [W/m]			
		Pipe 1 (Supply)	Pipe 2 (Return)	Pipe 3	Total
II (supply-to-supply recirculation)	A	2.35	/	2.35	4.70
	B	2.37	/	2.51	4.88
	C	2.39	/	2.63	5.02
	D	2.20	/	2.42	4.62

4. Conclusions

The evaluation of heat loss plays a central role in the assessment of the cost-effectiveness of DH networks. This means that a software-based tool, capable of carrying out fast and detailed calculation of heat loss in DH pipes, is desirable. Moreover, such a tool can be used to optimize the design of the pipes or to find the optimal amount of insulation. This paper proposes a detailed FEM model to calculate steady-state heat loss in DH pipes. The reliability of the model was validated by means of experimental data on total heat loss from 2 different sizes of Aluflex twin pipes, placed in ambient air. The measurements were validated with a modified FEM model, where the pipe is placed in air. Then, the accuracy of the model in the real case (pipes buried in the ground) is proved by comparison to the traditional way of modeling the ground, analytical formulas and data from literature, taking into account that the soil conductivity usually plays a minor role for modern, pre-insulated pipe systems [20]. The calculation method takes into account the temperature-dependency of the thermal conductivity of the insulation foam; in this way, we can enhance the accuracy of the heat transfer calculation for pipes embedded in the same insulation.

We investigated the temperature field of the soil around the pipes and demonstrated that the soil temperature at 0.5 m below the surface in Denmark varies between 2 °C in January–February and 14 °C in July–August. This knowledge can be used to improve predictions of the winter peak load and the temperature drop in the distribution line during summer.

Next, we proved that, in the case of small-size distribution/branch pipes, the traditional slab-model for steady-state heat loss calculations can be replaced by a model where the effect of the soil is represented by a circular soil layer around the DH pipe. With this model a single calculation for a given geometry takes usually less than 15 s.

Furthermore, we applied the method to show the potential for energy saving in the case of twin pipes, asymmetrical insulation of twin pipes, double pipes and triple pipes. With regard to twin pipes the results confirm that the vertical placement of twin media pipes inside the insulation barely affects the heat transfer, in comparison to the horizontal placement; the difference between the two configurations is less than 2% for the cases considered. Moreover, it was demonstrated that the asymmetrical insulation of twin pipes leads to lower heat loss from the supply pipe (from –4% to –8%). Consequently the temperature drop of the supply water decreases and that is relevant for low-temperature applications. At the same time, the heat loss from the return pipe can be close to zero.

With regard to the double pipe system, it is possible to cut heat losses by 6–12% if an optimal design of double pipes is used instead of traditional twin pipes, without increasing the investment costs.

Finally, we also described the development of an optimized triple pipe solution. This is suitable for low-energy applications with substations equipped with a HEX for instantaneous preparation of DHW.

The FEM model itself and the new knowledge of opportunities for improving the design of DH pipes can be used as tools for developing the next generation of low-energy DH systems.

References

- [1] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems – the case of Denmark in years 2030 and 2050. *Energy* 2009;34(5):524–31.
- [2] Lund H. Renewable energy strategies for sustainable development. *Energy* 2007;32(6):912–9.
- [3] Lund H, Möller B, Mathiesen BV, Dyrrelund A. The role of district heating in future renewable energy systems. *Energy* 2010;35:1381–90.
- [4] Froning S. Low energy communities with district heating and cooling. 25th Conference on passive and low energy architecture. Dublin; 2008.
- [5] Nilsson SF, Reidhav C, Lygnerud K, Werner S. Sparse district heating in Sweden. *Appl Energy* 2008;85:555–64.
- [6] Schmitt F, Hoffman HW, Göhler T. Strategies to manage heat losses – technique and economy. IEA-DHC ANNEX VII; 2005.
- [7] Olsen PK, Lambertsen H, Hummelshøj R, Bøhm B, Christiansen CH, Svendsen S et al. A new-low-temperature district heating system for low-energy buildings. 11th International symposium on district heating and cooling. Reykjavik; 2008.
- [8] Terminology of HVAC. Atlanta: ASHRAE; 1991.
- [9] Kilkis IB. Technical issues in low to medium-temperature district heating. *Int J Glob Energy Issues* 2002;17:113–29.
- [10] Claesson J, Bennet J, Hellström G. Multipole method to compute the conductive heat flows to and between pipes in a cylinder. Lund: Department of Building Technology and Mathematical Physics; 1987.
- [11] Wallentén P. Steady-state heat loss from insulated pipes. Lund: Department of Building Physics; 1991.
- [12] Bøhm B. On transient heat losses from buried district heating pipes. *Int J Energy Res* 2000;24:1311–34.
- [13] Korsman J, de Boer S, Smits J. Cost benefits and long term behavior of a new all plastic piping system. DHC ANNEX VIII; 2008.
- [14] www.logstor.com/; 2010.
- [15] Hovedrapport EFP 2007: udvikling og demonstration af lavenergifjernvarme til lavenergibyggeri (Final report 2007: development and demonstration of low energy district heating for low energy buildings); 2007.
- [16] Kvisgaard B, Hadvig S. Varmetab fra fjernvarmeledninger [Heat loss from pipelines in district heating systems]. Copenhagen; 1980.
- [17] DS418:2002. Calculation of heat loss from buildings.
- [18] Kristjansson H, Bruus F, Bøhm B, Vejjen NK, Rasmussen J, Christensen KP, et al. Fjernvarmeforsyning af lavenergiområder [District heating supply of low heat density areas]; 2004.
- [19] Persson T, Wollerstrand J. Calculation of heat flow from buried pipes using a time dependent finite element model. 45th International Conference of Scandinavian Simulation Society. Copenhagen; 2004.
- [20] Bøhm B, Kristjansson H. Single, twin and triple buried heating pipes: on potential savings in heat losses and costs. *Int J Energy Res* 2005;29:1301–12.
- [21] EN 13941:2003. Design and installation of pre-insulated bonded pipe systems for district heating.

ARTICLE

III

Modelling Transient Heat Transfer in Small-Size TwinPipes for End-User Connections to Low-Energy District Heating Networks

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Abstract

The low-energy district heating concept has the potential of increasing the energy and exergy efficiencies of heat supply systems and of exploiting renewable energy, provided technical solutions for its wide application can be developed and implemented. This paper investigates the dynamic behaviour of district heating branch pipes in low-temperature operation (supply temperature 50-55°C and return temperature 20-25°C). We looked at state-of-the-art district heating branch pipes, suitable for the connection of a typical single-family house to a substation equipped with a heat exchanger for domestic hot water preparation. Experimental measurements of the supply temperature profiles at the outlet of the pipe, i.e. at the inlet to the substation, were compared with detailed simulations based on the finite volume (FV) method. A programming code was developed to model these profiles, and this was validated against experimental measurements and compared to the results of an analytical formula and the FV simulations. The model proved accurate, since it gives results that well represent the outlet temperature profiles measured in the experiments and calculated in the FV simulations, both where there was a step change of the inlet temperature and where there was a sinusoidal inlet temperature profile. The model could be used for the development of improved substation concepts and enhanced control strategies.

Nomenclature

c	Specific heat [kJ/ (kgK)]
CFD	Computational Fluid Dynamic
d	Inner diameter of the media pipe
DN	Diameter, Nominal
DH	District Heating
DHW	Domestic Hot Water
FV	Finite Volume
HE	Heat exchanger
i, j, k	Iteration indices
L	Pipe length [m]
m	Number of pipe elements in the r-direction
m_j	Mass of the j-element [kg]
\dot{m}_w	Mass flow rate of the water [kg/s]
n	Number of pipe elements in the z-direction
PB	Polybutylene
PE	Polyethylene
PEX	Cross-linked polyethylene
PN	Pressure, Nominal
PUR	Polyurethane
$Q_{j,j+1}$	Heat flux between elements j and j+1 [W]
r	Radial direction
$R_{j,j+1}$	Linear thermal resistance between elements j and j+1 [(m.K)/W]
$R_{water,pipe}$	Linear thermal resistance between water and pipe wall [(m.K)/W]
RE	Renewable Energy
s	Number of time steps
SH	Space Heating
t	Thickness [mm]
T_{dl}	Dimensionless temperature [°C], defined as $T_{dl} = (T_{outlet} - T_{initial}) / (T_{inlet} - T_{initial})$
T	Temperature [°C]
T_j	Temperature at the j-node [°C]
T_{max}	Maximum allowed water temperature in the pipe [°C] for less than 110 h/year
T_N	Maximum allowed water temperature in the pipe [°C] for continuous operation
$U_{j,j+1}$	Linear heat transfer coefficient between the elements j and j+1 [W/(mK)]
$U_{overall}$	Overall linear heat transfer coefficient [W/(mK)]
U_{w1}	Linear heat transfer coefficient between water and the first PEX wall [W/(mK)]
v	Velocity [m/s]
z	Spatial coordinate along the longitudinal direction

Greek symbols

ΔL	Length of the z-pipe element [m]
$\Delta \tau$	Duration of the time step [s]
λ	Thermal conductivity [W/(mK)]
ρ	Density [kg/m ³]
τ	Time [s]
$\tau_{0,9}$	Time constant of the temperature sensors. It is the response time to reach 90% of the temperature raise in case of a step temperature change[s]

Subscripts

initial	Refers to time = 0 s
inlet	Refers to the coordinate $x = 0$ [m], inlet to the media pipe
outlet	Refers to the coordinate $x = L$ [m], outlet from the media pipe
pipe	Steel or cross-linked polyethylene (PEX) media pipe
target	Refer to the target value of the parameter considered
w	Water

Introduction

The low-energy concept applied to district heating

District heating (DH) accounts for 60% of the heating demand in Denmark and has considerable impact on the rest of the energy system [1, 2]. DH will also play a central role in the future Danish energy system based on renewable energy (RE) [3]. That is why many local authorities have prepared plans for DH to implement the vision of a society that fully relies on RE [4–6]. The potential for satisfying local energy demand with district energy is high, not only in cold climate countries, but also in other countries [7, 8]. Optimization of the energy flows in buildings and related supply structures, such as DH, helps in identifying the potential for increasing efficiency in the utilization [9] and exploitation of RE. The application of the low-energy concept to DH technology aims at three main targets. The first one is to guarantee human thermal comfort with regard to the fulfilment of domestic hot water (DHW) and space heating (SH) requirements by exploiting low-grade energy sources and RE. The second objective is to match the exergy demands of such applications with the exergy available in the supply system by bringing the temperature levels of the supply and the demand closer to each other. Finally, it aims at reducing heat loss in the distribution network to ensure cost-effectiveness. The main design concepts are:

- Small-size media pipes. This is achieved by allowing a high pressure gradient in the branch pipes connected to the unit with instantaneous DHW preparation or by installing units with storage of DH water. In the latter case, a heat exchanger (HE) is coupled to a water storage tank on the primary side, which enables low continuous water flow from the DH network and therefore low-size media pipes in house connections [10].

- Low temperatures: down to 50-55°C in the supply line and 20-25°C in the return line. The technical and economic feasibility of such systems has been demonstrated, both theoretically [11] and in practice [12]. Lowering the supply and return temperatures increases the overall energy efficiency of the heating systems [13] and

decreases their heat losses [14]. Nevertheless, the concept envisages the option of increasing the supply temperature in peak-load periods during the heating season to limit the size of the distribution pipelines.

- Twin plastic pipes are used rather than single steel pipes. This leads both to lower investment costs for the civil works in connection with the laying of the pipelines and to lower heat losses, as further explained in section “district heating pipelines”.

District heating pipes

At the present time, DH distribution and branch lines are based on the single pipe system (where the supply/return water flows in media pipes with their own insulation), on the twin-pipe system (where both pipes are placed in the same insulated casing), or on a mixture of the two. Advanced concepts, such as triple pipes and double pipes with asymmetrical insulation, are not fully commercially available, since they are products still at the experimental stage.

Table 1: Overview of materials, size, temperature and pressure limits of commercial pipes.

Material	Pipe Type	Size (DN)	T _N [°C]	T _{max} [°C]	PN [bar]
Steel	Single	20–1200	140	150	25
	Single	20–600	140	150	25
	Single	20–500	140	150	25
Steel	Twin	20–28	120	120	25
PEX	Single	16–28	85	95	10
	Single	20–110	85	95	6
	Twin	16–50	85	95	6
aluflex*	Single & Twin	16–32	95	105	10
Cu	Single	15–35	120	120	16
	Twin	15–28	120	120	16

* Layers of PEX/Aluminium/PE

Table 1 shows an overview of typical materials, sizes, temperature and pressure limits (nominal pressure, PN) of commercial DH pipes [15]; T_N refers to the temperature for continuous operation, while T_{max} refers to the maximum temperature for operation \leq 110 h/year). The normal design practice considers maximum pressure levels that are generally lower than the nominal values. Nevertheless, networks with higher operational pressure, and hence higher possible pressure loss gradients, lead to decreased media pipe sizes. Such innovative design is effective from the socio-economical point of view, since the advantage of decreased heat losses prevails over the increased pressure losses [16]. This is particularly effective in pipes for house connections, where there is no need for over-dimensioning to allow for future network enlargement. DH pipes made of plastic have become popular in the last twenty years

in all situations where steel pipes can be replaced. Plastic pipe systems are characterized by having the water medium pipe made in cross-linked polyethylene (PEX) or polybutylene (PB). Plastic pipes are covered by insulation, like traditional steel pipes; the insulation is usually made of polyurethane (PUR) foam, but in some cases of PEX foam or mineral wool. The outer cover is formed by a plastic jacket. The durability of plastic pipes is not a real issue because it has been shown that the expected life of PB pipes and PEX pipes is more than 40 years [17]. As a consequence of the even lower average operational temperature in low-temperature DH networks, longer lifetimes can be predicted according to annex A in [18]. Studies have indicated that cross-linked polyethylene (PEX) pipes have a cost advantage over steel pipes for pipe dimensions less than DN60 due to their greater flexibility, since the joints do not require welding [19]. The share of plastic media pipes in the DH market is constantly growing, because they are comparable to steel pipes in thermal performance and expected life time, and they are superior with regard to cost-effectiveness and flexibility of usage. Alternative design concepts can be considered in branch pipes from street lines to consumer substations: a pair of single pipes, twin pipes or triple pipes. Traditionally, most DH branch connections have been built with two single steel pipes: one for supply and one for return. Twin pipes can be made of steel, PEX or copper, with the supply and return pipes in the same casing. Heat losses from twin pipes are lower than from single pipes with the same dimensions and temperatures. Furthermore, commercially available twin pipes, with dimensions up to DN200 for steel media pipe or up to DN50 for PEX media-pipes are usually less expensive to install than single pipes [20]. Twin-pipe technology has been introduced in the Scandinavian countries (first in Sweden and Finland, then in Denmark), and it is used in daily operation in many DH networks. The choice of the house connection type depends mainly on the length of the branch pipe, supply and return temperatures, building heating load, and the type of substation. This last is decisive with regard to energy performance and thermal comfort. Substations are usually of three types, depending on the way they prepare and provide DHW: units with instantaneous preparation of DHW in an HE, units with a DHW storage tank where the tank is in the secondary-loop (DHW side), and consumer units with a DH water tank where the tank is placed in the primary loop (DH side). This paper considers the dynamic behaviour of branch pipe solutions in the case of low-temperature operation for a consumer unit with an HE and no storage tank. This is a simple and cost-effective configuration, which consists of a control system and an HE for instantaneous preparation of DHW, with a second HE for SH purposes only present in the case of indirect connection of SH. The main disadvantage of this type of substation is that only rather short lengths (4-6 m) of DH connection pipe can usually be applied without having to install a bypass circuit between the DH supply pipe and the DH return pipe; otherwise it would not be possible to ensure the required all-year-round DHW temperature at the tapping points in the required time, due to the unsatisfactory transportation time, i.e. the time that the water takes to flow through the entire pipe length. In such a case, a modified unit can be used which is equipped with a booster pump that ensures a quicker response to DHW demand, although a non-perfect cooling of DH water occurs when

the DHW tapping starts. In this case, the control method should give priority to DHW preparation over SH. Moreover, the need for by-pass flow can be minimized, if the SH is required even during the summer – for example to keep a high level of comfort in bathrooms by means of floor heating. As a result, media pipes with inner diameters as small as 10-15 mm (for a typical single family house) can be used in the primary loop, and the cooling of the return water to the design return temperature can be achieved all-year round. Figure 1 shows a unit of this kind, used in a demonstration project in Lystrup, Denmark [12].

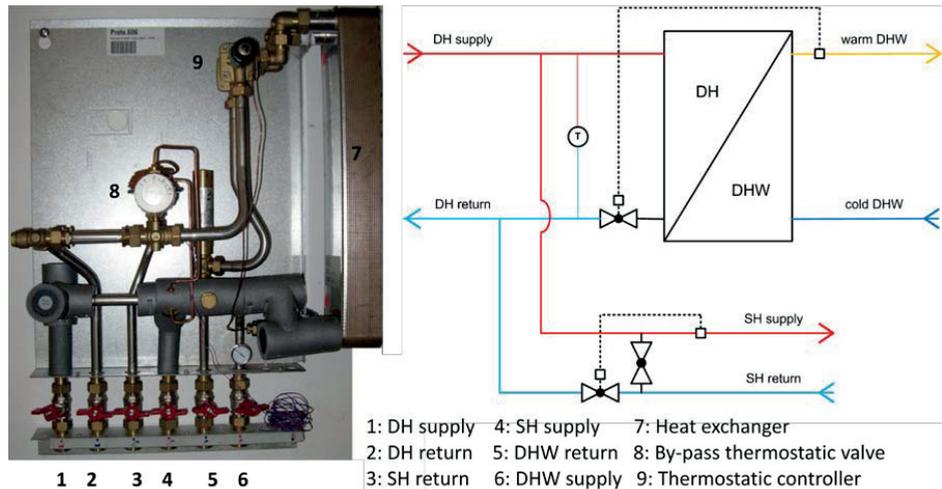


Figure 1: Prototype of a substation with a heat exchanger for domestic hot water preparation (left). Diagram of its functioning (right).

This type of substation uses only one HE between the primary side and the secondary side for instantaneous production of DHW, whilst there is a direct system for SH. The unit is equipped with an external by-pass through which the water flows to keep the temperature level needed for instantaneous preparation of DHW during periods without SH demand. The reference pipe type for the experiments and investigations described in this paper was the aluflex twin pipe 20-20/110, where the outer diameter of supply and return pipes is 20 mm and the outer diameter of the casing is 110 mm (see Table 2). This is an example of a typical pipe that well fulfils the low-energy DH concept with regard to branch connections for single-family houses. We also carried out investigations with the aluflex twin pipe 14-14/110, which is a product not yet commercially available, but which was used for the first time in the demonstration project in Lystrup, Denmark [12], coupled with a DH storage unit.

Table 2: Geometry of the aluflex twin pipe 14-14/110 and of the aluflex twin pipe 20-20/110.

Twin pipe	Media pipe inner diameter [mm]	Media pipe wall thickness (PEx) [mm]	Distance btw. media pipes centres [mm]	Casing pipe outer diameter [mm]	Casing pipe wall thickness (low-density PE) [mm]
Alx 14-14/110	10	2.0	26	110	2.5
Alx 20-20/110	15	2.5	32	110	2.5

Methods

In the following sections we present the methodologies applied in the investigation, namely existing modelling and calculation methods for the transient regime in DH pipes, experimental measurements, FV simulations, and calculations with the code we developed.

Existing methods for modelling dynamic fluid-thermal phenomena in district heating pipes

The transient heat transfer in DH pipelines depends primarily on the fluid flow regime, the geometry of the pipe, and the physical characteristics of the materials. The prediction of the phenomenon helps to select appropriate operational parameters for DH systems, which in turn optimizes system performance. Historically, the models can be divided into fully dynamic models and pseudo-dynamic models. In the first type, the energy and momentum equations are solved simultaneously, thus calculating the dynamic changes in both temperature and pressure. In the latter models, only the temperature is calculated dynamically, whilst the flows and pressure are calculated on the basis of a static flow model. The use of pseudo-dynamic models is recommended for DH networks, the main reason being that the dynamics of flow changes are about three orders of magnitude faster than the dynamics of temperature changes. In this paper, we consider only pseudo-dynamic methods. The following assumptions were made when implementing the pseudo-dynamic methods: a slug flow was assumed, which implies a uniform velocity in the radial direction; when defining the material properties of the water, constant values were prescribed that corresponded to the average water temperature; the heat transfer coefficient of the fluid flow was based on standard empirical correlations developed for steady-state conditions; hydraulic dispersion was disregarded; axial heat conduction, in both the fluid and the pipe wall, was held to be negligible; dissipation phenomena were disregarded.

The two approaches we used are described (and their limitations discussed) in [21], namely a pseudo-transient method implemented in a finite element method code, and the so-called “node method” [22]. In the pseudo-transient method, the pipe is covered with an insulation layer and casing, and placed underground to simulate real

conditions. The convective heat transfer and mass transport in the fluid are described by a fluid finite element which has four nodes: two to represent the fluid at the inlet/outlet and the other two to represent the pipe wall conditions at the inlet/outlet. Next, the heat transfer through the pipe wall is expressed by two conduction finite elements, one for the inlet and one for the outlet; each conduction element has two nodes, one on the internal surface and the other on the external surface of the pipe wall. The conductive heat transfer through the insulation, casing, and soil is similarly modelled. The temperature of the surrounding ground is the boundary condition.

The node method considers the pipe flow as consisting of two nodes, inlet and outlet, for which the values of mass flow rate and temperature are assigned. The outlet temperature is estimated from the temperature at the inlet node by taking into account the flow transportation time from one node to the other as well as changes in flow velocity. The temperature obtained is then corrected first to account for the effects of the pipe wall heat capacity and then for the heat losses. The node method ignores the heat capacity of the insulation, the casing and the surrounding ground.

In [21], it was found that both approaches have limitations in predicting peak temperature values and time moments for the temperature changes. The accuracy of the predictions is affected by both the flow velocity and the rate of changes in inlet temperature. Moreover, the effects of turbulence and viscosity in the water flow must be taken into consideration in order to predict temperature dynamics.

The numerical model proposed in section “development of the in-house code” is similar to the pseudo-transient method, both with regard to the hypothesis the model is based on and its methodology. Nevertheless, both the mesh geometry and the calculation method are different. The method is consistent with experimental results in low-size plastic media pipes, the products the model was developed for.

Experimental measurements

A hydraulic circuit was designed and constructed to validate the numerical simulations; this is diagrammatically shown in Figure 2. The set-up consisted of a 15-meter long aluflex twin-pipe coil, two fast-response temperature sensors, a digital scale for mass measurement, the data acquisition unit, and two hydraulic sub-circuits. The first hydraulic sub-circuit connected the hot water supply to the supply media pipe of the DH twin-pipe coil. It was equipped with a manually adjustable by-pass circuit to ensure that steady-state temperature and water flow conditions were reached at the inlet of the media pipe before starting a measurement cycle. We inserted a temperature sensor in the pipe which supplied hot water to the DH pipe to measure the supply water temperature at the pipe inlet. The return DH media pipe was empty and kept in ambient air. The second hydraulic sub-circuit connected the outlet from the DH supply media pipe to the mass scale and comprised the second temperature sensor, which measured the outlet water temperature over time. The temperature sensors were thermocouples type T, tolerance class 2, with a sheath diameter of 1.5 mm and with the hot junction insulated from the outer sheath. The time constant, $\tau_{0.9}$, given by the manufacturer was 0.6 s for a water velocity of 0.2 m/s.

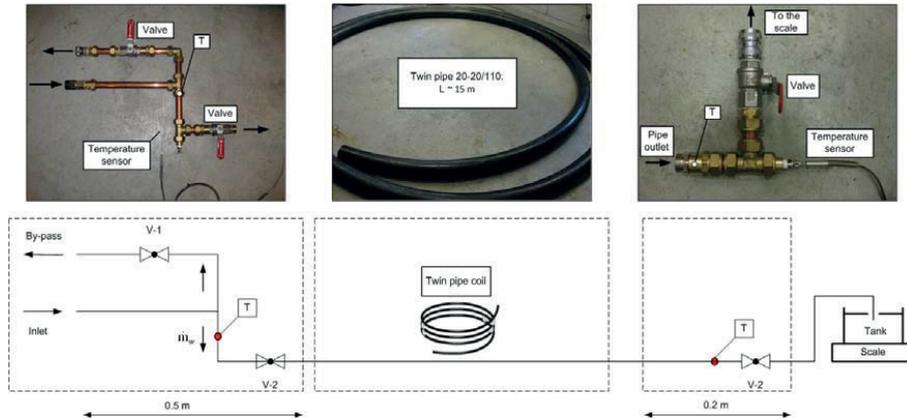


Figure 2: Diagram of the hydraulic circuit for the experiments. Hydraulic sub-circuit at the inlet (left), DH twin pipe (middle), hydraulic sub-circuit at the outlet (right).

The whole set-up was placed in ambient air. The measurement cycle consisted of three steps. First, the media pipe was filled with water at the specific temperature that fulfilled the desired initial value. Next, hot water was circulated at the set supply temperature and mass flow rate through the by-pass in the inlet hydraulic sub-circuit, so as to maintain the design conditions at the inlet of the DH supply media pipe. When steady-state conditions were reached, the valve V-1 was closed and then the valves V-2 were simultaneously opened, allowing the water to flow through the DH supply media pipe. The purpose of the hydraulic sub-circuit at the outlet was to measure the outlet water temperature continuously and to transport the flowing water to the tank, where the water mass was measured. We gathered data every 0.3 s, for a period of time between 60 s and 150 s, depending on the water mass flow rate. The ratio between the total water mass and the time gave the average water mass flow rate. Measurements of mass flow rates at specific intervals of time demonstrated that actual values could vary by up to 10% of the average value due to inertia phenomena, particularly during the first 5-10 s after the water started to flow. This affected the transportation time, since the actual water velocity was not constant during the start-up of the measurement, as assumed in the software-based calculation. Nevertheless, this effect was of minor magnitude and the computational models were still capable of accurately predicting the fluid-thermal phenomena and the measured transient propagation of the temperature wave, as shown in the results section. We performed 6 experiments for each type of pipe, making a total of 12 experiments. The inlet water temperature was maintained at around 50°C, which is a typical target value for the low-energy DH concept. This value was kept steady during the measurements, with maximum oscillations of less than 0.5°C. We chose two temperature levels as initial water conditions inside the media pipes, respectively 15°C and 30°C. The ambient temperature did not vary more than 1°C from the design values, and the effect of this variation on the dynamic phenomenon studied was negligible in the cases considered.. The section “comparison between the experimental data, detailed FV simulations and

the code we developed” presents the comparison between the outlet water temperature profile during the experiments and the calculated values from the code we developed, for two sizes of twin pipes: aluflex 14-14/110 and aluflex 20-20/110.

Detailed FV analysis

Computational fluid dynamics solves the fundamental flow governing equations which give detailed information about fluid flow, energy diffusion and dissipation. The commercial CFD software Fluent [23] was used to study the pre-insulated twin DH branch pipe in order to disclose detailed flow and temperature wave propagation, to compare the outcome with the experimental results, and to perform various inlet thermal boundary conditions which are difficult to realize through experiments. The 3-D computational domain was meshed with GAMBIT. Because the interest of this study was the transient temperature wave propagation, finer mesh was applied to the flow domain and the region close to the inner pipe, while coarser mesh was applied for the PUR insulation and the outer tube. FLUENT applies the FV numerical discretization approach to solve the unsteady Reynolds averaged Navier-Stokes equations and energy equations to include the heat transfer within the fluid and the interaction with the solid region. The SIMPLE algorithm was used for pressure-velocity coupling. The second order upwind scheme was applied for momentum, turbulence and energy equation discretization. Two turbulence modelling approaches were tested, both standard and RNG k-epsilon models, and no noticeable difference was observed based on these two methods. The pipe inlet turbulence level was specified with turbulence intensity and hydraulic dynamic by specifying pipe hydraulic diameter and flow Reynolds number. Enhanced wall treatment was applied for the near wall modelling. To achieve accurate results, various time steps were tested and 0.001 s was set for the final transient simulation. We investigated the temperature wave propagation both for step changes in the inlet temperature and for sinusoidal inlet temperature profiles.

Development of the in-house code

We developed a code in the commercial software MATLAB [24] with the aim of obtaining a model capable of predicting the temperature at the outlet of a house connection pipe (inlet to the substation) over time. The model was based on the hypothesis that the transient fluid-thermal field in one of the two media pipes in a DH twin pipe is independent of the condition in the other media pipe, because the transient period (maximum 2-3 minutes) is much shorter than the time required by the temperature field in one of the media pipes to affect the temperature distribution in the other media pipe (at least 1 hour). The model needs a number of input parameters. These refer first to the geometry of the pipe, i.e. length, L , the inner diameter of the media pipe, d , the thickness of the PEX or steel pipe, t_{pipe} , and the thickness of the PUR pipe, t_{PUR} . Secondly, the model needs the thermal properties of the materials

(water, PEx or steel and PUR): density, ρ , thermal conductivity, λ , and specific heat, c . Next, we chose the parameters that define the geometric mesh and the time step, i.e. the number of elements in the z-direction, n , the number of elements in the r-direction, m , and the number of time steps, s . Finally, the input parameters include the mass flow rate, \dot{m}_w , the supply water temperature, T_{inlet} , and the initial temperatures in all the nodes, $T_{j,i}$ ($\tau=0$). We defined three indices. The first two (i,j) lead the iteration loops with regard to the geometry, while the third one (k) leads the iteration over time:

$$i = 1 \dots n; j = 1 \dots m; k = 0 \dots s \quad (1)$$

Figure 3 shows a sketch of the model. The time step, $\Delta\tau$, is calculated so that it corresponds to the time that the water takes to pass through a z-element, with the hypothesis of slug flow, which implies a uniform water velocity, v .

$$\Delta\tau = \Delta L/v = (L/n)/v \quad (2)$$

First, we consider a generic time step $\tau_k = k\Delta\tau$ and the first z-element ($i=1$). We calculate the radial heat transfer between the node that represents the temperature of the water and the node that represents the temperature of the first pipe wall element in the r-direction ($j=1$).

$$U_{w1} = 1/(R_{water,pipe} + R_1) \quad (3)$$

$$Q_{w1,i}(\tau_k) = U_{w1} \cdot \Delta L \cdot [T_{w,i}(\tau_k) - T_{1,i}(\tau_k)] \quad (4)$$

This means we can calculate the water temperature at the outlet of the element i . This is used as the water temperature in the pipe element $i+1$ in the next time step, τ_{k+1} .

$$T_{w,i+1}(\tau_k) = T_{w,i}(\tau_k) - Q_{i,w1}(\tau_k)/(\dot{m}_w \cdot c_w) \quad (5)$$

At the same time, we can calculate the new node temperature in the first PEx-pipe element in the r-direction as:

$$T_{1,i}(\tau_{k+1}) = T_{1,i}(\tau) + (Q_{i,w1}(\tau) \cdot \Delta\tau)/(m_1 \cdot c_1) \quad (6)$$

Next, we can similarly calculate the temperature distribution in all the nodes j , for the element i . Such temperatures are used as input data for the calculation of the heat transfer during next time step, τ_{k+1} .

$$U_{j,j+1} = 1/(R_{j,j+1}) \quad (7)$$

$$Q_{j,j+1}(\tau_k) = U_{j,j+1} \cdot \Delta L \cdot [T_{j,i}(\tau_k) - T_{j+1,i}(\tau_k)] \quad (8)$$

$$T_{j,i}(\tau_{k+1}) = T_{j,i}(\tau_k) - (Q_{j,j+1}(\tau_k) \cdot \Delta\tau)/(m_j \cdot c_j) \quad (9)$$

$$T_{j+1,i}(\tau_{k+1}) = T_{j+1,i}(\tau_k) + (Q_{j+1,j+1}(\tau_k) \cdot \Delta\tau)/(m_{j+1} \cdot c_{j+1}) \quad (10)$$

This procedure is repeated for all the n z-elements. So, for the generic time step τ_k :

$$T_{\text{outlet}}(\tau_k) = T_{w,n}(\tau_k) \quad (11)$$

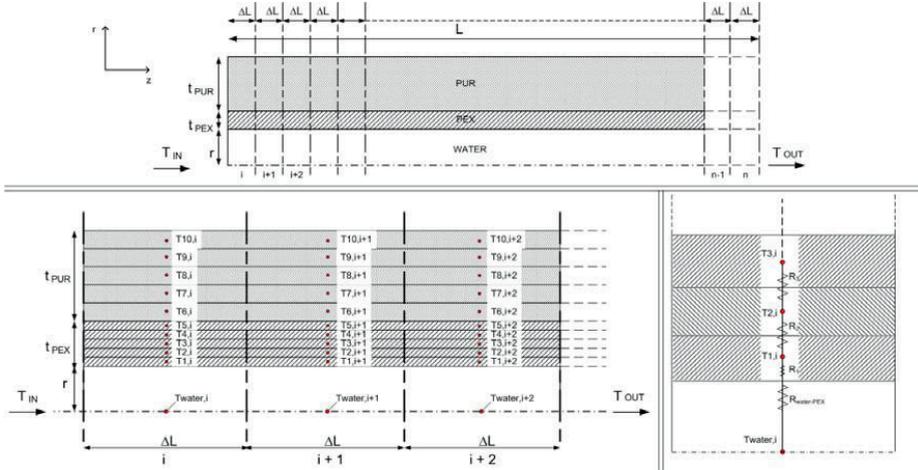


Figure 3: Sketch of the division of the pipe into computational elements. Overview (top); nodes in three adjacent elements (down-left); heat transfer scheme in three PEX layers (down-right).

After that, we repeat the whole procedure, time step after time step, so that we finally obtain the water temperature profile at the pipe outlet as a function of the time. Investigations of the effect of successive mesh refinements on the model accuracy suggest that very accurate results are obtained when $m > 4$, i.e. with at least three radial media pipe elements and a radial insulation element, and when $n > 500$. All the results reported in the results section were obtained with the following set of mesh parameters: $n = 1000$, $m = 10$ (5 radial media pipe elements and 5 radial insulation elements).

Results and discussion

First, we performed an FV analysis of the temperature wave propagation when there was a step change in the inlet temperature. This simulated the conditions that often happen outside the SH season in a DH pipe that connects a street distribution line to the end user's DHW installation (consisting of a HE): for a certain period there is no flow in the media pipe, when at a certain time the demand for hot tap water causes a sudden flow from the street distribution line to the branch pipe.

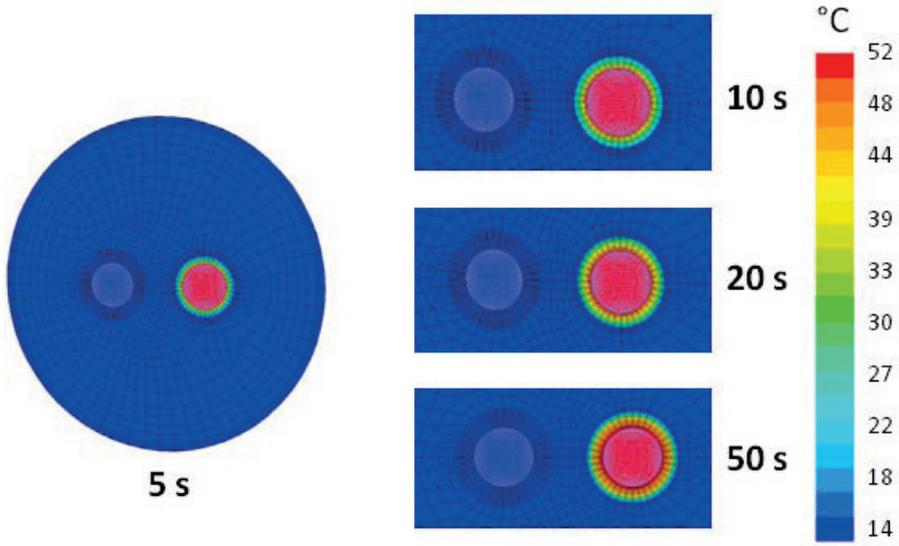


Figure 4: Temperature contour [°C] at the inlet cross section of the media pipe at different transition times. Aluflex 20-20/110, $T_{\text{supply}} = 51.5^{\circ}\text{C}$, $T_{\text{initial}} = 14.4^{\circ}\text{C}$, $v = 2.36 \text{ m/s}$.

In the example, the initial temperature of the twin pipe was set to 14.4°C . At time $\tau = 0 \text{ s}$, the inlet temperature of the supply pipe (right media pipe in the images in Figure 4) changed to 51.5°C , while the return pipe (left pipe) remained at the initial temperature. Figure 4 shows the temperature variation in time at the inlet cross section. Four temperature contours were plotted at time $t=5 \text{ s}$, 10 s , 20 s , and 50 s . The temperature contour variations showed that the temperature field interaction between the supply and return pipe, which is important in the steady state simulation [14], could reasonably be neglected in the transient temperature wave propagation simulation for the branch pipe studied. This allowed us to study the thermal dynamics in the supply media pipe as a single pre-insulated pipe and confirmed the hypothesis on which the method we developed is based. The water temperature profile results at the pipe outlet are expressed in the form of the dimensionless profile T_{d1} [21], if not otherwise stated. This is defined by:

$$T_{d1, \text{outlet}}(\tau) = (T_{\text{outlet}}(\tau) - T_{\text{water, initial}}) / (T_{\text{inlet, max}} - T_{\text{water, initial}}) \quad (12)$$

where $T_{\text{water, initial}}$ is the fluid initial temperature inside the media pipe, $T_{\text{outlet}}(\tau)$ is the transient fluid temperature at the outlet, and $T_{\text{inlet, max}}$ is the maximum supply temperature at the inlet, which corresponds to the target temperature in the case of a step change of the supply temperature or to the peak supply temperature when the supply temperature follows a sinusoidal pattern.

The dimensionless inlet temperature is defined as follows, when considering the response to a sinusoidal supply temperature:

$$T_{d1, \text{inlet}}(\tau) = (T_{\text{inlet}}(\tau) - T_{\text{water, initial}})/(T_{\text{inlet, max}} - T_{\text{water, initial}}) \quad (13)$$

where $T_{\text{inlet}}(\tau)$ is the transient fluid temperature at the inlet.

Step function response: comparison between an analytical formula, the node method, and the code we developed

In this section, we compare the dimensionless temperature profiles obtained with the analytical solution of the step function response proposed in [25], the node method, and the pseudo-transient method we developed. The node method and the numerical solution of the analytical formula were both implemented in a MATLAB code, as formulated by their authors in [22] and in [25], respectively. Figure 5 shows two examples. The first case considers a 10-metre long steel pipe DN300 and the water flow velocity of 2.71 m/s; the second case shows the results for a small-size, aluflex twin pipe and a water velocity of 1.00 m/s. The results show that there is good agreement between the dimensionless profiles predicted by the code we developed and the analytical solution. It should be emphasized that the analytical solution can be correctly calculated numerically only for relatively “small” values of the argument $(\tau - z/v)$. This is why the analytical solution is shown only in the first part of the curves of Figure 5. Moreover, the exact solution assumes adiabatic conditions at the external surface of the media pipe. This means it is not applicable from a practical point of view. In reference to the implementation of the node method, a time step of 0.10 s was chosen; the deviation of the results by the use of smaller time steps (such as 0.05 s or 0.02 s) was negligible in the cases considered. The node method, although useful when considering transient temperature propagation at network level, has limitations with regard to the detailed prediction of both temperature response time and the effect of the thermal capacity on the dynamics, particularly where there are sudden temperature changes. This is evident above all in the case of small-size plastic media pipes (see the graph on the right in Figure 5), which are critical for the development of optimal solutions for low-energy DH networks. The validation of the code we developed is therefore particularly important and it is reported below. First, we compared the results of our code with detailed 3-D FV simulation of sinusoidal inlet temperature profiles. Next, we carried out validation against the experimental measurements.

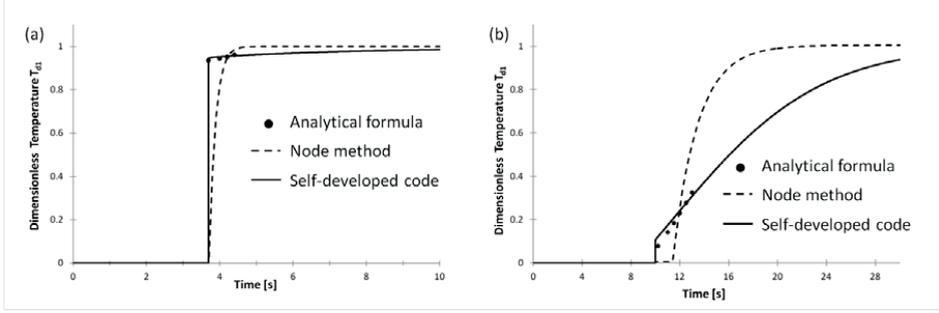


Figure 5: Dimensionless temperature profiles. Step function response. (a): single pipe, steel, DN300; characteristics: $L = 10\text{m}$, $d = 263\text{ mm}$, $t_{\text{pipe}} = 5\text{ mm}$, $v = 2.71\text{ m/s}$. (b): twin pipe, aluflex 20-20/110; characteristics: $L = 10\text{m}$, $d = 15\text{ mm}$, $t_{\text{pipe}} = 2.5\text{ mm}$, $v = 1.00\text{ m/s}$.

Sinusoidal function response

We now consider a sinusoidal inlet temperature profile that can be expressed in the form of:

$$A \cdot \sin[B \cdot (\tau - \tau_{\text{delay}})] + T_{\text{inlet,initial}} \quad (14)$$

where A is the amplitude of the sinusoidal function, B is the angular frequency, τ_{delay} is the time when an increase in the inlet temperature is first introduced, and $T_{\text{inlet, initial}}$ is the inlet water temperature at $\tau = 0$. Figure 6 shows to the temperature wave propagation in the reference pipe, aluflex 20-20/110, in terms of dimensionless parameters; it refers to the comparison between the outcome of FV simulations and of the self-developed code. The graph on the left shows the case in which the initial water temperature in the media pipe is equal to the initial temperature of the supply water, while the graph on the right shows an example with non-isothermal conditions. The results from our code and from the FV simulations are comparable, giving values for the temperature response time and for the peak values of the temperature wave that differ less than 0.2%. The predicted curves of the dimensionless profile of the outlet temperature are almost identical, during both the heating and the cooling periods. Our code predicts the temperature wave propagation with the same accuracy as in detailed 3-D FV simulation, but with much shorter computational time. The computational time is reduced from several hours to less than 60 s.

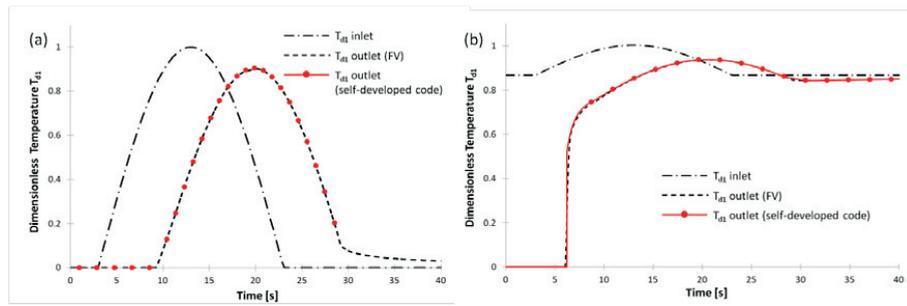


Figure 6: Dimensionless temperature profiles. Sinusoidal function response. $A = 5^{\circ}\text{C}$, $B = 0.157 \text{ s}^{-1}$, $\tau_{\text{delay}} = 3 \text{ s}$, $T_{\text{water, initial}} = 46.35^{\circ}\text{C}$. (a): $T_{\text{inlet, initial}} = 46.35^{\circ}\text{C}$ and (b): $T_{\text{inlet, initial}} = 14.25^{\circ}\text{C}$.

Comparison between the experimental data, detailed FV simulations and the code we developed

The outcome of the measurements is shown in Table 3 and in Figure 7, together with the results of the simulations using our code.

Table 3 : Main data describing the measures during the experiments.

Experiment no.	Twin pipe type	Temperature [$^{\circ}\text{C}$]			Mass flow [kg/min]	Velocity [m/s]	Transportation time [s]	
		Water Initial	Inlet Average	Air average			Measured	Calculated
1	Alx	12.9	52.2	21.1	16.42	3.48	4.5	3.6
2	14-	13.5	52	20.8	9.10	1.93	8.1	8.3
3	14/110	13.9	48.3	20.8	3.04	0.65	23.7	23.7
4	Alx	28.9	50.6	20.5	15.90	3.37	4.8	4.8
5	14-	30.5	52.7	20.8	9.34	1.98	8.1	8.1
6	14/110	30.1	51.3	20.7	2.88	0.61	25.8	26.4
7	Alx	14.3	51.5	22	25.00	2.36	5.7	6.3
8	20-	14.9	49.6	22	10.00	0.94	15	15.7
9	20/110	14.6	51.9	22.1	8.00	0.75	17.7	19.7
10	Alx	30.9	51.7	21.6	24.91	2.35	5.7	6.3
11	20-	31.2	49	21.1	8.91	0.84	17.6	17.1
12	20/110	30.9	48.4	21	5.29	0.50	28.2	29.7

The inlet and outlet temperature profiles are drawn in the SI unit system, so that it is possible to understand the actual transient behaviour of the pipes considered, when used in real low-temperature applications. The measured and calculated outlet temperature profiles differ in the period of time that immediately follows the transportation time, partially because the calculation assumes that the axial conductive

heat transfer is negligible. This is more evident for low water velocities, when the conductive axial heat transfer in the water and in the media pipe wall has more time to propagate. In addition to that, inertia phenomena affected the flow during the first phases of the measurements, so that the water flow rate was not perfectly constant, as supposed in the simulations. Nevertheless, the deviation is not of any practical relevance. Outside that period of time, the maximum deviation between the measured and the calculated outlet temperatures is below 0.5°C .

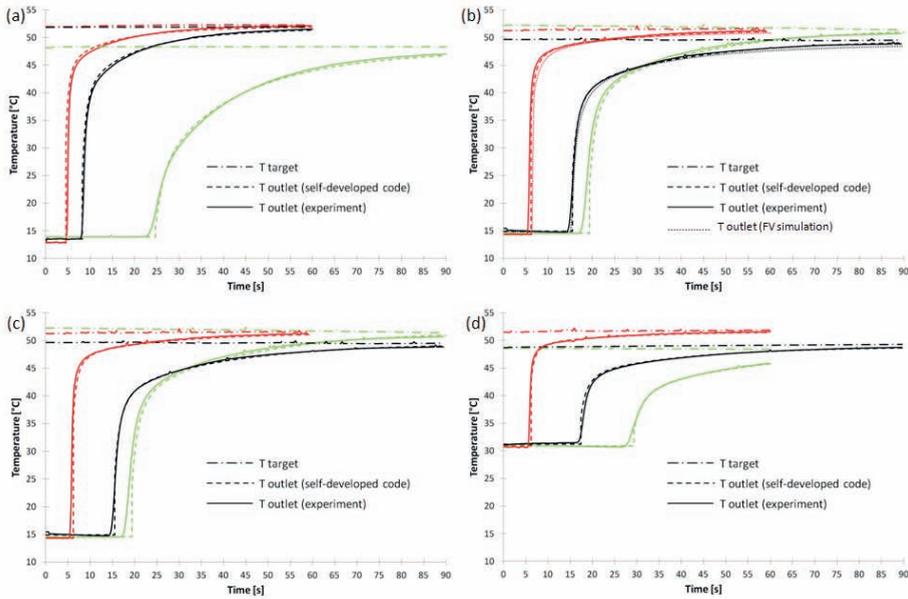


Figure 7: Comparison between the experimental data and the results from simulations with the in-house code. (a): Experiments I-III; (b): experiments IV-VI; (c): experiments VII-IX; and (d): experiments X-XII.

The code we developed is capable of predicting the temperature wave propagation with satisfactory results. The fine mesh the model is built on and the inclusion of the thermal capacity of the active part of the insulation both enhance the accuracy of the results. FV simulations have been carried out for the cases 7 and 8 (see Fig. 7b): the results demonstrated that the difference between the temperature output from the self-developed code and the detailed FV simulation is negligible.

Example: the effects of pipe size and water flow rate on temperature wave propagation

The simplest concept of DHW preparation consists of a substation with an HE and a branch pipe that connects the unit to the distribution network. This makes the in-house unit as cheap as possible, although the potential of energy storage, with all its

advantages at network level, is not exploited. An important issue for energy conservation and energy efficiency is operation over periods of time with by-pass water recirculation, which is used during periods of low heat demand to ensure a sufficiently fast response when DHW tapping occurs. An alternative to the by-pass is to increase the primary flow and the available pressure in the branch pipe when there is DHW demand, by introducing a local booster pump that can be integrated in the end-user unit.

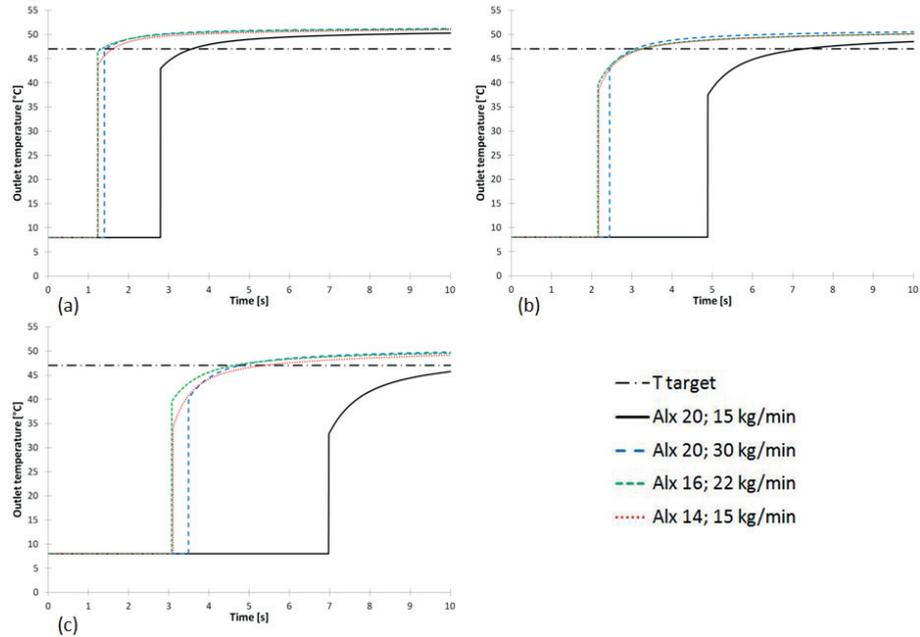


Figure 8: Effects of the media pipe diameter, pipe length and flow rate on the water delivery time and temperature. (a): $L = 4$ m; (b): $L = 7$ m; (c): $L = 10$ m;

In the following example, we took as reference the DH network located in Lystrup, Denmark. This was the first demonstration project in which low-energy DH principles were applied [26]. The single-family houses are equipped with a prototype substation for low-temperature operation, i.e. with supply temperature 50°C , return temperature 20°C , nominal power 32 kW, and nominal flow in the primary side 15 kg/min [27]. A by-pass strategy was implemented to satisfy the guideline included in [28] that envisages a maximum waiting time for DHW of 10 s for a reference DHW flow of 12 kg/min. The branch pipe is aluflex 20-20/110. When there is no water recirculation through the by-pass, the objective is to guarantee that the inlet water to the primary side of the HE is at least 47°C within 5 s of the tap being opened. The hypothesis is that the additional available 5 s are sufficient to prepare DHW in a properly designed HE and to transport it to the tap point. Figure 8 shows the transient temperature profile for 3 branch pipe lengths, respectively 4 m, 7 m and 10 m. It is assumed that the water in the branch pipe has initially cooled down to the annual average ground temperature of 8°C , due to an idle period of several hours. The results demonstrate

that the target time can be reached with the design conditions of 15 kg/min and aluflex 20-20/110, only with rather short lengths (< 4 m), whereas the by-pass is necessary for longer branch pipes. In the latter cases, the target time can be reached either by doubling the flow rate (aluflex 20-20/110, 30 kg/min), by keeping the same flow rate but using a lower media pipe diameter (aluflex 14-14/110, 15 kg/min), or by a combination of the two (aluflex 16-16/110, 22 kg/min). In all three cases, the installation of a booster pump is needed to overcome pressure loss that would otherwise be unacceptable, as can be seen in Table 4.

Table 4: Thermal and hydraulic characteristics of the branch pipe solutions considered in the example.

Branch pipe type	d [mm]	U_{overall}^* [W/(m ² K)]	Heat loss ^{**} [W/m]	Roughness [mm]	Mass flow [kg/min]	Velocity [m/s]	Pressure loss gradient ^{***} [Pa/m]
Reference: Alx. 20-20	15.0	0.130	3.77	0.020	15.0	1.43	1850
Alternative 1: Alx. 20-20	15.0	0.130	3.77	0.020	30.0	2.86	6922
Alternative 2: Alx. 16-16	12.0	0.101	3.20	0.020	22.0	3.27	11072
Alternative 3: Alx. 14-14	10.0	0.110	2.94	0.020	15.0	3.22	13463

*calculated according to [29] **considering 52/22/8°C as supply/return/ground temperatures ***calculated according to [30]

Furthermore, the design of the HE unit must be re-adjusted in the cases where the design primary flow rate changes from the original one of 15 kg/min. The development of improved substation concepts and enhanced control strategies can benefit from the detailed understanding of the temperature dynamics at the inlet to the HE that the model offers. A 10-metre long aluflex 20-20/110 branch pipe, with the hypothesis of a design by-pass temperature of 40°C in operation for 4000 h/year, has an annual heat loss of ~166 kWh. We now consider the application of alternative 3 in Table 4 to a reference house, whose gross area is 150 m². The Danish Building Regulations assign an equivalent DHW usage of 250 L/(m²year) at T = 55°C and the manipulation of the DHW design profile in [28] suggests the use of an average DHW flow rate of 5.76 L/min. So, the total duration of the DHW tapping in the reference house is ~30 min/day on average. We then select a booster pump suitable for the case [31], with the following characteristics: nominal flow rate 1.0 m³/h, nominal head 24 m_{H2O}, overall efficiency 0.17. The average electricity consumption for pumping is 320 W and that means that the DHW comfort requirements can be achieved without needing by-pass recirculation with an electricity consumption of ~58 kWh_{el}/year. In addition to the avoidance of the by-pass function, there are further heat loss savings outside the by-pass period of approximately 40 kWh/year due to the smaller media

pipe size. This means that the proposed solution is reasonable from an energy point of view because it gives a reduction in primary energy use of ~12% (the primary energy factor is 0.8 for DH and 2.5 for electricity). Even better results could be achieved if improved pumping solutions can be designed, since the overall efficiency of the pumps currently available on the market and suitable for this application is low. Any assessment of economic feasibility also needs to take into account the consequences of the lower return temperature in the network due to the avoidance of the by-pass, such as the improvement of energy efficiency in cogeneration plants and energy savings in the distribution network; hence, it has to be assessed with reference to the actual DH network layout and heat production systems.

Conclusions

This paper investigates temperature wave propagation in DH branch pipes, with the focus on low-temperature applications, i.e. when the supply temperature is generally below 55°C and the return temperature does not exceed 25°C. We focused on state-of-the-art DH branch pipes, suitable for the connection of a typical Danish low-energy single-family house to a substation equipped with an HE for DHW preparation. Experimental measurements of the temperature profiles at the outlet of the pipe, i.e. at the inlet to the substation, were compared with detailed 3-D FV simulations. We derived a computational code with the software MATLAB, based on a pseudo-transient method. The code was validated against experimental measurements and compared with data from an analytical exact formula and the FV simulations. The model is accurate, since it gives results that well represent the outlet temperature profile measured in the experiments, with deviations of less than 0.5°C. Moreover, it is in good accordance with the FV simulations, both when there is a step change in the inlet temperature and when there is a sinusoidal inlet temperature profile, without any significant temperature deviation. In the case of sinusoidal inlet temperature profiles, the temperature response time, the peak value of the temperature wave and the time they occurred differ less than 0.2% from the results of the FV simulations. We applied the program we developed to a case, where starting from an already innovative low-energy DH application, we proposed an integrated solution that consists of a branch pipe, an HE unit with a booster pump for DHW preparation, and the in-house service pipelines. The system satisfies the requirement for supply of DHW within 10 seconds and achieves heat savings greater than 200 kWh/year per installation with an additional electricity consumption of ~58 kWh. Altogether, the model is useful for the choice of optimal building connections and end-user substations, and particularly for the design of HEs and the development of improved control strategies of DH units. The model can be applied to a wide range of media pipe sizes and various media pipe materials, e.g. steel, copper and plastic, so that it can also be used for in-house DHW service pipelines. Understanding the dynamic thermal behaviour of the pipes is

important when attempting to design technical solutions that aim at avoiding the installation of the by-pass function and the DHW recirculation, without undermining the comfort requirements for DHW. These concepts are key to achieving the full potential of energy savings and increased energy efficiencies that low-energy DH offers.

References

- [1] Möller, B., Lund, H., Conversion of Individual Natural Gas to District Heating: Geographical Studies of Supply Costs and Consequences for the Danish Energy System, *Applied Energy*, vol. 87, no. 6, pp. 1846-1857, 2010.
- [2] Østergaard, P. A., Heat Savings in Energy Systems with Substantial Distributed Generation, *International Journal of Sustainable Energy*, vol. 23, no. 4, pp. 169-176, 2003.
- [3] Lund, H., Mathiesen, B. V., Energy System Analysis of 100% Renewable Energy Systems – The case of Denmark in years 2030 and 2050, *Energy*, vol. 34, no. 5, pp. 524–531, 2009.
- [4] Østergaard, P.A., Lund, H., A Renewable Energy System in Frederikshavn Using Low-Temperature Geothermal Energy for District Heating, *Applied Energy*, vol.88, pp. 479–487, 2011.
- [5] Wejs, A., Embedding Climate Planning and Planning Experiences from Danish Municipalities [Forankring af Klimaplanlægning e Planlægningserfaringer fra Danske Kommuner], 2009.
- [6] Østergaard, P. A., Mathiesen, B.V., Möller, B., Lund, H., A Renewable Energy Scenario for Aalborg Municipality Based on Low-Temperature Geothermal Heat, Wind Power and Biomass, *Energy*, vol. 35, no. 12, pp. 4892-4901, 2010.
- [7] Lund, H., Renewable Energy Strategies for Sustainable Development, *Energy*, vol. 32, no. 6, pp. 922-919, 2017.
- [8] Lund, H., Möller, B., Mathiesen, B.V., Dyrelund, A., The Role of District Heating in Future Renewable Energy Systems, *Energy*, vol. 35, pp. 1381-1390, 2010.
- [9] Schmidt, D., Low Exergy Systems for High-Performance Buildings and Communities, *Energy and Buildings*, vol. 41, pp. 331–336, 2009.
- [10] Paulsen, O., Fan, J., Furbo S., Thorsen, J.E., Consumer Unit for Low-Energy District Heating Net. *Proc. 11th International Symposium on District Heating and Cooling*, Reykjavik, Iceland, 2008.
- [11] Olsen, P. K., Lambertsen, H., Hummelshøj, R., Böhm, B., Christiansen, C.H., Svendsen, S., Larsen, C.T., Worm, J., A New Low-temperature District Heating System for Low-Energy Buildings, *Proc. 11th International Symposium on District Heating and Cooling*, Reykjavik, Iceland, 2008.
- [12] Brand, M., Dalla Rosa, A., Svendsen, S., Performance of Low-Temperature District Heating Systems for Low-Energy Houses. *Proc. The Future for Sustainable Built Environments with High-Performance Energy Systems Conference*, Munich, Germany, pp. 174-183, 2010.
- [13] Torio, H., Schmidt, D., Development of System Concepts for Improving the Performance of a Waste Heat District Heating Network with Exergy Analysis, *Energy and Buildings*, vol. 42, pp. 1601–1609, 2010.
- [14] Dalla Rosa ,A., Li H, Svendsen S., Method for Optimal Design of Pipes for Low-Energy District Heating, with Focus on Heat Loss, *Energy*, vol. 36, no. 6, pp. 2407-2418, 2011.
- [15] www.logstor.com. Accessed on February 8, 2012.
- [16] Development and Demonstration of Low-Energy District Heating for Low-Energy Buildings (EFP 2007: Udvikling og Demonstration af Lavenergifjernvarme til Lavenergibyggeri), 2007.
- [17] Klöpsch, M., Zinko, H., Plastic Pipe Systems for District Heating. Handbook for Safe and Economic application, IEA-DHC ANNEX V, 1999.

- [18] DSF/EN 253:2009/prA1. District heating pipes - Preinsulated bonded pipe systems for directly buried hot water networks - Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene.
- [19] Zinko, H., *The GRUDIS Technology for Low Heat Density District Heating (GRUDIS-Tekniken För Värmegles Fjärrvärme)*, 2004.
- [20] Lund, H.T., *Methods for Operational Optimization of District Heating Systems. (In Danish: Metoder til Optimering af Fjernvarmesystemers Drift)*, 1989.
- [21] Gabrieliutiene, I., Böhm, B., Sunden, B., Evaluation of Approaches for Modeling Temperature Wave Propagation in District Heating Pipelines. *Heat transfer engineering*, vol. 29, no. 1, pp. 45-56, 2008.
- [22] Pålsson, H., *Methods for Planning and Operating Decentralized Combined Heat and Power Plants*, Rept. Riso-R-1185(EN), 2000.
- [23] FLUENT[®], version 6.2.1.
- [24] MATLAB[®], version R2010b.
- [25] Arpaci, V. S., *Conduction Heat Transfer*, pp. 353-360, Addison-Wesley, New York, 1966.
- [26] CO₂-Reductions in Low-Energy Buildings and Communities by Implementing Low-Temperature District Heating Systems - Demonstration Cases in EnergyFlexHouse and Boligforeningen Ringgården, Danish Energy Agency, 2011.
- [27] Brand, M., Thorsen, J.E., Christensen, C.H., Svendsen, S., A Direct Heat Exchanger Unit Used for Domestic Hot Water Supply in a Single-Family House Supplied by Low-Energy District Heating, *Proc. the 12th International Symposium on District Heating and Cooling*, Tallinn, Estonia, 2010.
- [28] Standard DS 439:2000. Code of Practice for domestic water supply installations.
- [29] Wallentén, P., Steady-State Heat Loss from Insulated Pipes. Ph.D. thesis. University of Lund, Department of Building Physics, 1991.
- [30] Clamond, D., Efficient Resolution of the Colebrook Equation, *Ind. Eng. Chem. Res.*, vol. 48, pp. 3665–3671, 2009.
- [31] www.grundfos.com. Accessed on February 8, 2012.

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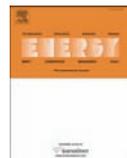
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ARTICLE

IV



Low-energy district heating in energy-efficient building areas

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ABSTRACT

This paper presents an innovative low-energy district heating (DH) concept based on low-temperature operation. The decreased heating demand from low-energy buildings affects the cost-effectiveness of traditionally-designed DH systems, so we carried out a case study of the annual energy performance of a low-energy network for low-energy houses in Denmark. We took into account the effect of human behaviour on energy demand, the effect of the number of buildings connected to the network, a socio-economic comparison with ground source heat pumps, and opportunities for the optimization of the network design, and operational temperature and pressure. In the north-European climate, we found that human behaviour can lead to 50% higher heating demand and 60% higher heating power than those anticipated in the reference values in the standard calculations for energy demand patterns in energy-efficient buildings. This considerable impact of human behaviour should clearly be included in energy simulations. We also showed that low-energy DH systems are robust systems that ensure security of supply for each customer in a cost-effective and environmentally friendly way in areas with linear heat density down to 0.20 MWh/(m year), and that the levelized cost of energy in low-energy DH supply is competitive with a scenario based on ground source heat pumps. The investment costs represent up to three quarters of the overall expenditure, over a time horizon of 30 years; so, the implementation of an energy system that fully relies on renewable energy needs substantial capital investment, but in the long term this is sustainable from the environmental and socio-economic points of view. Having demonstrated the value of the low-energy DH concept, we evaluated various possible designs with the aim of finding the optimal solution with regard to economic and energy efficiency issues. Here we showed the advantage of low supply and return temperatures, their effect on energy efficiency and that a DH design that relies on low-temperature operation is superior to a design based on low-flow operation. The total primary energy use in the best design was 14.3% lower than the primary energy use for standard, recently designed networks, and distribution heat losses were halved. Moreover, the exploitation of the entire available pressure by means of careful network design decreased the average pipe size required, which slightly lowers the investment costs for purchasing and laying the pipelines in the ground. This low-temperature DH concept fits the vision of the future energy-sustainable society.

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1. Introduction

1.1. The low-energy concept applied to district heating

District Heating (DH) covers 60% of the heating demand in Denmark and has a large influence on the rest of the energy system [1,2]. DH will also play a central role in the future Danish energy system based on Renewable Energy (RE) [3]. Many local authorities therefore have plans for preparing the energy system to implement the vision of a society that achieves dramatic energy savings and

fully relies on RE [4–6]. The potential to satisfy the energy demand in communities with DH is high, not only in cold climate countries, but also significant in other countries [7–9]. Nevertheless, the cost-efficiency of DH supply in energy-efficient building areas may be critical. In fact, DH can become uneconomic, especially due to the fixed costs that derive from capital-intensive investments. Furthermore, current Danish Building Regulations do not require low-energy buildings to be connected to DH. Finally, traditionally-designed networks often have sub-optimal energy performance, because of over-dimensioned design and unnecessarily high operational temperatures. The application of the low-energy concept to DH technology has three main targets. The first one is to guarantee comfort with regard to Domestic Hot Water (DHW) and Space Heating (SH) requirements, by exploiting low-grade energy sources

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Nomenclature

d	Diameter [mm]
e	Hourly energy use [kWh]
A	Heated area [m ²]
DH	District Heating
DHW	Domestic Hot Water
E	Specific annual energy use [kWh/(m year)]
GSHP	Ground Source Heat Pumps
LF	Load factor [-]
RE	Renewable energy
SH	Space Heating
T	Temperature [°C]

Subscripts

by-pass	By-pass in the substation
ground	Ground
i	Hour of the day [-]
j	Day of the month [-]
n	Number of days in a specific month [-]
return	Return pipe
supply	Supply pipe

and RE. The second objective is to match the exergy demand of such applications with the exergy available in the supply system, by bringing the temperature levels of the supply and the demand closer to each other. Thirdly, it aims at reducing the heat loss in the distribution network. The main design concepts are:

- Low-size media pipes. This is achieved by allowing a high pressure gradient in the pipelines, above all in the branch pipes connected to the unit with instantaneous DHW preparation [10], or by installing units with storage of DH water [11]. The latter consist of a heat exchanger coupled to a water storage tank on the primary side, which ensures low continuous water flow from the DH network and therefore low-size media pipes in house connections.
- Low temperatures: down to 50–55 °C in the supply line and 20–25 °C in the return line. The technical and economic feasibility of such systems have been investigated from the theoretical point of view in [12,13] and applied in [14,15]. Lowering the supply and return temperatures increases the final energy efficiency of the systems [16] and decreases the distribution heat losses [17].
- Using twin plastic pipes rather than a pair of single steel pipes. This leads to both lower investment costs for the civil works connected to the laying of the pipelines and lower heat loss.

1.2. Objectives of the study

The investigation described in this paper was aimed at developing and demonstrating a proposal on how best to apply the low-energy DH concept for low-energy buildings. We evaluated the annual energy performance and the socio-economics of a demonstration network, based on realistic energy loads that derived from a model of human behaviour with reference to the indoor environment. Next, we discussed a reasonable lower limit for the linear heat density for which connection to low-energy DH networks is cost-effective and energy-efficient. The linear heat density is defined as the ratio between the heating annually sold to the customers and the trench length of the DH network [9]. Finally, after demonstrating the value of the low-energy DH concept, we

evaluated various possible designs with the aim of finding the optimal solution with regard to economic and energy efficiency issues. The focus was the assessment of proposals for effectively designing low-energy DH networks, that supply heat to energy-efficient buildings. The investigations dealt mainly with the design and operation of the network, and the impact of operational parameters on its energy performance. This represents a step towards a complete holistic view, which must comprehend the building installations and the heat sources as well.

2. Methods

2.1. Simulation of the energy use in low-energy buildings

Dynamic energy simulations were carried out using the software IDA-ICE [18]. A special module, which was developed in [19], was used to evaluate the realistic human behaviour and its effects on the energy use. The model is based on measurements in 10 apartments and 5 detached houses, in which the following factors were measured every 10 min for an 8-month period: indoor-environment factors (operative temperature, relative humidity, CO₂ concentration), outdoor-environment factors (air temperature, relative humidity, wind speed, solar radiation), human behaviour (window state open/closed, opening angles, temperature set point of thermostatic valves in radiators). These factors were used to create a standardized human behaviour model for energy simulations in IDA-ICE; the model takes into account the window opening angles and the heating set point. A linear regression was used to calculate the relationship between the heating set point and environmental factors. Moreover, a realistic occupancy schedule was set by adopting the model of [20]. Finally, using the tools just mentioned, we determined the expected energy use and peak loads in two typical types of low-energy buildings: a terraced house with a floor area of 114 m² and a detached house with a floor area of 196 m². The terraced house complies with the definition of Low-Energy Class 1 in the Danish Building Regulations 2008, while it slightly exceeds the maximum annual specific primary energy use which is set by the Low-Energy “Class 2015” in the Danish Building Regulations 2010 [21]. The detached house complies with the requirements of the low-energy building “Class 2015”. The formulas for calculating the maximum annual specific primary energy use for SH, DHW and ventilation in residential buildings are:

$$E = 35 + 1100/A \left[\text{kWh/m}^2\text{year} \right] \quad (\text{Low - Energy class 1}) \quad (1)$$

$$E = 30 + 1000/A \left[\text{kWh/m}^2\text{year} \right] \quad (\text{Low - Energy class 2015}) \quad (2)$$

where E is the specific annual energy use and A is the heated floor area. A complete description of the two reference houses and the design parameters is available in [22,23]. We considered 5 different cases for the reference terraced house and 3 cases for the reference detached house. The cases were chosen with the aim of comparing the influence of human behaviour on energy use with the effect of various system control strategies and environmental parameters (see Table 1). The cases were:

- The input data as required by the software Be06 [24]. Be06 (updated in 2011 with the new version Be10) is the official Danish software for energy certification of low-energy buildings.
- The lighting and equipment were set with a schedule. The total electrical energy use in Case 2 was the same as in Case 1, but the constant loads were replaced by variable loads.

Table 1
Main input data for the energy calculations in the reference houses.

House type	Case	Internal gains [W]			Ventilation [L/(s m ²)]	Heating set point [°C]
		Occupants	Lighting	Equipment		
Terraced house	Be06	170	400 (lighting + equipment)		0.45 (CAV)	20
	1	2 persons, always	300	100	0.45 (CAV)	20
	2	2 persons, always	schedule ^b	schedule ^b	0.45 (CAV)	20
	3	3 persons, schedule ^a	schedule ^b	schedule ^b	0.45 (CAV)	20
	4	3 persons, schedule ^a	schedule ^b	schedule ^b	0.07–0.7 (VAV)	20
	5	Occupancy model	schedule ^b	schedule ^b	0.45 (CAV)	Human behavior
Detached house	Be06	294	686 (lighting + equipment)		–	20
	1	294	schedule ^c	schedule ^c	–	20
	2	2 persons, always	schedule ^c	schedule ^c	–	20
	5	3 persons, schedule ^a	schedule ^c	schedule ^c	–	Human behavior

^a Weekdays 17:00–8:00: 3 persons; 15:00–17:00 (1.5 persons). Weekends: 3 persons.

^b Lighting: 685 W, equipment: 240 W; schedule: 6:00–8:00 and 15:00–23:00.

^c Lighting: 1165 W, equipment: 475 W; schedule: 6:00–8:00 and 15:00–23:00.

- The lighting, equipment and human occupancy were set with a schedule; the constant loads were replaced with variable loads.
- Same as Case 3; a variable air volume (VAV) ventilation system replaced the constant air volume (CAV) ventilation system.
- The human behaviour and occupancy models were introduced.

2.2. Performance of the low-energy DH network

To investigate the dynamic energy performance of low-energy DH networks for low-energy buildings, an existing network layout was adapted from [25]. The consumer units in the simulations consist of substations equipped with a heat exchanger for instantaneous preparation of DHW and without energy storage; they have a nominal power of 32 kW and they require a minimum pressure difference of 0.3 bar. To ensure a reasonable waiting time for DHW outside the heating season, the design thermal bypass temperature was set to 40 °C in each consumer unit. Aluflex twin piping was selected for pipes with a nominal diameter of 32 mm or less, and steel twin piping for larger sizes, as seen in Table 2. The insulation characteristics of the pipes comply with Insulation Series 2. The pipe distance between consumers was multiplied by a factor of 3 in the network layout serving the detached houses. We performed a year's simulation in the commercial software TERMIS for each case defined by Table 1. The main input values consisted of the geometric and thermal parameters of the pipelines, the ratio between the average energy demand for a specific month and its maximum annual value (load factors), the number of hours for each month, and the mean monthly ground temperature. Fig. 1 shows the sketch of the network layout that supplies energy to the development with dense, terraced houses and an example of the input data representing the ambient temperature in the surroundings of the pipes and the load factors for the annual simulations. The results from such simulations were compared with dynamic simulations in TERMIS with a detailed 24-h load profile for a typical day during the heating season and for a typical

day in summer, in order to evaluate the accuracy of the annual simulations with averaged monthly energy use. Fig. 2 shows the hourly values of the load factor for the terraced houses and standard energy use. We considered a typical summer day in Denmark, during which heat is supplied only for the DHW preparation and a typical average day in January (SH + DHW). The load profile of the average day in a month was defined by the average hourly values of energy use, calculated as:

$$LF_i = \left(\frac{\sum_{j=1}^n e_{ij}}{\left(\sum_{j=1}^n e_{ij} \right)_{\max}} \right) \quad (3)$$

where LF_i is the load factor for a specific hour i , e_{ij} is the energy use during the hour i of the day j , and n is the number of days in the month considered. Finally, we compared the simulated low-energy DH networks to other reference examples of DH networks in areas with low heat demand density [26].

2.3. Degree of user connection

During the feasibility study of a DH network in an area of low heat demand density, an economic investigation of a minimal feasible degree of consumer connection to the network must be made, since connection for low-energy buildings is not mandatory, even in zones that were planned to be supplied by DH or with an already existing network. Simulations in the software TERMIS were performed to investigate the performance of the low-energy DH network at various percentages (from 100% down to 10%) of low-energy buildings connected. We kept the last consumer of each street connected, so that the total network length did not vary from case to case. The cost analysis shows the minimal cost-effective degree of connection, which can be generalized in terms of linear heat density.

2.4. Socio-economics

As the next step, we carried out a simplified socio-economic evaluation based on cost figures from reference reports [13,26,27]. The cost comparison refers to the cost of 1 kWh, when buildings are supplied with either DH or with individual Ground Source Heat Pumps (GSHP). We used a discount rate of 6% and a period of 30 years, which is in line with Danish Ministry of Finance requirements for public investment analyses. However, other long-term analyses suggest that a discount rate as low as 3% is reasonable [6,9]. The significance of the discount rate should not be

Table 2
Pipe types and length of the pipeline. Alx: Aluflex twin pipe. Tws: steel twin pipe.

	Length [m]							Total
	Alx 20	Alx 26	Alx 32	Tws 32	Tws 40	Tws 50	Tws 65	
Terraced houses	239.1	112	240.6	88.5	33.8	7.7	100.7	823.4
Detached houses	315.7	150.1	555.5	149.7	80.7	7.7	100.7	1360.1

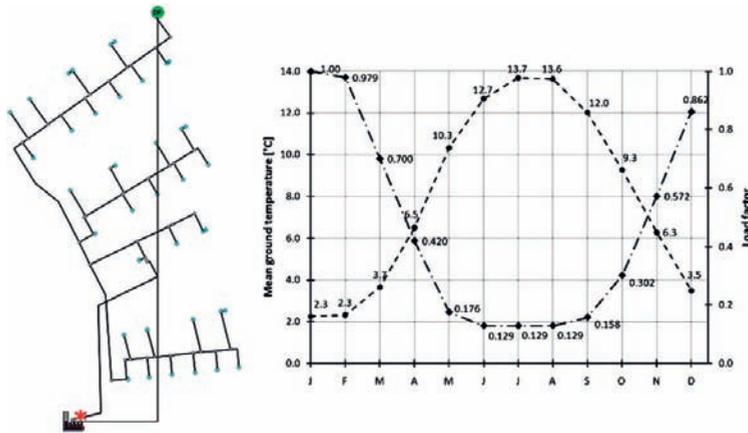


Fig. 1. Network layout for the terraced houses (left). Mean monthly ground temperature in Denmark (source: [17]) and heat load factor for the case with terraced houses and standard energy use (right).

underestimated, particularly in cases like the ones considered in this article where a shift from operational costs to investment costs is expected. It is important to emphasize that lower discount rates would improve the overall economics of the DH systems considered in this paper, and therefore our economic results are on the safe side.

2.5. Optimization of the DH network design

The design of energy-efficient DH networks for buildings with low energy demand has to limit the heat loss in the distribution pipes, since this heat loss is the main cause of energy inefficiency. There are two main concepts that the planners can apply to maximize the energy efficiency and thus the cost-effectiveness of the network. They are both based on the fact that a return water temperature as low as possible is desirable, because of its direct impact on the heat loss and on the energy efficiency of the production plants. Moreover, only well-insulated pipes, e.g. the standard series 2 or 3 are considered as valuable applications, since the thermal properties of lower insulation series pipes are not

sufficient to satisfy strict energy conservation policies. For the design concepts reported in this paragraph, we hypothesize the return temperature to be 25 °C and pipes belonging to the insulation series 2 were selected, with insulation thermal conductivity values of 0.023 W/(m K) and 0.024 W/(m K) for Aluflex pipes and steel pipes, respectively. In the first overall design concept (see Table 3, Design B), the supply temperature is kept to a medium-high level, i.e. 80–85 °C in Denmark, and high temperature differences between supply and return are ensured by choosing proper in-house heating systems dimensioning and operation. In this way, the flow is kept relatively small and consequently the media pipe sizes and the heat transfer to the surrounding ambient are reduced (low-flow DH). In the second design concept, called “low-temperature DH” (see Table 3, Designs C, D and E), the supply temperature is reduced to the level which is necessary for DHW preparation, i.e. 50–55 °C. The temperature difference between supply and return is 45%–60% lower than in the other concept, so that bigger media pipe diameters are necessary. Nevertheless,

Table 3 Design parameters for 5 different designs for the district heating network.

Design concepts	Design parameters
A. State-of-the-art design	Twin pipes; $T_{supply} = 85\text{ °C}$, $T_{return} = 40\text{ °C}$, $T_{by-pass} = 70\text{ °C}$, all-year round; max pressure gradient in branch pipes: 2000 Pa/m; max. velocity in distribution pipes: 1.20 m/s.
B. Low flow	Twin pipes; $T_{supply} = 85\text{ °C}$, $T_{return} = 25\text{ °C}$, $T_{by-pass} = 40\text{ °C}$, all-year round; max pressure gradient in branch pipes: 2000 Pa/m; max. velocity in distribution pipes: 1.20 m/s.
C. Low temperature	Twin pipes; $T_{supply} = 55\text{ °C}$, $T_{return} = 25\text{ °C}$, $T_{by-pass} = 40\text{ °C}$, all-year round; max pressure gradient in branch pipes: 2000 Pa/m; max. velocity in distribution pipes: 1.20 m/s.
D. Low temperature, optimization method	Twin pipes; $T_{supply} = 55\text{ °C}$, $T_{return} = 25\text{ °C}$, $T_{by-pass} = 40\text{ °C}$, all-year round; pipe sizes optimized according to max. available pressure in the network (10 bar)
E. Low temperature, optimization method, temperature boost in peak-load conditions	Twin pipes; $T_{supply} = 65\text{ °C}$, $T_{return} = 25\text{ °C}$, $T_{by-pass} = 40\text{ °C}$, in peak-load conditions (300 h/year); $T_{supply} = 55\text{ °C}$, $T_{return} = 25\text{ °C}$, for normal conditions; $T_{by-pass} = 40\text{ °C}$; pipe sizes optimized according to max. available pressure in the network (10 bar)

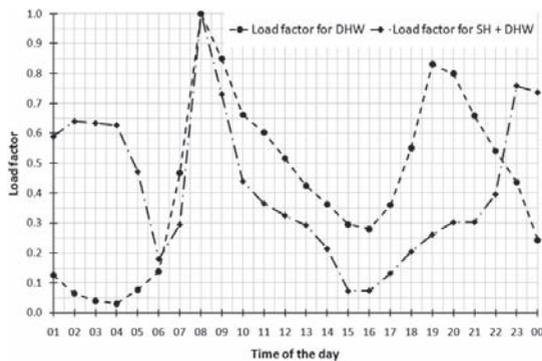


Fig. 2. Terraced houses and standard energy use. Load factors in a summer day (DHW only) and for an average day in January (SH + DHW). The peak values for the hourly energy use are 0.50 kWh and 2.45 kWh, respectively for DHW only and SH + DHW.

minimum heat losses are still possible: in fact, the linear heat loss coefficient decreases thanks to the lower operational temperatures. In the paragraph 3.4 below, we assess the energy performance of the two concepts and discuss criteria for choosing the best design solutions to suit the specific conditions. We first analysed the effect of the operational temperatures and media pipe diameters on the heat loss in commercially available pipes. Next, we considered the network layout and the settlement as presented in paragraph 2.1 and examined various design solutions for the network; they are listed and briefly described in Table 3. The expression “optimization method” refers to an innovative network design methodology, which aims at helping the engineering practice select optimal media pipe dimensions and operational parameters, such as supply and return temperatures, and pressure levels. The most commonly used dimensioning methods limit the maximum pressure gradient and/or the maximum velocity to specific values derived from practice and calculate the diameters of each media pipe segment. Such dimensioning approaches are very reliable, but often lead to over-dimensioned DH networks, resulting in more expensive installation costs and in energy inefficiency. The new optimization method is based on the consideration that the next generation of DH networks will ensure better cost-effectiveness if lower heat losses are guaranteed through reduced media pipe sizes, despite the consequent increase of the required pumping power. The method is applied in successive steps. First, the DH network is defined by node and pipe data series, which contains geographical and heat load data; the DH network is evaluated by randomly generated heat demand profiles of the consumers connected to DH network, based on the simultaneity of the heat demand by means of “simultaneity factors”. Secondly the heat loss and the pressure loss are modelled as functions of the operational and ambient temperatures, the thermal–hydraulic properties of the materials, and the geometry of the pipes. Next, the objective function of the optimization model is defined. The objective function consists of simultaneously achieving a target and satisfying some constraints. The target is to find the pipe size configuration that minimizes the total heat loss from the DH network, while the constraints refer to the requirement to exploit the maximum available pressure drop, e.g. the maximum available pressure drop in each route of a branched network. The maximum available pressure drop is limited by the maximum static pressure of the DH network, due to mechanical stress limitations in the media pipe wall. It is calculated for each independent route from the location of the closest pumping station, where the network pressure level is highest, to the node with energy use in the route which is critical from the hydraulic point of view (usually the node furthest from the pumping station). The optimization methodology was applied to the case study settlement, when assessing the Designs D and E. The optimal network configuration was reached by trials in the commercial software TERMIS [28], since the network complexity was relatively limited; so that a simplified approach of the design method for network optimization could be used. Fig. 3 shows the pressure level for Design E in the supply and return pipelines of the route which is critical from the hydraulic point of view. The pipe sizes in the other routes were designed so that the differential pressure available at the critical consumer, i.e. at the end of the route, did not exceed 1 bar and thus over-dimensioning was avoided.

3. Results and discussion

3.1. Energy use in low-energy buildings

The results from the energy simulations of the two reference houses indicate the same tendency, when considering the heating demand (see Table 4). First, the end-user demand for SH increases

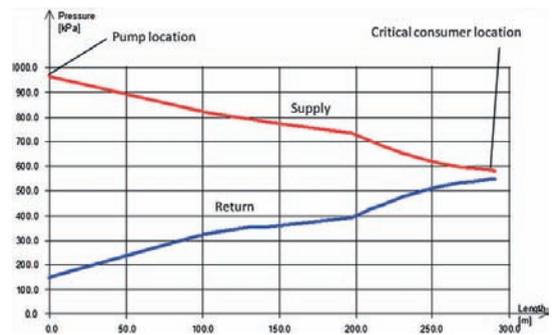


Fig. 3. Pressure level in the supply and return pipelines of the critical route, from the hydraulic point of view. Network Design E; maximum design pressure: 10 bar; minimum static pressure at the heating plant: 1.5 bar.

by a factor of 2 in comparison to standard calculations (from around 21 kWh/(m² year) to 44 kWh/(m² year)) when human behaviour is taken into account. Moreover, human behaviour significantly affects the magnitude of the heating peak load: +27% for the detached house and up to +60% for the terraced house, with standard simulation as reference. Next, the heating demand increases by about 5%, when internal gains are variable over the time.

3.2. Low-energy DH network

We did energy performance analyses of the DH network for terraced houses and of the DH network for detached houses. We considered simulation Case 1, where the energy demand is calculated by taking into account only the thermal properties of the building envelope and simulation Case 5, where human behaviour is taken into account. The parameters that summarize the relationships between building area, land area, energy demand and energy supply are listed in Table 5. The values of the plot ratio and of the effective width indicate that the settlements are in heat sparse areas, according to the classification in [9]; the linear heat density points to the fact that such building developments are typical examples of areas that are currently considered critical for DH supply. So, the investigation aimed at giving an insight into the real possibilities of supplying such areas with DH, and into the most effective technical solutions to make it possible.

3.2.1. Annual energy figures

The heat production (equivalent to the sum of the heat use in the buildings and the distribution heat loss), the distribution heat

Table 4
Primary energy demand in the reference houses for the various cases.

Type of house	Case	Primary energy demand ^a [kWh/(m ² year)]					
		Lighting	Equipment	Other el.	SH	DHW	Total
Terraced house	Be06	–	–	4.7	18.8	12.8	–
	1	54.3	19.3	4.3	17.1	13.1	108.0
	2	54.3	19.3	4.3	18.0	13.1	108.9
	3	54.3	19.3	4.3	17.1	13.1	108.0
	4	54.3	19.3	2.0	11.7	13.1	100.3
Detached House	5	54.3	19.3	4.3	35.0	13.1	125.9
	Be06	–	–	2.4	15.4	12.3	–
	1	54.3	22.3	2.4	17.2	11.6	107.7
	2	54.3	22.3	2.4	18.1	11.6	108.6
	5	54.3	22.3	2.4	31.8	11.6	122.3

^a Primary energy factor for electricity = 2.5; primary energy factor for heat = 0.8 [21].

Table 5
Total land area, plot ratio, linear heat density and effective width.

	Terraced houses		Detached houses	
	case 1	case 5	case 1	case 5
Total land area [ha]	1.5		4.5	
Plot ratio ^a [-]	0.30		0.18	
Linear heat density ^a [MWh/(m year)]	0.22	0.33	0.22	0.31
Effective width ^a [m]	18.2		33.1	

^a As defined in [9].

loss, and the distribution heat loss as a percentage of the heat production for each month of the year are shown in Fig. 4. The low-energy DH concept is technically a good solution both for terraced houses and for detached houses, with a share of heat loss between 14% and 20% of the total heat production on an annual basis. The ratio between the heat loss and the year-round heat production typically decreases from 20%, in standard energy calculations, to 14%, if human behaviour is taken into account. On the one hand, this demonstrates that human behaviour has a great impact on the energy efficiency of the network; on the other hand, it confirms that the energy-saving policies in the building sector cannot be based solely on technological aspects, but need to address the role of the end-users. Moreover, the network design is robust and is capable of handling heat loads greater than the design values, without any hydraulic issues and ensuring the security of the heat supply to each customer. An example of such a situation occurs when we go from heat demand calculations based purely on building material physics and standard indoor-environment conditions in energy-efficient buildings, to heat demand calculations that take into account users' (mis) behaviour. This is not to underestimate the importance of energy savings, since they are the prerequisite for implementing the vision of a fossil-fuel-free energy sector. The point is that the involvement of the end-users is decisive for whether the society can achieve the full potential of energy conservation measures in buildings and their integration into an efficient energy supply system.

The annual simulation with average monthly input values gives sufficient accuracy in comparison to the 24-h dynamic simulations, during the SH season, as can be seen in Table 6. Nevertheless, it is important to emphasize that the accuracy of the network energy performance figures in long periods without SH (summer season) is less than during the heating season. The variation can be up to 9% for the calculation of heat losses. This is due to the simplification introduced when considering average monthly load values, which leads to a smoother load profile than the calculation with hourly load values.

3.2.2. Energy performance as function of the linear heat density

In the DH sector in Denmark as a whole, the ratio between the distribution heat loss and the produced heat is 16%, and the value rises to 21% if the networks serving the 3 biggest metropolitan areas are not included (derived from [29]). Fig. 5 shows the ratio between the annual distribution heat loss and the annual heat production as a function of the linear heat density, for our case study. Each point in the graph represents a specific linear heat density, which corresponds to a specific number of buildings connected to the network. The various values of linear heat density are set by disconnecting 10% of the dwellings in each step from the original network. The procedure was repeated with 10 different disconnection patterns, from purely randomized to more uniform ones. The values of the heat loss/produced heat ratio lay between the curve showing the case with terraced houses and energy use including human behaviour and the curve representing the case with detached houses and standard energy use. The distribution heat loss in the low-energy DH network is less than 20% of the heat produced, if the linear heat density is higher than 0.20 MWh/(m·year). This demonstrates that it is possible to integrate low-energy buildings in the existing Danish DH networks without decreasing the energy performance of the whole DH system. On the other hand, it indicates the need for the majority of the buildings in such settlements to be connected to the common DH network, otherwise unacceptable economic and energy inefficiency is likely; this is particularly true for detached houses: in the case study at least 90% of the buildings must be connected to keep the cost of the

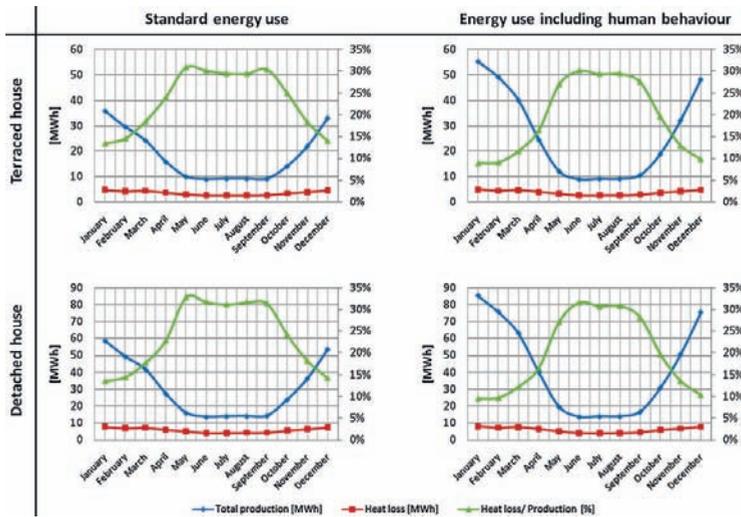


Fig. 4. Monthly heat production and heat loss [MWh] and quota distribution heat loss and heat production. DH supply/return temperatures: 55/25 °C. Cases with terraced houses (top); cases with detached houses (bottom). Standard energy use (left); energy use including human behaviour (right).

Table 6

Comparison between network energy simulation with average monthly values and hourly values in January and July.

	Type of buildings	Case	Total heat production [MWh]		Heat loss[MWh]	
			January	July	January	July
Hourly simulation	Terraced houses	1	35.21	9.13	4.68	2.87
		5	58.25	9.13	4.91	2.87
	Detached houses	1	58.26	14.25	7.73	4.74
		5	87.31	14.25	8.10	4.74
Annual simulation	Terraced houses	1	35.76	9.20	4.81	2.71
		5	57.40	9.23	4.93	2.71
	Detached houses	1	58.58	14.06	7.93	4.38
		5	85.29	14.02	8.12	4.31
Difference hourly/annual [%]	Terraced houses	1	1.6	0.7	2.8	-5.6
		5	-1.5	1.1	0.4	-5.6
	Detached houses	1	0.5	1.3	2.5	-7.7
		5	-2.3	-1.6	0.2	-9.2

energy below 20 c€/kWh and the heat loss below 20% of the heat production. The results not only confirm, but even go beyond the statement made in [26], where the authors claimed that areas with a linear heat density of 0.30 MWh/(m year) can be supplied by DH in a cost-efficient way. The low-energy DH concept is strategic for reaching ambitious energy and climate targets and has the potential for being widely implemented in Europe, taking into account the conclusion in [30] about the European heat market: the demand for heat dominates the demand side in the European energy system and almost the same specific heat demands appear in Western, Central, Eastern, and Northern Europe. A similar conclusion can be drawn for other countries outside Europe where energy-saving measures and efficiency in the energy supply are priorities in the political agenda. The curves reporting the cost of the energy unit show that for houses with the lowest total heat demand, i.e. the case of dense, terraced houses and standard energy use, the specific energy cost is the highest, while the specific energy cost is lowest for houses with the highest total heating demand (detached houses). Nevertheless, the overall expenditure for heating purposes depends strictly on the actual total energy use, and it is therefore higher for detached houses than for dense, terraced houses.

3.3. Socio-economics

The levelized cost of energy for low-energy DH supply is competitive with the GSHP-based scenario, which is considered

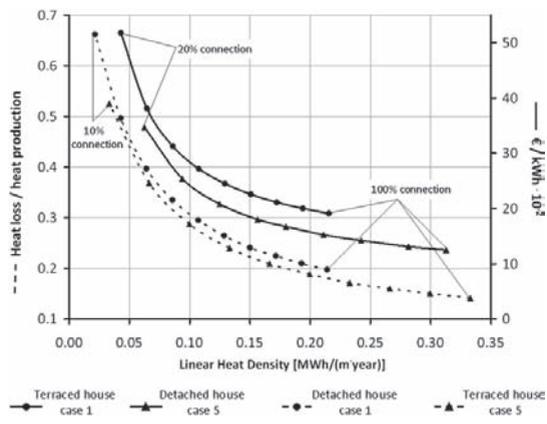


Fig. 5. Heat loss/total produced heat vs. the linear heat density (---). Specific energy cost (—). The picture shows the bottom and top curves. All the values are between the top and bottom lines, for all the cases considered.

among the best possible solutions for efficiently heating low heat density areas. The cost of heat for the end-user is between 13.9 and 19.3 c€/kWh (excl. VAT) for Low-Energy “Class 2015” detached houses and Low-Energy Class 1 terraced houses, respectively. This is approximately 20% lower than the corresponding energy unit cost for the GSHP scenario. Considering that the heat price for final users in the capital region of Denmark was ~6.9 c€/kWh (excl. VAT) in 2010, this means that the specific heat price for the final consumer would be 2–3 times higher than the current price. Nevertheless, the overall expenditure could very well be similar to the current bill, thanks to dramatic energy savings that offset the effect of higher energy prices. The figures consider a 30-year time horizon, 6% interest rate, energy use as expected from standard calculations and current energy prices for heat and electricity purchase for DH companies in Denmark. In the future energy systems based on RE, it is expected that the operational costs, i.e. neglecting the investment costs, will increase due to higher prices for RE purchasing. On the other hand, this is not critical for two reasons: 1) the price for fossil-fuel-based heat will increase as well, and 2) the share of operational costs in the overall energy costs is not the most critical, especially in energy-efficient areas; in fact the energy costs for DH energy supply account for 18–28% of the total costs, while the investment costs represent 63–72% of the overall expenditure (see Fig. 6). A similar conclusion can be drawn for GSHP heat supply, because the energy-related cost has a share of 12–19%. The implementation of an energy system that fully relies on RE needs substantial capital investment, which is sustainable in the long term from the environmental and socio-economic points

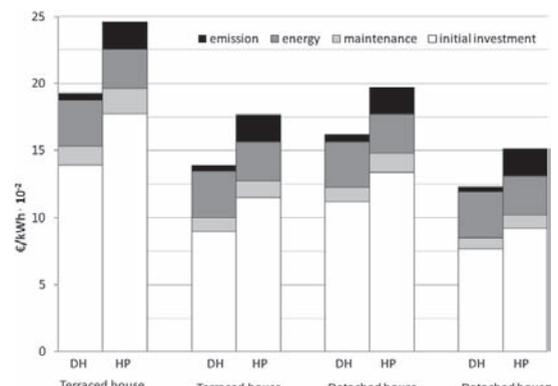


Fig. 6. Levelized cost of energy in case of DH supply and HP supply.

Table 7Effect of the supply temperature on the heat loss of district heating pipes. Alx: twin Aluflex media pipe; Tws: twin steel media pipe; $T_{\text{return}} = 25\text{ }^{\circ}\text{C}$, $T_{\text{ground}} = 8\text{ }^{\circ}\text{C}$.

Pipe type	Alx14	Alx16	Alx20	Alx20	Alx26	Alx32	Tws40	Tws50	Tws65	Tws50	Tws65	Tws80
Inner d [mm]	10	12	15	15	20	26	48.3	60.3	76.1	60.3	76.1	88.9
Casing d [mm]	110	110	110	110	125	125	180	225	250	225	250	280
T_{supply} [$^{\circ}\text{C}$]	93	75	55	115	76	55	105	75	55	94	66	55
Heat loss [W/m]	5.4	4.8	4.3	8.4	6.3	5.9	11.8	8.4	7.6	10.3	9.0	8.4

of view. The cost of such a scenario is at a comparable level with the current situation or even lower, if the environmental costs of maintaining current standards of heating comfort with energy systems based on fossil fuels, fuel savings, and health issues are taken into account. We can conclude that the low-energy DH concept fits the vision of the future energy-sustainable society, as expressed in [31].

3.4. Comparison of design concepts for low-energy district heating

In the previous chapters we demonstrated that the low-energy DH can be applied to energy-efficient settlements, with current technology and design methodology. In this chapter we discuss possibilities for design optimization. The aim of this paragraph is to assess the performance of the two main design concepts for low-energy DH (“low-flow DH” and “low-temperature DH”), to demonstrate the utility of the optimization method for pipeline dimensioning, and to find synthetic conclusions that can be used to enhance the penetration of energy-efficient networks in communities. We start with the assessment of the effect of the supply temperature on the heat loss in existing commercial pipes. In Table 7, four groups of pipes are listed by size, with the diameters increasing from the left to the right in each block. Each group consists of 3 pipe types, whose supply temperature is calculated so that the various solutions are equivalent from the operational point of view, with the same capability of carrying heating power, at a specific water velocity and at the same return temperature. The results demonstrate that bigger pipes with lower supply temperatures have a better energy performance than smaller pipes

with higher supply temperatures. Although the amount of insulation in each pipe type differs, even in the same group, and affects the magnitude of the heat loss, a general trend is recognizable: the conclusion is that the effect of the temperature on the heat loss is more significant than the effect of the media pipe diameter. That is one of the main reasons why low-temperature operation is the first objective to be addressed when designing low-energy DH networks, as well as the increase in the potential to exploit renewable energy that the low supply and return temperatures offer. Tables 8 and 9 show the impact that this concept had when applied in practice to the reference network. Table 8 compares the investment costs for purchasing and laying the pipelines; Table 9 shows the energy performance of the 5 different designs introduced in chapter 2.5, i.e. the annual figures for total distribution heat losses and the theoretical hydraulic energy (without considering the efficiency of the pumping system). The DH network serving the developments with dense, terraced houses and standard energy use (Case 1 in Section 2.1.) was chosen for the investigation, because of its low linear heat density. Moreover it has general value, since its linear heat density is similar to the case with detached houses and standard energy use. The first conclusion is that capital savings can be obtained (in the case study between 2.7% and 4.6%), when applying a proper design methodology (Designs B, D, and E), which is more advanced than the “state-of-the art” design method (Design A). Additional capital costs – in the case study approx. +3% in comparison to current practice – are necessary when the low-energy DH concept is applied without putting strong focus on the optimization of the pipe size and pressure levels (design C in comparison to design A). The economic figures vary in other DH network configurations, due to the large number of parameters involved; nevertheless, they were calculated according to average national data in Denmark, so they represent a general situation. Next, the results from the simulations show that the magnitude of the distribution heat loss affects not only the thermal energy demand, but also the hydraulic power demand. In fact, the reduced temperature drop along the pipeline that is achieved thanks to lower heat losses makes it possible to reduce the water flow and therefore the electricity used for pumping purposes. One

Table 8

Investment costs for purchasing and laying the pipelines for the 5 different designs for the district heating network serving the settlement with dense, terraced houses.

	A	B	C	D	E
Investment cost (pipelines) [$\text{€} \cdot 10^3$]	334.8	319.4	344.7	325.9	323.4

Table 9

Annual heating demand, energy loss and hydraulic energy for 5 different designs for the district heating network serving the settlement with dense, terraced houses.

Period	Duration [h/year]	Energy [MWh]										
		Heating Demand	Heat loss					Hydraulic energy				
			A	B	C	D	E	A	B	C	D	E
1	50	5.78	0.44	0.34	0.27	0.25	0.28	<0.01	<0.01	<0.01	0.01	<0.01
2	100	8.2	0.87	0.67	0.54	0.50	0.55	<0.01	<0.01	<0.01	0.01	0.01
3	150	9.77	1.30	1.01	0.80	0.74	0.82	0.01	<0.01	0.01	0.02	0.01
4	150	8.52	1.30	1.00	0.80	0.74	0.71	0.01	<0.01	0.01	0.02	0.01
5	500	24.2	4.3	3.32	2.66	2.46	2.37	0.02	0.01	0.02	0.06	0.05
6	500	20.6	4.27	3.3	2.65	2.45	2.36	0.02	0.01	0.02	0.06	0.05
7	500	17.78	4.25	3.27	2.64	2.44	2.35	0.02	0.01	0.02	0.06	0.05
8	500	14.64	4.22	3.24	2.63	2.43	2.34	0.02	0.01	0.02	0.06	0.05
9	500	10.46	4.16	3.17	2.59	2.4	2.31	0.02	0.01	0.02	0.06	0.05
10	1000	15.78	8.31	6.22	5.11	4.74	4.56	0.04	0.02	0.05	0.13	0.10
11	2000	21.27	16.79	12.03	9.98	9.27	8.93	0.07	0.05	0.09	0.25	0.20
12	2811	13.8	26.37	15.89	13.05	12.1	11.85	0.1	0.07	0.13	0.35	0.27
Total [MWh]		170.8	76.57	53.47	43.73	40.6	39.42	0.31	0.21	0.4	1.1	0.86

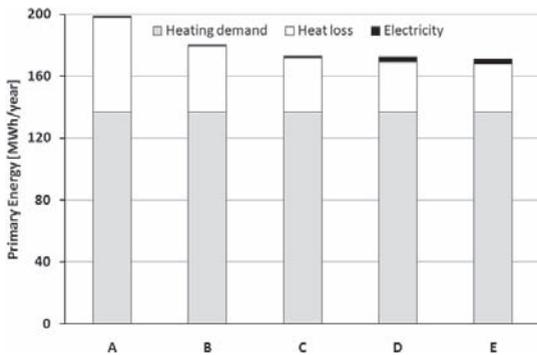


Fig. 7. Primary energy use in a year of operation for 5 different designs.

might say that the operation of the pumping station benefits from the lower energy consumption that derives from the lower distribution heat loss. So, a correlation between the heat losses and pressure losses is recognizable: lower heat losses lead to a lower temperature drop, which means lower flow at a specific heating power, and thus lower demand for pumping energy. Finally, the network designed for low-temperature operation with a temperature boost during the 300 h/year of heating peak-load and exploitation of the maximum allowable pressure drop (Design E) has the best primary energy performance (see Fig. 7). The calculations hypothesized an annual average pump efficiency of 0.80 and primary energy factors of 2.5 and 0.8 for electricity and DH, respectively. Its total primary energy use is 170.9 MWh/year, which is 14.3% lower than the primary energy use for standard recently designed networks (Design A). This is made possible by the synergy between low operational temperatures and accurate network design (Design E), which almost halve the heat loss in comparison to the standard medium-temperature design (Design A). The designs based on low-temperature operation (Designs C, D and E) are superior to the design based on low-flow operation (Design B). This demonstrates the importance of the low supply and return temperatures and their effect on energy efficiency.

4. Conclusions

In this paragraph, we collect together the main findings of this paper and present guidelines that can be followed to improve the energy efficiency and the exploitation of RE in the heating sector. First, human behaviour can lead to 50% greater heating demand and 60% higher peak loads than expected according to reference values in the standard calculation of energy demand patterns in energy-efficient buildings. Energy savings are the prerequisite for implementing the vision of a fossil-fuel-free energy sector. So, society can achieve the full potential of energy conservation measures in the building sector and their integration into an efficient energy supply system only with the decisive involvement of the end-users. The users' awareness on their impact on the energy use must be always addressed, otherwise the opportunity of keeping the energy use as low as it would be technically possible would be missed; moreover that would undermine the optimal network design, leading to the increase of the investment costs for the network, due the necessity of larger media pipe sizes. Although the cases considered refer to the Danish climate and the Danish tradition in the construction sector, they have a general value and are adaptable to other situations. Human behaviour is the factor that most affects the energy use in low-energy buildings and should be included in energy simulations. Next, we showed that

low-energy DH systems are promising solutions, when assessing cost-effective and reliable solutions for supplying the heating demand of energy-efficient areas. The expected linear heat density can be used as the representative value for feasibility studies of DH networks. Low-energy DH networks are capable of supplying heat in a cost-effective and environmentally friendly way in areas with a linear heat density as low as 0.20 MWh/(m year). Furthermore, such systems are robust and can ensure the security of supply to each customer, even where energy use patterns differ from expectations. The low-energy DH concept is strategic for reaching ambitious energy and climate targets and has the potential for being widely implemented in Europe. A similar conclusion can be drawn for other countries where energy-saving measures and energy supply efficiency are priorities in the political agenda. This suggests that the mandatory connection of low-energy buildings to DH in specific areas, by means of detailed energy planning (as in Denmark in the 1970s) would improve the potential for energy efficiency and is strategic for effective energy policy. The levelized cost of energy of low-energy DH supply is competitive with the GSHP-based scenario, which is considered among the best possible solutions for efficiently heating low heat density areas. The cost of heat for the end-user is between 13.9 and 19.3 c€/kWh (excl. VAT) for Low-Energy "Class 2015" detached houses and Low-Energy Class 1 terraced houses, respectively. This is approximately 20% lower than the corresponding energy unit cost for GSHP. The energy costs for DH energy supply account for 18–28% of the total costs, while the investment costs represent 63–72% of the overall expenditure. This is similar to the use of GSHP heat supply, where the energy-related cost has a share of 12–19%. The implementation of an energy system that fully relies on RE needs substantial capital investment; in turn, that is sustainable in the long term from the environmental and socio-economic points of view. The cost of such a scenario is at a comparable level with the current situation or even lower, if the environmental costs of maintaining current standards of heating comfort, opportunities for fuel savings, and health issues are taken into account. Having demonstrated the value of the low-energy DH concept, we evaluated various possible designs with the aim of finding the optimal solution, with regard to economic and energy efficiency issues. The importance of low supply and return temperatures and their effect on the energy efficiency of the DH network was demonstrated. The designs based on low-temperature operation (Designs C, D, E) are superior to the design based on low-flow operation (Design B). The total primary energy use in the most energy-efficient design (Design E) is 14.3% lower than the primary energy use for standard recently designed networks (Design A) and the distribution heat losses are halved. Moreover, with careful network design that exploits the entire available pressure it is possible to reduce the average pipe size, which slightly lowers the investment costs for purchasing and laying the pipelines in the ground. Although this increases the energy use for pumping purposes by almost 3 times, this is not a real issue, because the share of the pumping energy in the total primary energy demand is at most approx. 2%. The results demonstrate that this low-temperature DH concept fits the vision of the future energy-sustainable society.

References

- Möller B, Lund H. Conversion of individual natural gas to district heating: geographical studies of supply costs and consequences for the Danish energy system. *Applied Energy* 2010;87(6):1846–57.
- Østergaard PA. Heat savings in energy systems with substantial distributed generation. *International Journal of Sustainable Energy* 2003;23(4):169–76.
- Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems – the case of Denmark in years 2030 and 2050. *Energy* 2009;34(5):524–31.

- [4] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. *Applied Energy* 2011;88(2):479–87.
- [5] Wejs A. Embedding climate planning – planning experiences from Danish municipalities [Forankring af klimaplanlægning]. Aalborg University; 2009.
- [6] Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg municipality based on low-temperature geothermal heat, wind power and biomass. *Energy* 2010;35(12):4892–901.
- [7] Lund H. Renewable energy strategies for sustainable development. *Energy* 2007;32(6):912–9.
- [8] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. *Energy* 2010;35:1381–90.
- [9] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. *Applied Energy* 2011;88:568–76.
- [10] Dalla Rosa A, Li H, Svendsen S. Modelling transient heat transfer in small-size twin pipes for end-user connections to low-energy district heating networks. Submitted to *Heat Transfer Engineering*.
- [11] Paulsen O, Fan J, Furbo S, Thorsen JE. Consumer unit for low-energy district heating net. 11th international symposium on district heating and cooling; 2008. Reykjavik.
- [12] Olsen PK, Lambertsen H, Hummelshøj R, Bøhm B, Christiansen CH, Svendsen S, et al. A new low-temperature district heating system for low-energy buildings. 11th international symposium on district heating and cooling; 2008. Reykjavik.
- [13] Udvikling og demonstration af lavenergifjernvarme til lavenergibyggeri [in Danish]. Copenhagen, Denmark: Danish Energy Authority; 2009.
- [14] Brand M, Dalla Rosa A, Svendsen S. Performance of low-temperature district heating systems for low-energy houses. The future for sustainable built environments with high-performance energy systems conference; 2010. Munich.
- [15] CO₂-reductions in low-energy buildings and communities by implementation of low-temperature district heating systems. Demonstration cases in Boligforeningen Ringgården and EnergyFlexHouse. Copenhagen, Denmark: Danish Energy Authority; 2011.
- [16] Torio H, Schmidt D. Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis. *Energy and Buildings* 2010;42:1601–9.
- [17] Dalla Rosa A, Li H, Svendsen S. Method for optimal design of pipes for low-energy district heating, with focus on heat loss. *Energy* 2011;36(5):2407–18.
- [18] IDA-ICE user guide. Available at, www.equa.se; October 2011.
- [19] Andersen RV. Occupant behaviour with regard to control of the indoor environment. Ph.D. thesis; 2009.
- [20] Richardson I, Thomson M, Infield D. A high-resolution domestic building occupancy model for energy demand simulations. *Energy and Buildings* 2008; 2008(40):1560–6.
- [21] The Danish building regulations. Available at, www.ebst.dk; 2010. October 2011.
- [22] Nagla I. Profitability of low energy district heating for areas with low energy buildings. M.Sc. thesis. Technical University of Denmark; 2010.
- [23] DS/EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics; 2007.
- [24] www.sbi.dk (October 2011).
- [25] COWI A/S. Ledningsdimensionering og konceptuelt layout; 2009 [in Danish].
- [26] Zinko H, Bøhm B, Kristjansson H, Ottosson U, Rama M, Sipilä K. District heating distribution in areas with low heat demand density. International Energy Agency; 2008.
- [27] The Danish Energy Authority. Forudsætninger for samfundsøkonomiske analyser på energiområdet [in Danish]. Copenhagen, Denmark: Danish Energy Authority; 2009.
- [28] TERMIS user guide. Available at, www.7t.dk; June 2011.
- [29] Dansk Fjernvarme Benchmarking statistik; 2008–2009. Danish District Heating statistics 2008-2009.
- [30] EcoHeatCool project. Available at, www.euroheat.org; 2006. June 2011.
- [31] A roadmap for moving towards a competitive low carbon economy in 2050, European commission. Available at, www.ec.europa.eu/clima; 2011.

ARTICLE

V



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

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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) ($70\text{ °C} \leq T_{\text{supply}} \leq 90\text{ °C}$) had better energy delivery performance than high-temperature district heating (HTDH) ($T_{\text{supply}} > 100\text{ °C}$), decreasing the heat loss by approximately 40%. The low-temperature networks ($T_{\text{supply}} < 60\text{ °C}$) 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 $3\text{ MWh}/(\text{m yr})$ could economically be supplied by DH. Areas with linear heat density below $1.5\text{ MWh}/(\text{m yr})$ 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.

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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 energy 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

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.

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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. Secondly, 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.

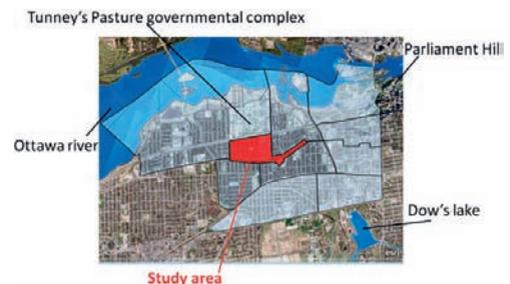


Fig. 1. Case study site in Ottawa, Ontario, Canada.

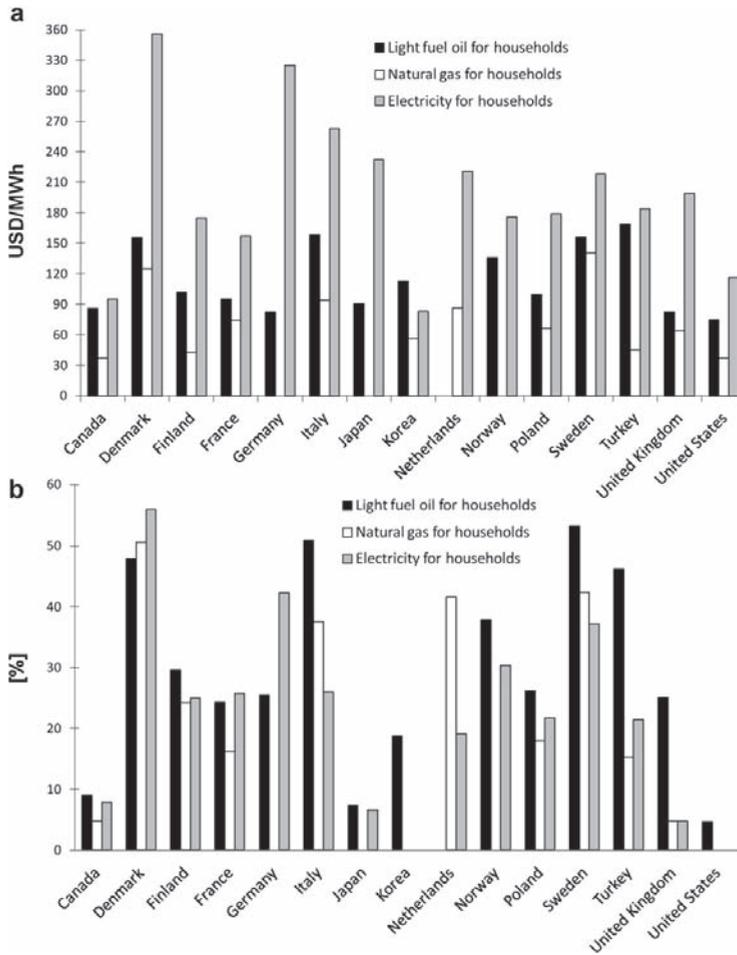


Fig. 2. Energy prices (a) and impact of taxes (b) on the total energy price for household in OECD countries in 2010. Missing columns mean that no data were available. Source: [25].

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 decision 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]:

$$z = E_{\text{electricity, loss}} / E_{\text{heat, production}} \tag{1}$$

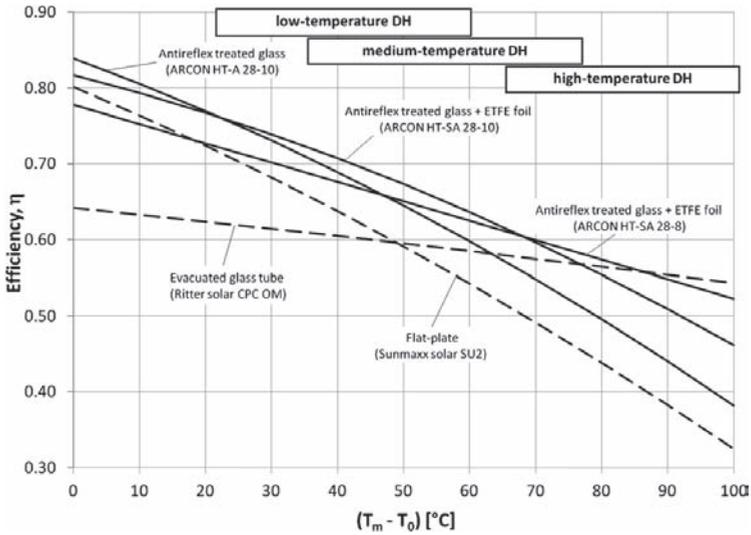


Fig. 3. Efficiency of solar collectors as function of the difference between the average T of the fluid in the collector, T_m and the ambient temperature, T_0 ($G = 1000 \text{ W/m}^2$). — Large-scale solar thermal collector, source: [27]; - - - Small-scale solar thermal collector, source: [28].

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

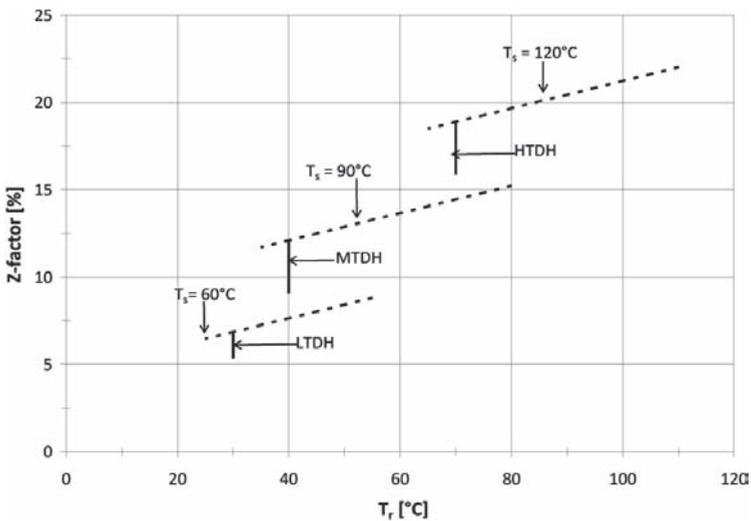


Fig. 4. z -Factor in an extraction-condensing turbine for CHP as function of the DH operating temperatures.

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

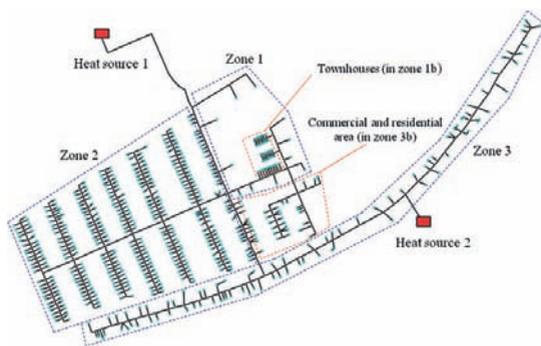


Fig. 5. Network layout in the case G. The layout in the cases A–F consists in modification of portions of it.

explore the technical and economical possibilities to implement DH in a typical Canadian urban city and finally prepare heat plans.

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:

$$kW_{\text{peak}} = \frac{kWh_{\text{Jan}}}{744 \times LF} \quad (2)$$

where 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 × 1000]	Building area/parcel area	Peak power [MW]	Heat demand		Heat density [kW h/(m ² yr)] ^b
							[GWh]	[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 $\leq T_{supply} \leq 90$ °C) and low-temperature ($T_{supply} \leq 60$ °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).

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:

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

Return media pipe:

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

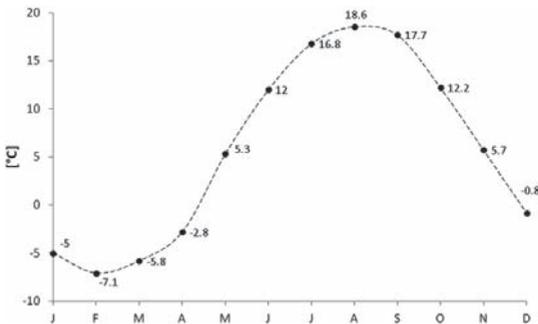


Fig. 6. Soil temperature in Ottawa at 1.0 m depth from the surface [31].

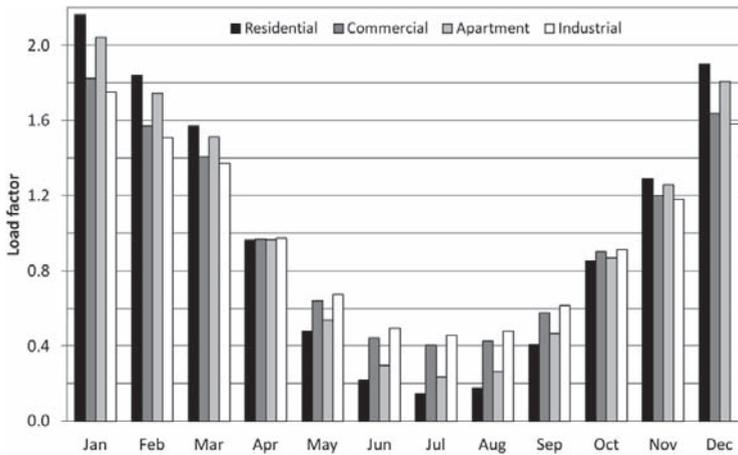


Fig. 7. Monthly heat load factors used in the annual energy simulations.

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.

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

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

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

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.

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

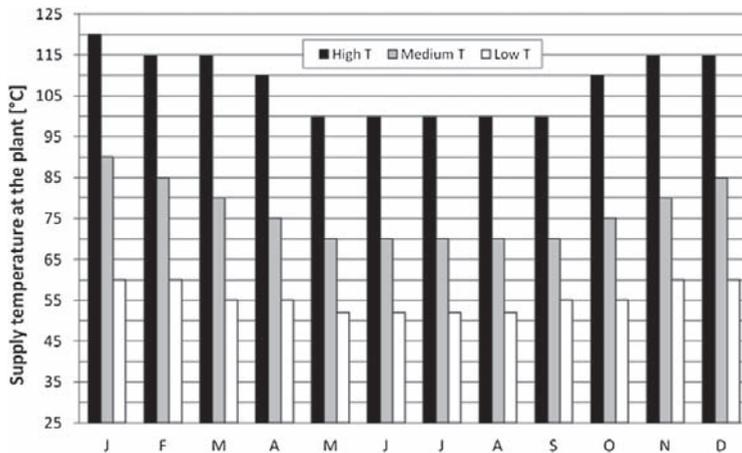


Fig. 8. Variation of the supply temperature during the year, at the heating plant, in case of high-, medium- or low-temperature operation.

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	
	Single		1, 2 and 3	16–28	85	95	10
PEX	Single	1, 2 and 3	20–110	85	95	6	
	Twin		1, 2	16–50	85	95	6
	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:

$$S(N) = 0.62 + 0.38/N \quad (7)$$

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]:

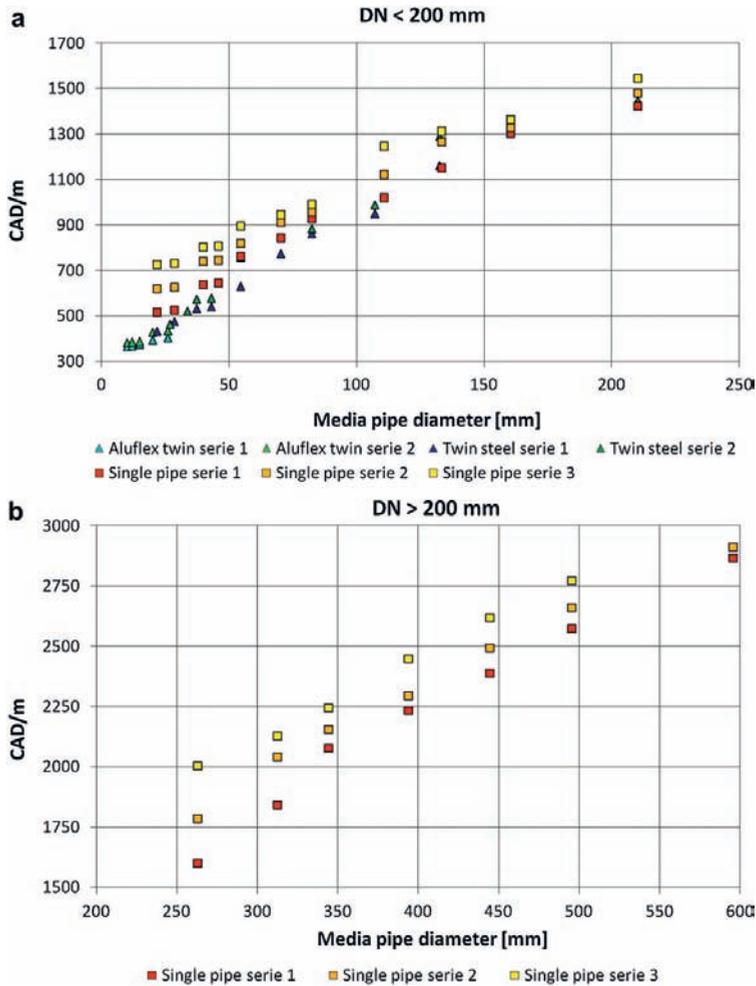


Fig. 9. Specific net present cost for single and twin pipes in a highly-dense urban area in Ontario, Canada; a) single and twin pipes with DN < 200 mm; b) single pipes with DN > 200 mm.

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

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/(m² 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.

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

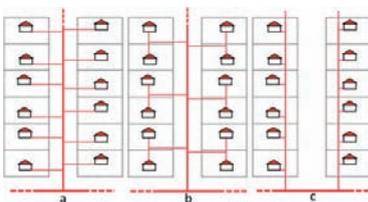


Fig. 10. Sketch of possible designs of service pipelines: a) traditional; b) “T-connection”; c) “house-to-house”.

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

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 [GWh/yr]	Pipeline system	Material	Insulation	Heat loss [MWh/yr]	Investment cost [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/Alulflex	Series 1	205.6	1.151
		Steel/Alulflex	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/Alulflex	Series 1	735.2	4.155
		Steel/Alulflex	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

design operational temperature, according to the definition of HTDH, MTDH and LTDH of chapter 2.3.

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 choose 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	A	B	C	D	E	F	G
	T [°C]							
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-term 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

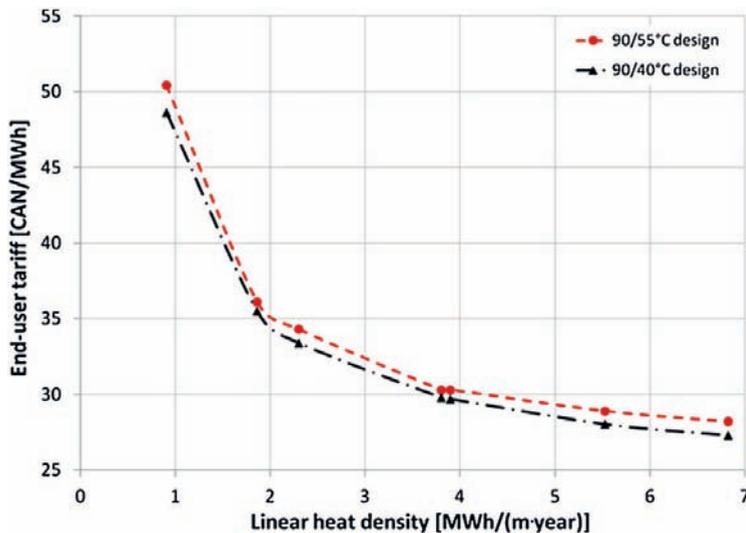


Fig. 11. End-user tariffs as function of the linear heat density.

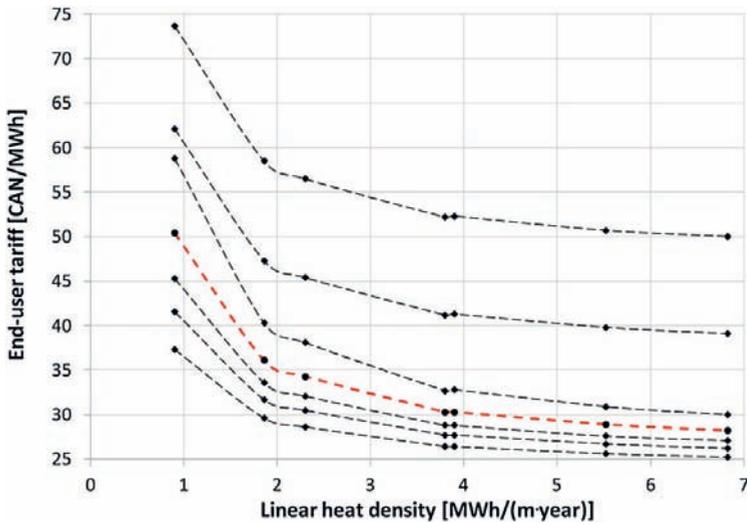


Fig. 12. Sensitivity of the end-user tariff to economic parameters, network investment costs and energy costs. The reference curve (red, dotted line) corresponds to the case with 90/55 °C design temperatures (For interpretation of the references to color in this figure legend, the reader is referred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

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 $\times 10^6$]		
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.

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.

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

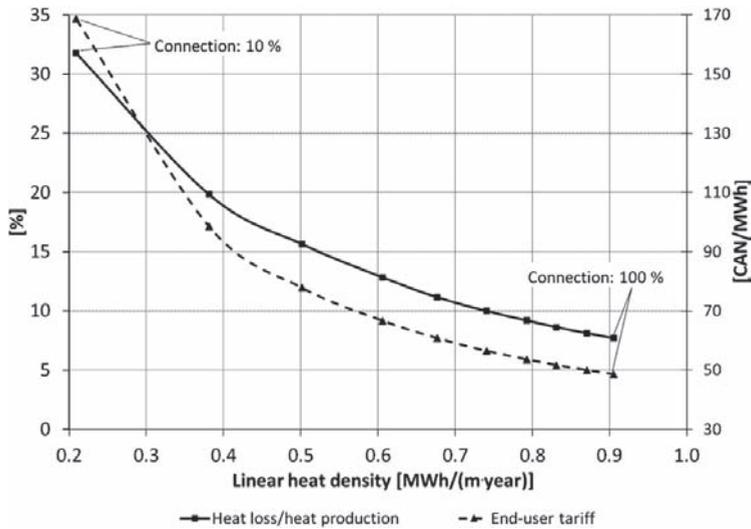


Fig. 13. Degree of connection in the single-family house settlement (area 2, case C). Energy performance and specific network investment cost as functions of the linear heat density. Heat production at 100% connection rate: 8.81 GWh/yr; trench length at 100% connection rate: 9736 m.

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_{supply}/T_{return} [°C] (zone 2)	Heat loss [MWh/yr]	Pumping [MWh/yr]	$T_{return,plant}$ [°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.

References

- Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems – the case of Denmark in years 2030 and 2050. *Energy* 2009;34(5):524–31.
- Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. *Applied Energy* 2011;88(2):479–87.
- Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg municipality based on low-temperature geothermal heat, wind load and biomass. *Energy* 2010;35(12):4892–01.
- Lund H. Renewable energy strategies for sustainable development. *Energy* 2007;32(6):912–9.
- Lund H, Möller B, Mathiesen BV, Dyrrelund A. The role of district heating in future renewable energy systems. *Energy* 2010;35:1381–90.
- Persson U, Werner S. Heat distribution and the future competitiveness of district heating. *Applied Energy* 2011;88:568–76.
- Torio H, Schmidt D. Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis. *Energy and Buildings* 2010;42:1601–9.
- Improvement of operational temperature differences in district heating systems. IEA-DHC Annex VII 2005. Available at, www.iea-dhc.org; January 2012.
- Optimization of district heating systems by maximizing building heating system temperature difference. IEA-DHC Annex VI 2002. Available at, www.iea-dhc.org; January 2012.
- Efficient substations and installations. IEA-DHC Annex IV 1996. Available at, www.iea-dhc.org; January 2012.
- Improved cogeneration and heat utilization in DH networks. IEA-DHC Annex VIII 2008. Available at, www.iea-dhc.org; January 2012.
- Lin F, Yi J. Optimal operation of a CHP plant for space heating as a peak load regulating plant. *Energy* 2000;25(3):283–98.
- Hepbasli A. A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs). *Energy Conversion and Management* 2010;51:2041–61.
- Exergy evaluation of space-heating options. *Energy* 1993;18(7):779–90.
- Li Y, Fu L, Zhang S, Jiang Y, Xiling Z. A new type of district heating method with co-generation based on absorption heat exchange (co-ah cycle). *Energy Conversion and Management* 2011;52:1200–7.
- Linderberger D, Bruckner T, Groscurth HM, Kummel R. Optimization of solar district heating systems: seasonal storage, heat pumps, and cogeneration. *Energy* 2000;25:591–608.
- Optimisation of operating temperatures and an appraisal of the benefits of low temperature district heating. IEA-DHC Annex V 1999. Available at, www.iea-dhc.org; January 2012.
- Dalla Rosa A, Li H, Svendsen S. Method for optimal design of pipes for low-energy district heating, with focus on heat loss. *Energy* 2011;36(5):2407–18.
- Dalla Rosa A, Christensen JE. Low-energy district heating in energy-efficient building areas. *Energy* 2011;36:6890–9.
- Dalla Rosa A, Li H, Svendsen S. Modelling transient heat transfer in small-size twin pipes for end-user connections to low-energy district heating networks. Accepted in *Journal of Heat Transfer Engineering* 2012.
- Olsen PK, Lambertsen H, Hummelshøj R, Bøhm B, Christiansen CH, Svendsen S, et al. A new-low-temperature district heating system for low-energy buildings. 11th International symposium on district heating and cooling. Reykjavik; 2008.
- www.canmetenergy-canmetenergie.nrcan-rncan.gc.ca; May 2012.
- Energy policies of IEA countries – Canada. IEA; 2009. 2009 review.
- An action plan for growing district energy systems across Canada. CDEA/ACRT; 2011. Available at, www.cdeca.ca; May 2012.
- Energy prices and taxes, quarterly statistics. IEA; 2011. second quarter.
- Private communication with Mr. Michael Wiggin, PWGSC (Public Works and Government Services Canada), July 2011.
- www.arcon.dk/produkter/HT-solfangere.aspx; May 2012.
- www.sunmaxxsolar.com; May 2012, www.rittersolar.de; May 2012.
- Winkens HP. Economic outgoing temperatures in DH supply. *Fjernvarme International yearbook*; 1988.
- Li H, Svendsen S. Energetic and exergetic analysis of low and medium temperature district heating network integration. 2nd International exergy, life cycle assessment, and sustainability workshop & symposium, 2011, Nisyros, Greece.
- EnergyPlus software, online material. US Department of Energy. Available at, www.eere.energy.gov; May 2012.
- 2008 Commercial & institutional consumption of energy survey summary report. Natural Resources Canada. Available at, www.oee.nrcan.gc.ca/publications/statistics; 2011.
- Energy use data handbook 1990–2008. Natural Resources Canada. Available at, www.oee.nrcan.gc.ca/publications/statistics/cices08/12010; 2011.
- Optimisation of operating temperatures and an appraisal of the benefits of low temperature district heating. International Energy Agency; 1999.
- www.logstor.dk; May 2012.
- Wallentén P. Steady-state heat loss from insulated pipes. Lund: Department of Building Physics; 1991.
- Bøhm B. On transient heat losses from buried district heating pipes. *Int J Energy Research* 2000;24:1311–34.
- Kulvertkostnadskatalog (“Culvert cost catalog”, in Swedish), 1. Swedish District Heating Association; 2007. Report.
- Paulsen O, Fan J, Furbo S, Thorsen JE. Consumer unit for low-energy district heating net. 11th International symposium on district heating and cooling. Reykjavik; 2008.
- Brand M, Dalla Rosa A, Svendsen S. Performance of low-temperature district heating systems for low-energy houses. The future for sustainable built environments with high-performance energy systems conference. Munich; 2010.
- Thorsen JE, Kristjansson H. Cost considerations on storage tank versus heat exchanger for hot water preparation. Presented at: 10th International symposium on district heating and cooling 2006, Hannover, Germany.
- District heating distribution in areas with low heat demand density. IEA-DHC Annex VIII 2008. Available at, www.iea-dhc.org; January 2012.
- Canadian crude oil, natural gas and petroleum products: review of 2009 & outlook to 2030. Natural Resources Canada, ISBN 978-1-100-16436-6; 2011.
- Comparison of electricity prices in major North American cities. Hydro Quebec, ISBN 978-2-550-59432-1; 2010.
- Zinko H, Bøhm B, Kristjansson H, Ottosson U, Rama M, Sipilä K. District heating distribution in areas with low heat demand density. International Energy Agency; 2008.

Appendices

Appendix A

Low-temperature District Heating System in Lystrup, Denmark.

Appendix B

The Heat Plan for a Carbon-Neutral City. The case of Aarhus, Denmark.

Appendix C

Matlab Code for Calculation of Transient Heat Transfer in Small-Size District Heating Pipes.

APPENDIX A

**Low-temperature District Heating System
in Lystrup, Denmark.**

Low-temperature District Heating System in Lystrup, Denmark

General description

Title of the project

Low-temperature district heating network for newly-built low-energy single family-houses in Lystrup, Denmark.

Project background and objectives

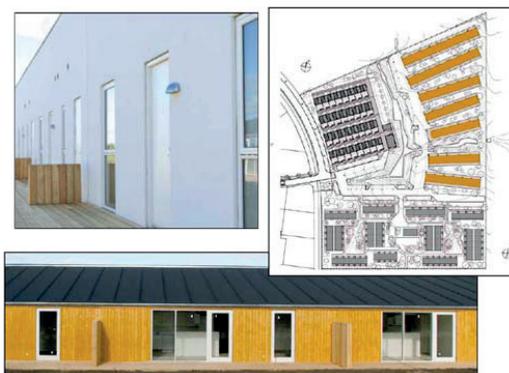
The project deals with the integration of sustainable solutions both for the end-user side and the energy supply side and aimed at:

- Demonstrate the technical and economical feasibility of District Heating (DH) applied to low-energy buildings and that the heat loss in the network can be maintained below 15-20% of the total delivered heat.
- Test two designs of low-temperature DH substations.
- Evaluate the simultaneity of the heat demand in case of low-energy buildings.

General information	
Country	Denmark
City	Lystrup, Århus
Heating degree days ¹	4568
Specific information	
Project initiator /leader	Housing Association Ringaarden
Year of construction/energy renovation	2008-2009 (new construction)
Site area [ha]	1.7
Building units (residential)	40 terraced houses
Number of residents	92 (estimated)
Building units (tertiary)	1 common building
Heated area [m ²]	4115
Plot ratio ²	0.24

¹ (base temperature: 20°C)

² built floor area/site area



The terraced houses in Lystrup, Denmark and their spatial layout.

Technical description

Heat demand

The Danish Building Regulation 2008, later superseded by the Building Regulation 2010, sets the maximum building primary energy demand for new constructions. There are separate targets for residential building (SH, DHW and the electricity use to the related installations, but not including lighting) and non-residential buildings (including lighting). The requirement in residential building is defined as follow:

$$E = 70 + 2200/A \text{ [kWh/(m}^2\cdot\text{yr)]}$$

where E is the maximum annual primary energy demand and A is the gross heated area [m²]. The energy requirements also include two classes of low-energy buildings, whose energy demand limit is calculated as follow:

$$\text{Low-energy class 1: } E = 35 + 1100/A \text{ [kWh/(m}^2\cdot\text{yr)]}$$

$$\text{Low-energy class 2: } E = 50 + 1600/A \text{ [kWh/(m}^2\cdot\text{yr)]}$$

The settlement in Lystrup consists of 40 low-energy class 1 terraced houses and a low-energy class 2 building. The calculated primary energy use for SH was 30 kWh/(m²·year). The insulation thickness of the building envelope is as follows: roof, 450 mm; external walls, 335 mm. The U-value of the window is 1.1 W/(m²K). The layout of dwellings consists of seven blocks of houses, divided in 2 size categories: size C1 (87 m²) and size C2 (110 m²), see the table below.

Block number	Total size [m ²]	Number of dwellings	
		Type C1	Type C2
1	771	5	3
2	727	2	5
3	594	3	3
4	528	1	4
5*	479	1	2
6	484	3	2
7	532	6	0

* Including the common building, 170 m², low-energy class 2

Peak power [kW]	116 (measured)
Total heat demand [GJ/yr]	66 (measured)
Specific heat demand (expected from calculations)	
Specific space heating demand [kWh _{th} /(m ² ·yr)]	30
Specific domestic hot water demand [kWh _{th} /(m ² ·yr)]	13.1*
Total [kWh_{th}/(m²·yr)]	43.1
Specific heat demand (calculated from measurements)	
Specific space heating demand [kWh _{th} /(m ² ·yr)]	50.4 (derived)
Specific domestic hot water demand [kWh _{th} /(m ² ·yr)]	7.6
Total [kWh_{th}/(m²·yr)]	58

* Based on DHW use of 250 m³/m² and ΔT=45°C, as suggested by the Danish reference software Be06

Building installations

Space heating installations

The building installations, in terms of heating system, consist of a combination of radiators and floor heating. The housing type C1 has got 4 radiators and the housing type C2 has got 5 radiators, which were chosen based on design supply/return temperature of 55/25°C. All the bathrooms are equipped with floor heating.

Characteristics of the radiators installed in the buildings.

Length [mm]	C1: design power [W]				C2: design power [W]				Common house: design power [W]			
	70/40*	60/30	55/25	50/25	70/40	60/30	55/25	50/25	70/40	60/30	55/25	50/25
400	396	254	189	158	396	254	189	158				
500					495	317	236	198				
600	594	381	283	237	594	381	283	237				
800									792	507	378	317
1000	990	634	472	396					990	634	472	396
1400					1386	888	661	554				
1800	2032	1296	962	805					2032	1296	962	805
2000									4516	2880	2137	1788
2200					2484	1584	1176	963				
Tot. [W]	4012	2565	1906	1596	5354	3423	2545	2131	8329	5318	3949	3305

* Supply/return temperature [°C]

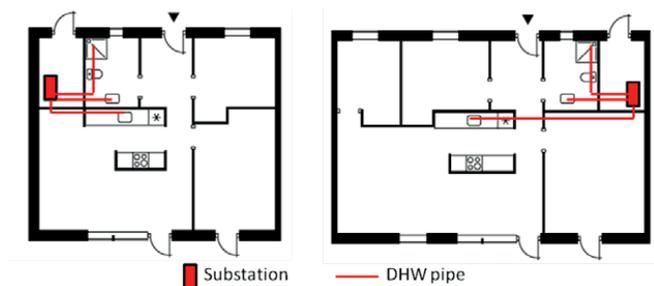
Note: the height of the radiators is 555 mm. The design indoor temperature is 20°C.

Domestic hot water installations

The DHW is prepared by one of the low-temperature DHW systems described in [1]: the low-temperature Instantaneous Heat Exchanger Unit (IHEU) and the low-temperature District Heating Storage Unit (DHSU).

Domestic hot water distribution

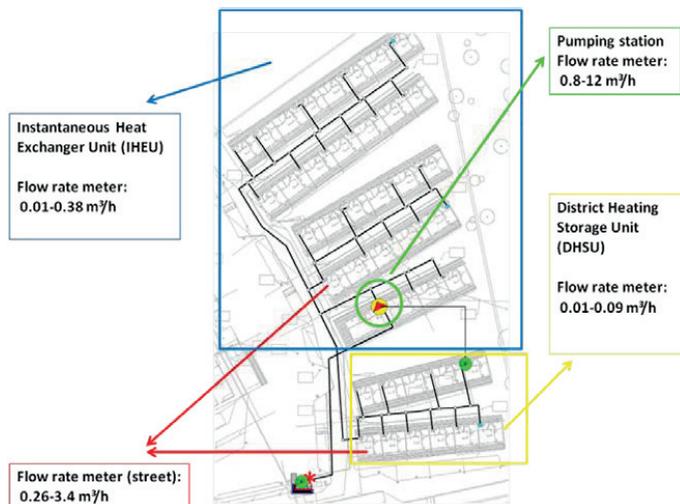
The layouts of the DHW distribution pipes and the floor plan of the dwellings were carefully designed, so that there is a separate pipe supplying each DHW fixture and the length of the pipe is minimized. Consequently, the water content in each DHW supply line, including the volume in the secondary side of the DHW heat exchanger, is kept to a minimum and it is below 3 L: this is the maximum allowable water content that assures safety in relation to the Legionella risk, even without any treatments (thermal, UV-rays or chemical), according to the German guidelines for DHW systems (DVGW, W551).



Floor plan and layout of the DHW distribution pipelines. Types: C1 (left), C2 (right).

Heat distribution network

A sketch of the DH network with the location of the main flow meters during the monitoring project is shown here below. Moreover, temperature and flow sensors were placed in each of the in-house substations, as well.



Sketch of the DH network with the location of the meters.

The main characteristics of the network and the design operating temperatures are listed in the table below.

Trench length [m]	767
Linear heat density [kWh/(m·yr)]	0.31
Average T_{supply} [°C] (heating season) ¹	55 (design value)
Average T_{return} [°C] (non-heating season) ²	25 (design value)
Average T_{supply} [°C] (heating season)	55 (design value)
Average T_{return} [°C] (non-heating season)	25 (design value)

¹ In Denmark, 1st November – 30th April

² In Denmark, 1st May – 31st October

Network Dimensioning

The network consists of flexible plastic twin pipes for dimensions up to DN32 and of steel twin pipes for larger dimensions. Heat loss coefficients are calculated according to [2].

Pipe specifications. Alx: Aluflex twin pipes; Tws: Steel twin pipes.

	Inner diameter [mm]	Heat loss coefficients [W/(m ² K)]		Roughness [mm]	Length [m]	Estimated cost in 2010 [€/m]	
		U ₁₁ =U ₂₂	U ₁₂ =U ₂₁			Purchase	Total
Alx 14/14-110	10	0.05	0.035	0.02	123	47	162
Alx 20/20-110	15	0.065	0.037	0.02	221	56	166
Alx 26/26-125	20	0.071	0.049	0.02	155	67	207
Alx 32/32-125	26	0.088	0.053	0.02	130	78	211
Tws-DN 32	37.2	0.085	0.056	0.1	90	82	240
Tws-DN 40	43.1	0.099	0.053	0.1	32	88	246
Tws-DN 50	54.5	0.096	0.06	0.1	16	122	268

The other assumptions for the design were:

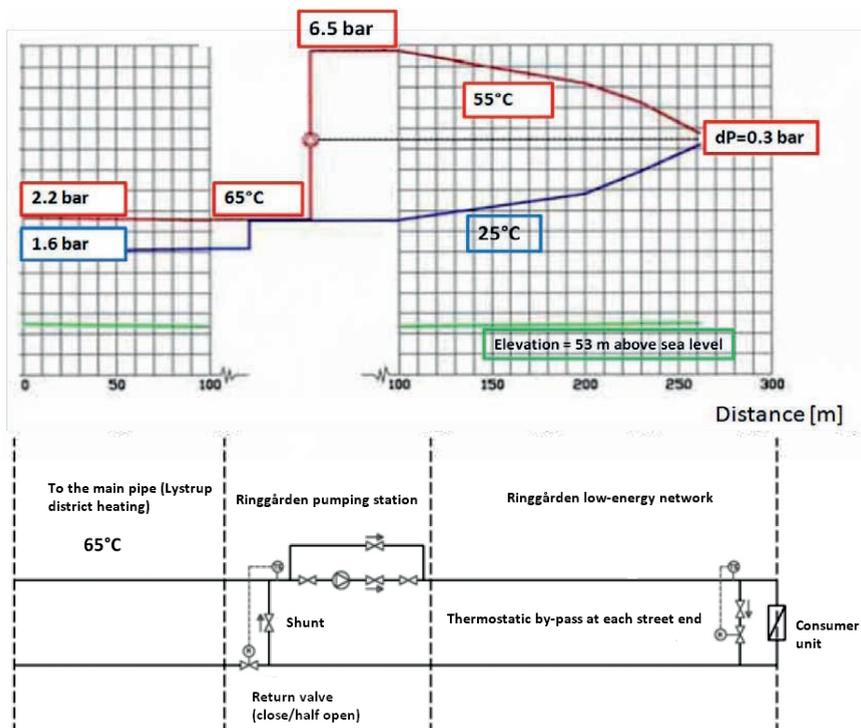
- Maximum pressure level: 10 bar. It is reasonable to design the network according to the maximum hydraulic load that can be withstood by the distribution pipeline; in the case the limit is drawn by the plastic service pipes, which requires pressure levels below 10 bar. In fact the pipeline systems must by regulations withstand pressures 1.2-1.5 times the nominal value. Moreover, the duration of peak load situations is marginal, e.g. generally below 300 h/yr.
- Thermostatic bypass valves set to 40°C, in the customer's substation at the end of each street line and set to 35°C, in all the other customers' substations.
- Design supply temperature from the heat source: 55°C; design return temperature: 25°C.
- Maximum water velocity: 2.0 m/s in distribution pipes.
- Maximum pressure loss gradient in service media pipes: 1500 Pa/m.
- Minimum supply/return pressure difference at the end-user's substation: 0.3 bar.

Heat sources

The distribution network in this case study is a typical example of how a low-temperature DH scheme can be integrated to an existing network at higher operating temperature. There are no heat sources on the site, being the heat provided directly from the main municipal, medium-temperature DH system. The water flow at low supply temperature comes from a mixing shunt, where the water coming from the existing DH network in Lystrup is mixed with the return flow from the local network.

The facility is placed in the common house together with the pumping station. The performance of the mixing loop is controlled by a temperature sensor in the main supply pipe to the local network. Such temperature sensor controls a valve in the return line of the same network. The valve closes the return flow to the existing

network and increases the amount of water that is mixed with the supply line, until the set temperature is reached. The system is shown in the figure.



Simplified pressure/temperature diagram of the mixing shunt.

Special R&D topics/issues

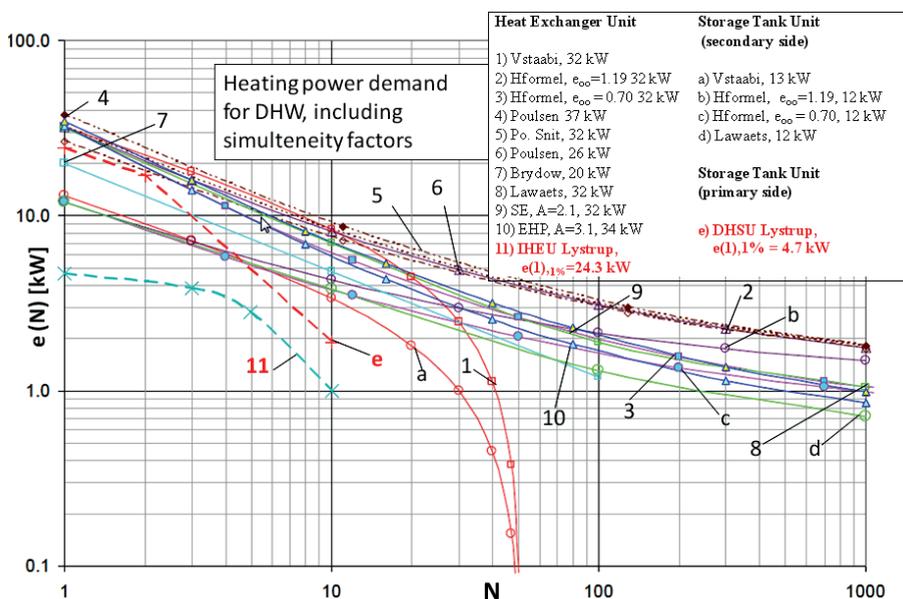
Heat demand simultaneity and simultaneity factors

During the planning processes the simultaneity factors considered derived from engineering practice in existing networks and buildings belonging to the building stock. The simultaneity factor was assumed to be 1.0 in case of DHSU, due to the low semi-constant flow the unit was designed for. The simultaneity factor for the IHEU depended on the number of consumers instead, according to the table below.

Simultaneity factors for IHEU vs. number of consumers

Number of consumers	Simultaneity factor	Number of consumers	Simultaneity factor	Number of consumers	Simultaneity factor
1	1.00	5	0.39	9	0.28
2	0.66	6	0.34	10	0.25
3	0.56	7	0.31	20	0.19
4	0.47	8	0.30	30	0.12

There are not any simultaneity factors that have been consolidated by experience for areas with low-energy buildings. Hence, the measurements carried out during the project provide an improved method for designing DH networks in such areas.



Based on the monitoring data, curves were drafted for the simultaneity factor up to 10 users, both for the case with IHEU and the case with DHSU. The parameter $e(1)$ corresponds to the heat power of one consumer and was determined to be 4.7 kW for the DHSU case and 24.3 kW for the consumers with IHEU. The parameter $e(1)$ for the case with IHEU is lower than what is usually used in the design, e.g. 32.3 kW in Denmark. On one hand, this result must be seen in relation to the housing type and inhabitants behaviors. On the other hand, the analysis points at the fact that the dimensioning of DH systems need a better basis for simultaneity factors and that in future a greater consideration must be given to the installations types, for the calculation of the optimal size of the heat distribution system.

Planning principles and implementation strategies

Applied energy models/tools

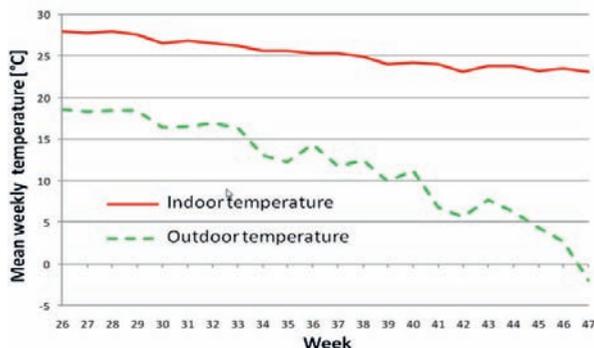
The design and simulation of the network was carried out with the commercial software Termis.

Tools used for energy monitoring

An extensive monitoring program was established; the measurements were conducted during the weeks 26-47, 2010.

Energy demand and operating temperatures

The measurements of the indoor temperature in individual homes suggest that a room indoor temperature of at least 22°C should be assumed in the calculation of the heating demand of low-energy buildings.



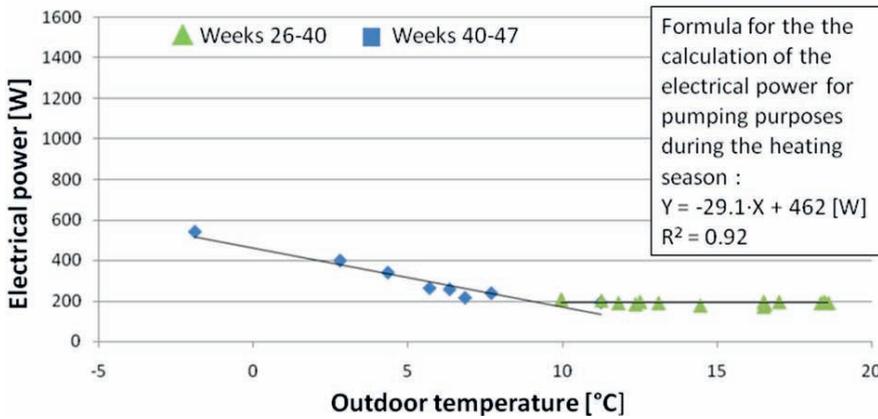
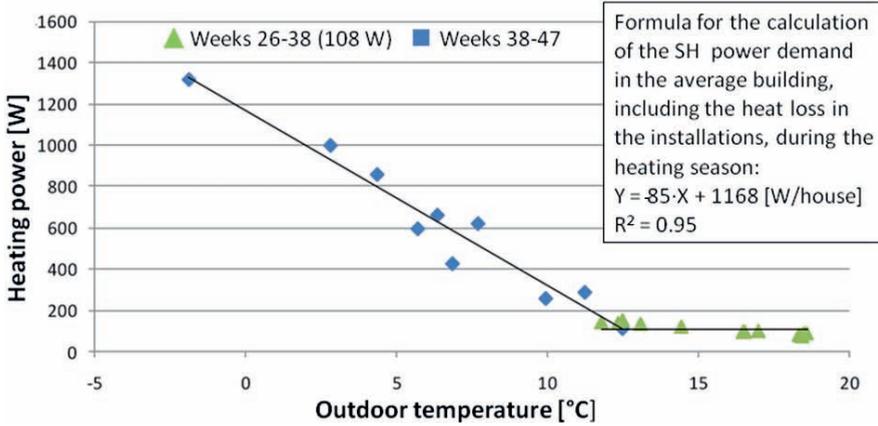
Outdoor temperature and mean weekly indoor temperature in the 41 buildings.

Based on the measurements in the monitoring period, the average annual heating demand per dwelling was estimated to be approximately 5.8 MWh for the reference year, corresponding to a measured heat density of 0.31 MWh/m and a heat density of 14 kWh/m². The analysis of the measurements of the actual heat demand show that in the case considered there is a higher heat use for SH than expected. The main reason is that the indoor temperature was kept in average 2-3°C above the set point temperature of 20°C.

The results show that it is possible to supply the customers with a supply temperature to the customers of approximately 50°C, with a 56°C supply temperature at the shunt site, at maximum.

The average DHW use was measured to be 65 L/(day·house). It is a low value, which is probably related to the number of occupants and their composition (mainly senior persons). Based on an estimation of the number of residents in the dwellings, it is assessed that the DHW use was equivalent to approximately 28 L/(day·person). It should be noticed that the average cold water temperature was 15°C and the average DHW temperature was 40-45°C, giving an average temperature difference of 25-30°C. Literature's estimates suggested instead an average DHW use of 30-40 L/(day·person) and a temperature difference of approx. 40°C, values that in the case study would give an expected heat demand for DHW of 11.8-15.8 kWh/(m²·yr).

The measures demonstrated that DHW can be produced at temperature of just 3°C below the primary supply temperature, e.g. 47°C at a DH supply temperature of 50°C. The average annual SH demand, the heat loss in the distribution network and the annual electricity use of the pump were calculated based on duration curves divided in 8 representative intervals and the data plotted in the figures below, which derived from the measurements.



The results are as follows:

- Total heat production: 287,211 kWh
- Heat demand: 238,070 kWh
- Heat loss: 49,141 kWh (17.1% of the total heat production)
- Electricity use: 2,585 kWh

The measured distribution heat loss is in line with the expected heat loss calculated in the design phase and comparable with the present share of the heat loss in the existing city-wide distribution network. The heat losses in the low-temperature network are approximately ¼ of the estimated heat loss in the case the design had followed the conventional design practice (80/40°C). The electricity use for pumping was estimated to be 2,600 kWh/yr and equivalent to 9 kWh_{el}/MWh_{th}. This is comparable with the electricity demand for pumping purposes in existing well-established systems, being the average electricity demand for pumping in the Danish DH systems 9.9±6.7 kWh_{el}/MWh_{th}. According to the design method, it was expected to measure a greater pumping demand; the lower electricity use for the pump is explained in

practice by the fact that the pressure levels in the network were still well below the limits set. This points that there is room for optimizing the network design method, so that the heat loss can further decreased, at expenses of an additional, but less significant from the primary energy point of view, pumping demand. In the 11 homes with DHSU, the average return temperature was 39.4°C in the weeks 26-47; in summer – weeks 26-38 – the average return temperature was 43.6°C. The high return temperature was primarily due to the malfunction of a single unit. The best performing DHSU registered a return temperature of 29°C in summer. In the 11 homes with IHEU, the average return temperature was 34.7°C in the weeks 26-47; in summer – weeks 26-38 – the average return temperature was 40.3°C. The high return temperature was primarily due to 2 units, where the control valves were defected and allowed a relative large amount of supply water to flow to the return pipe. The best performing IHEU registered a return temperature of 26°C in summer.

The results demonstrate that it is possible to guarantee very good operation, but it is very important to obtain the proper functioning in each substation, otherwise unacceptable return temperatures result.

In general, the return temperature in the heating season (week 39-47) was lower than in the heating season, which confirms that the radiators delivers low return temperatures (28-33°C). This occurred although the indoor operative temperatures during operation (22-23°C), which were higher than the design conditions (20°C) set a higher limit to the minimum achievable return temperature.

Overall, the demonstration project showed that the concept works, and that is confirmed by the fact that there were no complaints from residents about the lack of heat or DHW.

Cost figures

The Danish Energy Authority financed the projects [1] and therefore funds were made available for R&D purposes and partly covered the investment costs for designing and implementing the low-temperature DH network.

Costs for the low-temperature DH network and related installations.

Item	Costs (2010)		
	[€/m]	Nr. of unit	Total
Pipes*	120		65,000
Pipe fittings*	32		17,000
Pipe laying**	131		100,500
DHSU*		3,700	41,000
IHEU*		2,600	78,000
Unit installation**		1,000	41,000
Pump + frequency controller*		2,400+2,000	4,400
		Total Cost	346,900

* Real cost in the project

** Calculation cost from national average data in Denmark

SWOT Analysis

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin	<p><i>Strength</i></p> <ul style="list-style-type: none"> - Low-temperature operation - Use of advanced technologies (prototypes) - Vicinity to an existing medium-temperature DH network 	<p><i>Weakness</i></p> <ul style="list-style-type: none"> - Constant supply temperature during the year (no supply temperature boost during peak loads) - Use of advanced technologies (prototypes) - Failure in the functioning of some substations - Insufficient or no insulation of the substations and connection pipes
External origin	<p><i>Opportunities</i></p> <ul style="list-style-type: none"> - Construction of the DH network in parallel with the buildings - Involvement of best available expertise - R&D funds from the Energy Authority 	<p><i>Threats</i></p> <ul style="list-style-type: none"> - No heat zoning in case of settlements with low-energy buildings - Limitations in the amount of investments available for the project

Conclusions and lessons learnt

The demonstration project of a low-temperature DH network for low-energy buildings shows that the concept works. The results show that it is possible to supply the customers with a supply temperature of approximately 50°C and satisfy both the SH requirements and the safe provision of DHW. This fact is confirmed by the fact that there were no complaints from residents about the lack of heat or DHW. The energy efficiency target was met, being the distribution heat loss equal to 17% of the total heat production.

The duration of the non-heating season is longer in low-energy buildings than in existing buildings. This points that the importance of operation of the network during periods with use of bypass flow is more critical and as therefore a relatively larger impact on the energy performance of the system than in traditional systems. This is strengthened by the fact that in low-energy buildings it is expected that the heat demand for DHW could generally be comparable to the demand for SH. Nevertheless, the measures in the case study points that the users' behavior strongly affects the heat demand structure.

In DH networks of this kind, serving low heat density areas with no possibilities for future expansion, the design should envisage the exploitation of the maximum pressure that can be withstood by the media pipes. The network design method can thus be optimized, so that the distribution heat loss can significantly decreased, at expenses of an additional, but less significant, pumping demand.

The analysis points at the fact that the dimensioning of DH systems need a better basis for simultaneity factors and that a greater consideration must be given to the operation of the SH and DHW installations, for the calculation of the optimal size of the heat distribution system.

The results demonstrate that it is possible to guarantee an energy-efficient operation, but it is very important to obtain the proper functioning in each substation, otherwise unacceptable return temperatures result.

In the case considered, the heat losses from the area with DHSUs are marginally lower than in the area with IHEUs. The sum of the distribution heat loss and the heat loss from the substations is marginally larger for the case with DHSUs than for the case with IHEUs, because the additional heat loss due to the storage tanks more than counteracts the reduction of the distribution heat loss. On the other hand, in areas with hydraulic limitations, such as outer urban areas, DHSUs offer in turn some advantages, thanks to the lower peak pressure requirements. Moreover, the smallest media pipe diameters of the house connection pipes in the market have still a valuable water flow overcapacity and this suggest that smaller volume of the storage tank can be chosen and this would reduce the substation heat loss. The conclusion is that there is no superior substation concept, but the best system should be chosen taking into account the specific characteristics of the site and of the demand.

The DHSU should be well insulated, in particular if they are placed in a room that is not provided with a ventilation system with heat recovery. In fact, the heat loss from the unit must not be neglected.

References

- [1] Udvikling og demonstration af lavenergifjernvarme til lavenergibyggeri (Development and demonstration of low energy district heating for low energy buildings, in Danish); Energystyrelsen, 2009.
- [2] Wallentén P. Steady-state heat loss from insulated pipes. Lund: Department of Building Physics; 1991.
- [3] CO₂-reductions in low-energy buildings and communities by implementing low-temperature district heating systems. Demonstration cases in energyflexhouse and boligforeningen Ringgården. Danish Energy Agency, 2011.

APPENDIX B

The Heat Plan for a Carbon-Neutral City.

The case of Aarhus, Denmark.

Subtask C – Part I

Implementation Strategies for Municipalities

1. General information

General information	
Country	Denmark
City	Aarhus
Population (City)	311000 (December 2010)
Heating degree days (HDD 18/15)	3180

2. Target definition

Aarhus CO₂-neutral in 2030

In 2007 the City of Aarhus set the political goal to become CO₂-neutral by 2030. This is the objective for Aarhus, as one of the six official “EcoCities” in Denmark, the others being Skive, Kolding, Copenhagen, Herning and Albertslund. With this title the City of Aarhus has achieved an official seal of approval, verifying that the city’s contribution to the climate challenge is well-reflected, future-proof and ambitious to such an extent that it makes the city stand out from others plans. The city has been working with climate issues for a number of years, by means of environmental action plans, energy management systems, wastewater plans, green accounts and environmental appraisal of construction projects. Furthermore, Aarhus is one of the leading cities in Denmark when it comes to the district heating supply (among other things, a result of an efficient waste incineration system), public transport possibilities and extensive cycle path system. The City of Aarhus has committed itself to CO₂ reduction through several national and international agreements in 2009:



- The City of Aarhus was the first Danish city to sign the European Covenant of Mayors. This means that Aarhus has to reduce its energy use with more than 20% before 2020.
- The City of Aarhus entered into a Curve Breaker Agreement with the Danish Electricity Saving Trust for a four year period (2009-2012). This means that Aarhus has to reduce the annual electricity consumption of the municipal buildings with at least 2%/yr.
- The City of Aarhus signed an agreement with the Danish Society for Nature Conservation to become a so-called Climate Community. Among other things this means that Aarhus is obligated to reduce CO₂ emissions by 2% each year until 2030.

Approach: Implementation by phases, mainly following a fore-casting approach (from input to output)

-) PHASE 1: set the goal and the vision
-) PHASE 2: analysis of the potential and definition of the climate target, with regards to the quantitative target and the time frame
-) PHASE 3: Implementation. The climate plan for the City of Aarhus consists of several generations of climate plans reaching towards 2030. The plans have generally a 2-year perspective in order to guarantee progress, adjustment and evaluation. The climate plans are versatile, and they priorities' and coordinate across the municipal organization, the business community and educational institutions.

3. Implementation strategy

The Municipality is the initiator of the 2030 target and of many projects. The Department of Engineering and Environment has the responsibility for having the executive and organizing role. The Climate Secretariat carry out campaigns and information events and it is responsible for the website www.co2030.dk.

Climate Plan 2008-2009

Table 1: Overview of projects launched by the Climate Plan 2008-2009.

The projects launched by the Climate Plan 2008-2009, are projects that the City Council chose to start to gain new insights and knowledge. Projects have led to a quorum and readiness in relation to choosing the projects to be launched with the second generation of the climate plan, the Climate Plan 2010-2011.		
Project title	Total budget [million DKK]	Result
Topic: Urban Development		
There is no separate economy linked to the operations area in the Climate Plan 2008-2009. The focus area is addressed through the Municipal Plan 2009 and local planning. Work continued in 2010-2011.		Climate is incorporated in the municipal plan "City Council Resolution on the requirement for low-energy use in local plans".
Topic: Buildings		
Energy Efficient municipal construction and renovation of municipal buildings and district heating supply	2.5	Analysis and knowledge development
Energy efficient new construction of municipally owned land: competition project	1.0	EUROPAN10-architectural competition.
The focus area is also supported through demonstration projects in energy efficient new buildings, in land not municipally owned.		Knowledge development and demonstration.
Topic: Heat		
There is no separate economy linked to the operations area in the Climate Plan 2008-2009. The focus area is addressed through the "Climate Heating Plan - CO ₂ neutral district heating".		Launching the "Climate Heating Plan - CO ₂ neutral district heating".
Topic: transport, cycling		

Cyclist Town - tools and concrete action	3.5	Accounting of bicycle use
Topic: rural areas		
Opportunities in rural areas	0.5	Knowledge development and demonstration.
Topic: Local procurement		
There is no separate economy linked to the operations area in the Climate Plan 2008-2009. the focus area.		
Topic: Civic engagement, information, guidance and campaigns		
Information campaigns	1.7	Website: www.CO2030.dk and events.
Topic: Climate Secretariat		
Climate Secretariat	1.5	Climate Plan and CO ₂ mapping.
Total	10.7	

Climate Plan 2010-2011

Table 2: Overview of projects launched by the Climate Plan 2010-2011 (bold numbers: projects already financed).

Project No.	Project title	Total [million DKK]	2009	2010	2011	2012	2013
Topic 1: Urban Development. There is no separate economy linked to the operations area in the Climate Plan 2010-2011. The focus areas are addressed through the Municipal Plan 2009 and local planning.							
Topic 2: Construction							
1	Model for CO ₂ -neutral residential districts	0.25 1.5		0.15 0.25	0.1 1.25		
11	Energy Management of Technology and Environment, Aarhus Municipality	2.8	1.0	1.8			
2	Municipal buildings	10.0 20.0		6.0 8.0	4.0 12.0		
Topic 3: Utilities - heat and electricity							
15	Intelligent electricity grid	0.5		0.5			
16	Innovative community solutions – district heating	0.5		0.5			
The focus area is addressed also by the “Heating Plan” and “City Plan 2009”.							
Topic 4: Transport							
3	Environmentally-friendly vehicles in Aarhus	3.0 2.0		1.0 0.5	1.0 1.0	1.0 0.5	
The focus area is also supported through the Collective Traffic Plan, the Bicycle Plan and the light rail project.							
Topic 5: Business							
8	Involvement of the private sector on climate and energy issues	8.3		0.5	3.8	2.0	2.0
9	Climate Package for production and business establishments	0.42			0.42		
The focus area is also supported by Aarhus Public Enterprise Action plan.							
Topic 6: R							
14	Forestation: 2009-2012	12.0		2.0	5.0	5.0	
There is no separate economy linked to the focus area in the Climate Plan 2010-2011. The focus area is							

addressed through the Forestation Plan and the Water and Nature Plan.						
Topic 7: Climate Change Adaptation						
10	Plan for adaptation to the floods	0.6 2.5		0.6	1.9	0.6
Topic 8: Local shopping						
12	Shopping area near Aarhus Municipality	0.8		0.2	0.6	
There is an agreement with an external partner to develop processes, procedures and agreements with emphasis on energy.						
Topic 9: Communications and Campaigns.						
4	Dissemination and climate campaigns	2.8		1.0	1.0	0.8
7	Project CO2030, 2010-2013	3.3		0.9	0.9	0.75
5	COP15 i Århus	0.6 0.4	0.3	0.3 0.2	0.2	
6	Energy efficiency in the heating sector	60.0	20.0	20.0	20.0	
13	Information to end users about their heat and electricity with IT	0.8		0.3	0.5	
17	“Climate employees” in Aarhus municipality offices	0.3		0.15	0.15	
Total	Climate Plan 2010-2011	90.25 43.12	21.3	32.85 11.0	30.1 23.72	6.0 5.65
						2.75

Climate Plan 2012-2015

The draft Climate Plan 2012-2015 was prepared by the Engineering and Environment Department of Aarhus municipality. Its final form will be the foundation of Aarhus Municipality's climate action after 2011. The climate plan focuses on the involvement of companies and knowledge institutions in the development of solutions that can handle the climate and energy challenge. The Climate Plan main themes prioritize: phase-out of fossil energy, energy efficiency in buildings, energy efficient transport, intelligent energy systems, and green technology export. The 9 focus areas are: energy supply, integration of wind, transportation, energy demand, energy purchasing and export, spatial planning, the rural area, adaptation to climate change. The Climate Plan 2012-2015 draft will be discussed during the stakeholder consultation period (summer 2011) and the revised version must be approved by the City Council.

Table 3: Overview of projects to be launched by the Climate Plan 2012-2015.

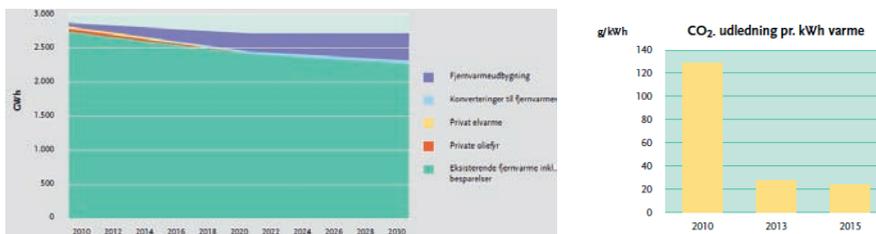
Focus area	Tot. per focus area [million DKK]	2012	2013	2014	2015
Energy supply	4	1.45	0.95	0.8	0.8
Integration of wind energy	5.8	1.6	1.4	1.3	1.5
Transport	3.7	1.9	1.1	0.45	0.25
Buildings	21.95	10.95	10.8	0.1	0.1
Energy use	3.4	0.85	0.75	0.9	0.9
Energy purchasing and export	1.15	0.500	0.25	0.2	0.2
Spatial planning	-	-	-	-	-
Rural areas	-	-	-	-	-
Adaptation to climate changes	1.6	1	0.2	0.2	0.2
Promotion of energy technology export	1.6	0.6	0.6	0.2	0.2
Climate secretariat and other costs	15.6	4.5	4.4	3.35	3.35
Climate plan 2010-2011	8.4	2.75	-	-	-
Total	58.8	26.35	20.45	7.5	7.5

Heat Plan Aarhus

The “heat plan” states that the heat supply shall be CO₂-neutral by 2030. In general there are plans of new residential areas and implementation of renewable energy in the district heating (DH) systems. The existing DH system is expected to be extended. Both new built areas and existing housing areas with natural gas or oil boilers will be connected. At the same time the existing pipe system is continually being upgraded with newer pipes and the DH distribution company (Affalvarme Aarhus) has focus on lowering the DH temperature. Affalvarme Aarhus has some energy saving initiatives levelled at the heat consumers and in cooperation with them:

- Guidance regarding DH installations and operation
- Subsidy for conversion from oil-fired boiler to district heating
- Subsidy to energy savings (improvement of buildings insulations, installations, etc.)

Affalvarme Aarhus is like other energy companies committed by the Danish legislation to carry out a certain amount of energy savings every year (either on network level or at the end-user level). The heat use is expected to increase by 195 GWh (at the main heat exchanger station) until 2030 as a result of the network extension. Further, it is expected that the conversion from individual natural gas and oil boilers will increase the heat consumption with 34 GWh until 2030. In the same period, the energy savings carried out are expected to exceed the increased heat consumption caused by the extension and conversions. So the total heat demand is expected to decrease. The heating forecast for the next 20 years is shown below.



Heating forecast for AVA based on the Danish Building Code 2010 (left). The CO₂-emission per produced kWh heat at the main heat exchanger (right).

The heat plan is consistent with the Climate plan and it is one of the pillars is built on. As result large amount of renewable energy supply and surplus heat resources will be applied. Affalvarme Aarhus is starting to look at the possibilities for heat production from solar energy, wind energy (coupled to a large-scale heat pump) and biogas. Also utilisation of surplus heat from industry in the harbour area is considered, while the plans of implementing biomass in the heat supply system is getting ready. The large Studstrup plant will be converted into a biomass plant, where wood pellets are used as fuel. Also a new biomass plant is planned to be built in Lisbjerg outside Aarhus, close to the present location of the district heating transmission line of the waste-to-energy

plant. This plant will be a straw burning plant. The implementation of biomass will result in significant reduction in the CO₂-emission for the heat supply. See the graph on this page.

Initiator: Aarhus Municipality

Knowledge management: Climate Secretariat, website: www.co2030.dk

4. Coordination

City Council

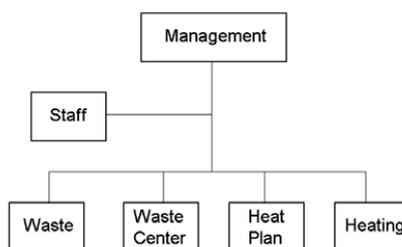
The overall administration of local government lies in the hands of the members of the City Council. The City Council determines its activity and service levels within a framework which is either laid down by law – e.g. legislation related to social welfare, the environment and schooling – or agreed with the central government on a voluntary basis. The local authorities set their own rates of taxation within limits defined by the Danish Parliament. The revenue raised by the local authorities is supplemented by government block grants and refunds for certain social-welfare costs. In Denmark, the central government undertakes approximately 30% of all publicly funded activities with local authorities undertaking approximately 45%: Danish local authorities play a larger role than their equivalents in any other European country. This gives them a great level of responsibility and many opportunities. Local authorities own administrative buildings, institutions, utilities, roads, residential accommodation, land etc. This property can be bought and sold at market value, but cannot be used as security for loans. Local authorities are not permitted to distort the free market by providing subsidies or undertaking production or any other commercial activity that competes with private-sector business. Some services are performed by the municipalities, but are fully paid for by the users, e.g. the supply of water and heat. As one of very few municipalities in Denmark, the City of Aarhus is run by a City Executive Board. The organizational management of the City of Aarhus is called the City Executive Board and consists of the mayor and the five aldermen who each head a municipal department. The aldermen are appointed on the basis of the share of votes obtained by each party in the city council election. This means that political disagreements may arise between an alderman and the political majority in the City Council. As opposed to the other councillors, the members of the City Executive Board are employed full-time to run the City of Aarhus. The City Executive Board prepares the meetings of the City Council and is thus responsible for recommendations to the City Council. The City Executive Board has the formal responsibility for implementing the decisions made by the City Council. In practice, the decisions are implemented by the relevant municipal departments, which have the professional expertise.

Department of Engineering and Environment, Aarhus Municipality

Engineering and Environment has seven departments (e.g. Waste Heat, Property Management, Environment and Nature, Buildings and Planning, Traffic and Roads), a joint administration and a management secretariat. There are a total of approx. 1400 employees. The management is lead by the alderman and the head of the Department.

Affaldvarme Aarhus

Affaldvarme Aarhus (“Waste Heat Aarhus”) is an entity under the control of the Department of Engineering and Environment, Aarhus Municipality. The organization has four main sections: “Waste”, “Waste Centre”, “Heating Plan Aarhus”, and “Heating”. The sections share part of their staff.



Organizational chart of the “waste heat” department.

5. Stakeholders and Commitment

Municipality

First of all, Aarhus Municipality took the role to bring together stakeholders to create and support the necessary framework and to influence the legislation bodies in areas where the current laws result to become barriers to the development of the necessary solutions. Aarhus Municipality, through climate partnerships, tries to facilitate collaborations between companies and knowledge institutions on concrete development projects and new use of existing solutions. The department of Engineering and Environment is developing own expertise to contribute to knowledge-based decision. Next, Aarhus Municipality decided to address its own energy/related potential by taking the lead in projects finance by the State within the nine focus areas. This makes the municipality an essential actor for the implementation of new solutions that are developed in cooperation between companies and knowledge institutions, even innovative solutions that have not yet been tested nationally or globally. Hence, Aarhus Municipality is the main actor in pushing the whole community to get involved in climate-related projects.

Climate Partnerships

Climate Partnership is a framework for creating concrete cooperation and preparing binding agreements between business entities, knowledge institutions and public bodies. Each agreement is tailored to the specific partnership, so that all parties gain a profit. In the period 2012-2015 the municipality has decided to focus on entering into partnerships with companies that are front runners in the energy and climate technology and big businesses with many employees or a large production, which typically possess great energy efficiency or CO₂ reduction potentials. Climate Partnerships has been chosen as a major method because:

- Climate partnerships create growth and company results.

- Relevant results cannot be achieved without the commitment of the private sector.
- All parties achieve a mutually off-exchange.

The first part of a climate partnership agreement obliges companies to reduce their internal energy demand. The second part of a climate partnership agreement commits the companies to participate in innovative projects to develop new concepts and products that can create a green growth in the community. Climate Partnership agreements commit Aarhus Municipality to help create the necessary framework for actors' cooperation, including e.g. to influence the legislative and infrastructural framework that is needed for development of commercial climate solutions. Aarhus Municipality has signed partnership agreements with knowledge institutions and private companies.

Methodologies: Energy Roadmaps

6. Monitoring

Aarhus was the first city in Denmark to monitor and map its total CO₂ emission. Furthermore, the City of Aarhus has participated in the development of a tool – the “CO₂ calculator” – that other cities now use to monitor their CO₂ emission. The foundation for working with the climate plans is an annual CO₂ mapping where Aarhus calculates its emission from the geographical area of Aarhus as well as from the City of Aarhus as a business organization. In this way, the City of Aarhus obtains awareness of where the city needs to focus its attention and the opportunity to estimate the effect of its efforts.

In 2007 the mapping shows a CO₂ emission of 2.21 million tonnes, equivalent to 7.5 tonnes/capita; 94 % of the CO₂ emission comes from heat, electricity and transportation.

Carbon footprint in the workplace

In 2007, the CO₂ emission from the City of Aarhus as a business organization was approximately 110,000 tonnes. This corresponds to about 5% of the total emission and to an average of 4.7 tonnes per full-time employee. This is why the City of Aarhus is also focusing on reducing CO₂ emission from the City of Aarhus as a business organization.

- Energy management system in the Department of Technical Services and Environment: implementation of certified energy management and exchange of experience with the other departments. The focus is on how the City of Aarhus as a business organization can reduce its energy use and its impact on the environment.
- Municipal buildings and facilities: one of the largest investments in the Climate Plan 2010-2011 is connected to the municipal buildings. They are to become energy efficient, both when it comes to renovation and new developments, according to the

Danish building regulations 2008 (low-energy Class 1). The work takes the form of demonstration projects.

External Boundary conditions: National policy

Financial support: Normal Municipality budget, additional grants from the central government.

Reasons for success/failure

- Front-runner in CO2 mapping
 - Highly committed management in the Municipality
 - Separate groups with the necessary expertise has been established to prepare energy plans, e.g. the “heat plan”
 - Introduction of Climate Partnerships
 - Existence of well developed climate friendly technologies and businesses on site (e.g. district heating and wind energy)
 - The Climate Plans are versatile and are revised every 2 years.
-
- Lack of back-casting. The overall goal and strategy are set and projects are launched, but it is not fully clear if the effort is enough to reach the goals.

7. Sources

www.naturstyrelsen.dk (January 2012)

“Oversigt over statslige interesser i kommuneplanlægningen – 2009 ”(Overview of national interests in municipal planning – 2009), available at www.naturstyrelsen.dk (January 2012).

“Guidance for local planning content, provision and void”, Danish Ministry of the Environment, 2009.

“Spatial Planning in Denmark”, Danish Ministry of the Environment, 2009, available at: wcd.coe.int.

“Vejledning om kommuneplanlægning” available at www.naturstyrelsen.dk (January 2012).

www.co2030.dk (January 2012).

Subtask C – Part II

Implementation Strategies for Municipalities

Content

A. Current situation (CO ₂ Balance)	10
B. District heating network	12
C. Steering models	13
D. Process	16
E. Technology	17
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A. Current situation (CO₂ Balance)

In 2008 the Municipality of Aarhus carried out a survey of the municipal CO₂ balance in 2007, by sector. An additional survey was carried out to investigate the CO₂ balance of the Municipality as institution, since the municipal as a company employed around 30,000 people and thus have a significant role.

Activity	CO ₂ emissions [tonnes/year]	CO ₂ emissions [%]
Electricity	883,276	41
District Heating	338,094	15
Individual heating: trade, services and households	45,672	
Individual heating and process heating: industry	154,703	9
Individual heating: agricultural	0.0	
Road transport	452,200	
Railway traffic	6,289	
Air traffic	5,791	
Vessel traffic	24,617	29
Fishing	20,723	
Other industry	59,021	
Other: agricultural and forestry	64,208	
Other: household gardens	12,590	
Process emissions: industry	3,900	<1
Solvents	4,726	
Agriculture	66,895	2
Land use (CO ₂ uptake)	-19,399	
Waste Disposal	74,510	
Sewage	17,444	4
<i>Total</i>	2,211,750	1

Electricity

Sector	Energy use [MWh/year]	CO ₂ emissions [tonnes/year]	CO ₂ emissions [%]
Private households	441,292	239,092	27%
Public institutions	439,671	238,214	27%
Commercial and services	374,617	202,968	23%
Industry	255,860	138,625	16%
Agriculture	59,782	32,390	4%
Hotel and restaurant	36,891	19,988	2%
Construction	22,148	12,000	1%
Total	1,630,262	883,276	100%

* Excluding electric heating (23860 MWh /year)

District heating

Sector	Energy use [MWh/year]	CO ₂ emissions [tonnes/year]	CO ₂ emissions [%]
Private households	1,980,000	240,047	71
Agriculture	52,000	6,762	2
Industry	81,000	10,143	3
Construction	31,000	3,381	1
Trade and service	248,000	30,428	9
Public institutions	430,000	50,714	15
Total	2,801,000	338,094	100

Individual heating

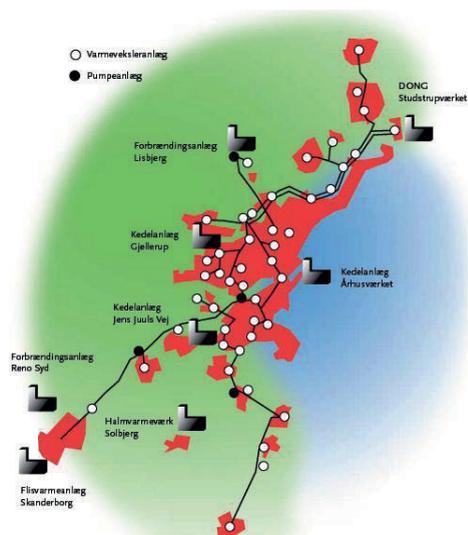
Individual heating	Heat use [MWh/year]	CO ₂ emissions [tonnes/year]
Oil	81,310	30,898
Electrical heating	23,860	12,789
Other boilers	13,103	1,848
Total	118,273	45,534

Transportation sector

Traffic type	CO ₂ emissions [tonnes/year]
Road	452,200
Railway (passenger trains)	6,050
Railway (goods trains)	239
Air	5,791
Sea	24,617
Fishing boats	20,723
Off-roads vehicles	135,819
Total	645,439

B. District heating network

The district heating (DH) distribution company in Aarhus, AffaldVarme Aarhus (“Waste Heat Aarhus”), supply today more than 50,000 private houses, commercial costumers and many thousand building owners who account their DH consumption on behalf of their tenants. About 285,000 of Aarhus Municipality's 300,000 citizens are supplied with DH, so in total 95% is connected. The DH production for the transmission system comes from basic load plants, i.e. the CHP plant in Studstrup and the incineration plant (AffaldsCenter) in Lisbjerg, and from other surplus heat, peak load or backup units.



Heat supply map of Aarhus.

The transmission system consists of more than 130 km twin pipes and pumping stations. The heat mainly comes from the Studstrup CHP plant and the incineration plant and is transmitted by high pressure (PN25) and temperature (120°C, in winter) to the heat exchanger stations. Here the heat is transferred via large plate heat exchangers to the distribution networks, where the pressure and temperature level is lower (PN 16 or PN 10 and 80°C, in winter). The transmission and distribution systems are monitored 24 hours a day via 70 intelligent substations connected in an IT-network. Heat production forecasts are performed to ensure optimal utilisation of the production capacity and to minimise the fuel consumption and the environmental impact. In 2009 the total trench length was 1888 km including service pipes. The climate adjusted heat consumption was 2,438,782 MWh and the network heat loss was about 16%. The average temperatures in distribution network were 77°C and 42°C for supply and return respectively, giving an average cooling of 35°C.

AffaldVarme Aarhus' present standard for new DH pipes and installations are:

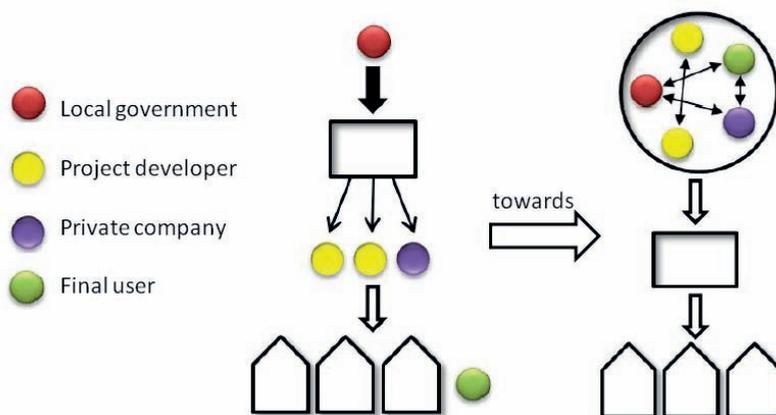
- Twin pipes, insulation class 2 in dimensions up to Ø139 mm
- Single pipes, insulation class 2, in dimensions above Ø139 mm
- Direct heat exchanger units, normally with a 32 kW heat exchanger unit for domestic hot water (private consumers).

District heating consumer types, AffaldVarme Aarhus, 2010.

Type of residence	Number of customers	Residential area [m ²]	Commercial area [m ²]	Total area [m ²]
Farmhouses	343	59,690	1,594	61,284
Detached single-family houses	28,304	4,166,642	28,113	4,194,755
Terraced houses etc.	17,581	1,725,751	1,889	1,727,640
Blocks of flats	78,644	5,743,466	3,762	5,747,228
Dormitories	4,792	150,855	270	151,125
24-hour care centre (old people home, children home etc.)	361	67,994	27,436	95,430
Other permanent residence buildings	80	10,293	40	10,333
Total for residential incl. care centre	130,105	11,924,691	63,104	11,987,795
	94.8%	99.7%	3.8%	88.1%
Other buildings (commercial etc.)	7,115	30,476	1,593,638	1,624,114
	5.2%	0.3%	96.2%	11.9%
Total	137,220	11,955,167	1,656,742	13,611,909

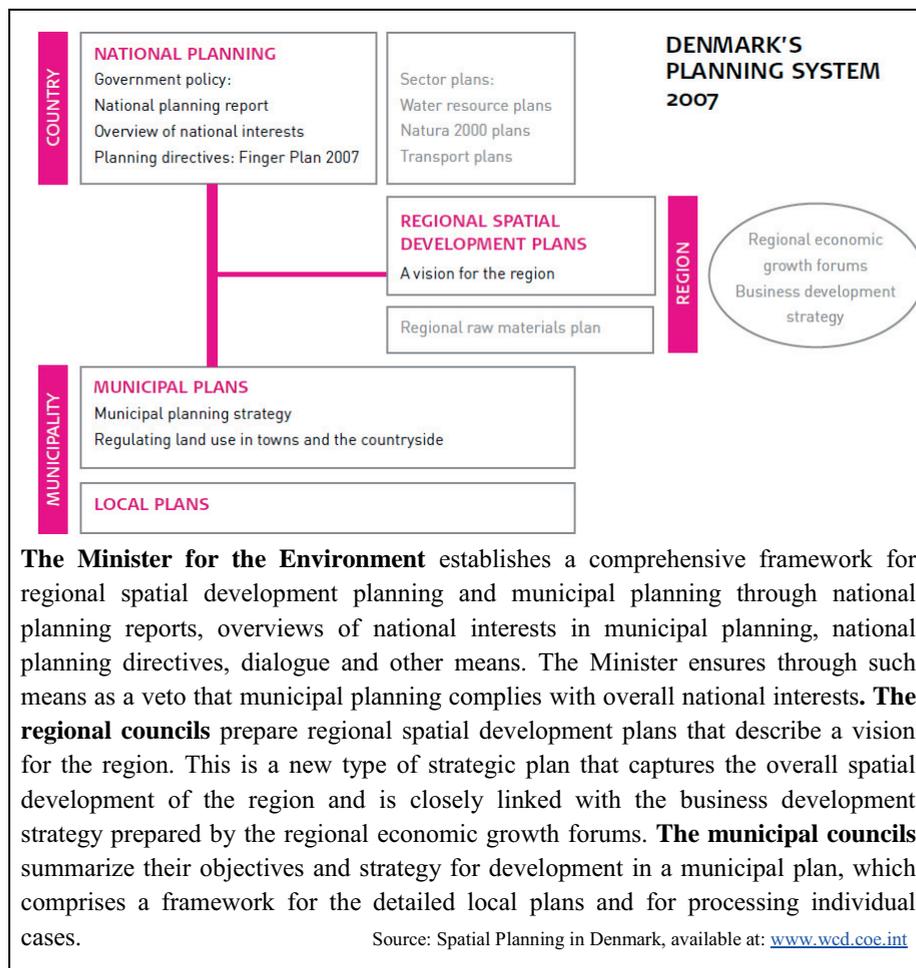
C. Steering models

The Municipality is leading the process of converting a governmental-driven and local-authority-driven urban planning into a climate partnership with the private sectors and the citizens. In practice the municipal authority is acting as a front-runner and tries to fully exploit its role, as stated in the Danish Planning act, being the main promoter of climate-related projects, but trying also to involve the private sectors and all the citizens, starting from its own employees.



The description of the legal framework of urban planning in Denmark, which is the basis of the Climate plan and of the planning process in Aarhus, is described here. The urban planning policy in Aarhus, likewise in Denmark is based on “The Planning Act”, which entered into force in 1992. The planning act separates responsibility for

planning in Denmark among the Environment Minister, 5 regional councils and 98 municipal councils.



The State generally provides the overall guidance for planning, while the local plans translate the broad guidelines and vision to actually planning. The five regions are responsible for the regional development plans that ensure a more strategic development planning. All physical planning in Denmark is anchored to the Planning Act, which is based on the two basic elements of the planning legislation reform in the 1970s: decentralization of the decision making authority and the public involvement in the planning process. The State ensures the consistency of the overall plan and is responsible for particularly complex environment, nature and planning matters. The Minister of Environment establishes national planning directives for specific geographic areas to ensure national interests. Both regions and municipalities must consider the list of national strategic interests that the Minister publishes every four

years. The list provides an overview of the interests and concerns arising from political decisions taken in the form of legislation, action plans, sector plans, national planning decisions and agreements between authorities. The first statement was issued in 2006 and contained a catalogue of the national interests, sector plans and requirements that new local plans must comply with. The local government reform, which came into force in 2007, drew up long-term development strategies to ensure consistency between central and local government planning and various employment and development strategies. The regional development plans are not as concrete plans as former county region plans (the counties were abolished in 2007), but they are more general strategic plans, which outline some guidelines that municipalities must follow during their planning process. Municipalities are the main decision makers and they are responsible for planning for cities and the countryside. They do this through long-term municipal plans, supplemented by four-year plan strategies. In practice it is municipalities that plan how Danish cities and landscapes evolve, but it is within the general guidelines and strategies that state and regions set.

Regional development planning

The regional councils prepare regional development plans, which provide the strategic vision for regional development. The regional development plans can be seen as a joint project between the municipalities, the industry, regional councils and the other actors in the region. The development plans describe a desirable future development of the urban, rural and remote areas within the region. They are strategic plans that do not contain precise designations on maps. The regional development plan explains the correlation among future residential, commercial or industrial development and the state and municipal plans, the potential for cooperation with neighboring countries' authorities on planning and development issues, the actions that the regional council will undertake to follow up the development plan. The regional development plan ensures consistency among the national business and employment development strategy and the local action groups, the rural development programme, local and regional Agenda 21 strategies and other regional strategies and plans. The guidelines of the regional plans are gradually incorporated into municipal plans. All regional plans and local plans can be found on the "Environment Portal". They are available online at www.plansystemdk.dk.

Municipality planning

Local councils have a major responsibility for planning in the cities and the countryside. Each municipality in the country, after the enforcement of the Planning Act, must preserve and maintain its municipal plan. The plan determines the municipal overall objectives and guidelines for the municipality's development, or a period of 12 years, both in urban as in rural areas. In the first half of the term of 4 years, the local council provides a strategy for municipal planning and thereby provide a decision on the necessary revisions to the municipal plan. The municipality plan provides the framework for preparing local plans and it is the basis for treatment

of a number of cases including the applications for construction permission. The Minister of Environment has the duty to oppose a proposal to the town if it is not in accordance with broad interests.

Local planning

Local plans are the cornerstones of the Danish planning system. In fact, the municipal policy strategy and objectives are made concrete through local plans. While the municipal plan provides a comprehensive overview of the developments within the municipality, local plans provide actual plans for the use of the land in a specific zone. Local plans are legally binding on landowners. A local plan can be said to be a local law that regulates the construction and use of land within the plan area. It can regulate issues relating for example to: zoning status, use of land, buildings size and extent of properties, roads and paths, tracks, pipelines for water, gas, heat, location and size of buildings, building density and design, etc... It is therefore the main tool for the municipalities to achieve the targets on energy conservation and exploitation of renewable energy. The Municipal Council may at any time make a new local plan, if the plan remains within the municipal limits for local planning. Local plans can regulate the use of a whole urban area, or even single properties. A local plan may also regulate a single theme, such as signs or building facades. There can be made local plan for properties in both urban, rural and cottage areas. When an area is transferred from one of the three types of land, it always happens through a local plan. A district plan must not conflict with municipal or general planning, such as national planning directives. Local plan proposals must be submitted for public discussion for at least 2 months before the municipal council adopts them permanently. Governmental authorities can give a veto against a local plan proposal, if it conflicts with the specific terms of the national plan. In connection with the public presentation of a local plan proposal, the municipality submits it to PlansystemDK. Municipalities often publish their local plans on the municipal website.

D. Process

PROCESS	Bottlenecks	Solutions
Initiative phase (including target setting)	Understanding the potential for GHG reductions and the critical sectors with high GHG emissions	CO ₂ accounting and mapping
Planning phase	Long-term commitment, assignment of capital resources	List of priorities areas, biannual and versatile climate plans
Realization	Involvement of the private sector	Climate partnerships
	Involvement of the citizens and support of front-runners	Address the 30,000 employees of the Municipality offices and nominate "climate ambassadors"
Management and exploitation	Knowledge management, public involvement	Creation of the Climate Secretariat

E. Technology

TECHNOLOGY	BOTTLENECKS	SOLUTIONS
District heating network	Cost-effective reduction of fossil-fuel-based heat production	Biomass CHP
Electricity grid	Exploitation of large-scale renewable energy	Off-shore wind farms
Energy products	Know-how, R&D, education	- Climate partnerships and support to “green business” - Involvement of knowledge institutions

F. Laws and regulations

LAWS AND REGULATIONS	BOTTLENECKS	SOLUTIONS
Heat Plan Aarhus	Definition of the target and time frame	Make a plan which is consistent with the “Heat Plan Denmark” and the “Climate Plan Aarhus”

G. Financing

FINANCING	BOTTLENECKS	SOLUTIONS
Capital investment	Often capital from many different actors or from central governments are necessary.	Local capital investments through normal Municipality budget, no extraordinary State subsidies. It is made possible by relatively high municipal taxes in Denmark

APPENDIX C

**Matlab Code for Calculation of Transient Heat
Transfer in Small-Size District Heating Pipes**

Matlab® Code Developed and Used in the Article III for Modelling Transient Heat Transfer in Service Pipes

DEFINITIONS

`% BY-PASS: Period of time [s] when a relatively small water flow circulates in the supply pipe to maintain a sufficient temperature level, while there is no DHW tap at the end user's side. The programme creates a mesh (1000 longitudinal elements X 11 radial elements) and calculates the outlet temperature for a number of time steps. The duration of the time step is constant and it is equal to the time the water needs to flow across the length of a pipe element.`

`STAND-BY: Period of time [min] with no water flow in the DH pipe. The water in the service pipe cools down during this period. The code calculates the temperature profile along the pipe longitudinal coordinate x during such period, by means of a regression curve, derived from dynamic simulation in the software COMSOL Multiphysics.`

DESCRIPTION

`This software considers the dynamic in a DH house-connection pipe (service pipe), with an intermittent water flow (cycles of by-pass periods and stand-by periods. The code can calculate:`

- `1) The outlet temperature from a service pipe (inlet temperature to the substation), considering the transient state, for given supply temperatures, water flow, desired set point temperature of the by-pass and the initial temperature conditions of the pipe along the longitudinal coordinate.`
- `2) The outlet temperature from a service pipe (inlet temperature to the energy transfer unit), considering the dynamics in the coupled fluid-thermal phenomenon, for given supply temperature profile, water flow, desired set point temperature of the by-pass and the time-dependent temperature profile along the length of the pipe after a "stand-by" period.`
- `3) The comparison of the heat loss of the operating mode consisting in cycles of by-pass and stand-by periods ("intermittent by-pass") and the ideal operating mode with a continuous constant by-pass flow ("continuous by-pass") that keeps the water temperature at the entry of the energy transfer unit equivalent to the average temperature in case of intermittent by-pass.`

INSTRUCTIONS

- `- Insert the required data in the "input data menu";`
- `- set m=2(or any other integer ~= 1) OR`
- `- set m=1 if the interest is just the study of the temperature dynamics at the outlet of the service pipe/entry to the energy transfer unit, for a constant supply water flow and a specific supply temperature profile;`
- `- if m~= 1, set the duration of the stand-by; in this version of the`

code you must choose among 15, 30, 60 or 90 minutes.
 N.B.: The software calculates the duration of the by-pass for a given by-pass set temperature.

OUTPUT

- a) FIGURE 1: The outlet temperature [°C] during the by-pass period [s].
- b) FIGURE 2: The temperature profile [°C] along the pipe length [m] just after the by-pass period.
- c) FIGURE 3: The temperature profile [°C] along the pipe length [m] just after the stand-by period/just before the by-pass period.
- d) .txt files:
 - "Tout during by-pass" stores the data of figure 1.
 - "after by-pass" stores the data of figure 2.
 - "after stand-by" stores the data of figure 3.
 - "energy" compares the energy use in case of a cycle of intermittent by-pass with the case of continuous constant by-pass flow.

```
clear all
close all
clc

% Input data menu
n = 1000; %nr. of pipe elements in the longitudinal
direction.DEFAULT: 1000
mass_flow=0.08; %Mass flow of water [kg/s]
t0 = 8; % Initial temperature for the whole pipe [°C]
tg = 8; % Ground temperature
tsupply = 52; %Temperature of the water at the service pipe inlet
[°C]
L= 10; % Pipe lenght [m]
d=0.015; %Inner media pipe diameter. DEFAULT: Aluflex 20-20/110 [m]
thickness_pex = 0.0025; %Thickness of PEX pipe [m]
thickness_pur = 0.025; %Thickness of PUR insulation[m]. DEFAULT:
0.025 m
t_set_bypass = 40;
m=2;
% Additional input data,when considering stand-by periods
time_standby =30; % duration of the stand-by period [min]
% Geometry of the mesh
Dm_pex=d+thickness_pex; %Average pipe diameter [m]
D=d+2*thickness_pex; %External diameter pipe[m]
Dm_pur = D + thickness_pur;
D_pur = D+2*thickness_pur; %External diameter (insulation) [m]
D1 = d + thickness_pex*1/5;
D2 = d + thickness_pex*3/5;
D3 = d + thickness_pex;
D4 = d + thickness_pex*7/5;
D5 = d + thickness_pex*9/5;

D6 = d + thickness_pur*1/5;
D7 = d + thickness_pur*3/5;
D8 = d + thickness_pur;
D9 = d + thickness_pur*7/5;
D10 = d + thickness_pur*9/5;

% Tinitia of the PEX nodes(media pipe wall) and PUR nodes
(insulation)
t1=ones(1,n+1)*t0;
t2=ones(1,n+1)*t0;
```

```

t3=ones(1,n+1)*t0;
t4=ones(1,n+1)*t0;
t5=ones(1,n+1)*t0;
t6=ones(1,n+1)*t0;
t7=ones(1,n+1)*t0;
t8=ones(1,n+1)*t0;
t9=ones(1,n+1)*t0;
t10=ones(1,n+1)*t0;

% array pre-allocation, for calculation speed purposes
Q = ones (1,n);
tw = ones(1,n+1); % tw(1)=Tsupply and tw(n+1)=Toutlet
tw(1)= tsupply; % Supply temperatuRe at the inlet of the service pipe
tw(2:n) = t0; % T initial of the water along the service pipe
tw(n+1) = 0; %allocation for Toutlet
d_tw = ones (1,n+1)*0; %allocation for arrays with temperature
differences
d_t = ones (1,n+1)*0;
d_tw_t = ones (1,n+1)*0;
d_t1= ones (1,n+1)*0;
d_t2= ones (1,n+1)*0;
d_t3= ones (1,n+1)*0;
d_t4= ones (1,n+1)*0;
d_t5= ones (1,n+1)*0;
d_t6= ones (1,n+1)*0;
d_t7= ones (1,n+1)*0;
d_t8= ones (1,n+1)*0;
d_t9= ones (1,n+1)*0;
d_t10= ones (1,n+1)*0;

% Thermal properties water at the average Twater
Tmean = 52; % Average Twater along the pipe
rho_w=rho(Tmean); %Density of water [kg/m3]
lambda_w=lambda(Tmean); %water thermal conductivity
cp_w=cp(Tmean); %Cp [J/(kg*K)]
vis_w=vis(Tmean); % cinematic visc.
Pr_w=Pr(Tmean); %Prandtl Number

% Thermal properties PEX
rho_pex=925; %Density of PEX [kg/m3]
cp_pex=2300; %Cp value for PEX [J/(kg*K)]
lambda_pex= 0.38; %Thermal conductivity PEX [W/(m*K)]

% Thermal properties PUR
rho_pur=60; %Density PUR [kg/m3]
cp_pur=1500; %Cp value PUR [J/(kg*K)]
lambda_pur= 0.023; % Thermal conductivity PUR [W/(m*K)]

% Calculation of the thermal transfer parameters
A = pi/4*d^2; % Cross sectional area of the pipe
v=mass_flow/A/rho_w; %water velocity inside the pipe [m/s]
Re=(v*d)/(vis_w); %Reynolds Number (N.B.: Cinematic viscosity)
if Re > 10000
    Nu=0.023*(Re^0.8)*Pr_w^0.3; % Dittus-Boelter eq.
elseif Re < 2300
    Nu=1.86*(Re^0.33)*Pr_w^0.33*(d/L)^0.33; % Sieder-Tate eq.
else
    Nu=0.0033*Re*Pr_w^0.37; % Bohm eq.
end
alfa=(Nu*lambda_w)/d; % Convective heat transfer coefficient
[W/(m2*K)]

```

```

Rconv=1/(pi*alfa*d); % Convective linear thermal Resistance water-PEX
% Conductive linear thermal Resistance PEX (half element)
R1= log(D1/d)/(2*pi*lambda_pex);
R2 = log(D2/D1)/(2*pi*lambda_pex); % Conductive linear resistance PEX
R3= log(D3/D2)/(2*pi*lambda_pex); % Conductive linear resistance PEX
R4= log(D4/D3)/(2*pi*lambda_pex); % Conductive linear resistance PEX
R5= log(D5/D4)/(2*pi*lambda_pex); % Conductive linear resistance PE
% Conductive linear thermal Resistance PEX(half element)+PUR(half
element)
Rpexpur= log(D/D5)/(2*pi*lambda_pex) + log(D6/D)/(2*pi*lambda_pur);
R7= log(D7/D6)/(2*pi*lambda_pur); % Conductive linear resistance PUR
R8= log(D8/D7)/(2*pi*lambda_pur); % Conductive linear resistance PUR
R9= log(D9/D8)/(2*pi*lambda_pur); % Conductive linear resistance PUR
R10= log(D10/D9)/(2*pi*lambda_pur); % Conductive linear resistance
PUR

U1=1/(Rconv+R1); %U-value water-PEX [W/(mK)]
U2=1/R2; %U-value PEX-PEX [W/(mK)]
U3=1/R3; %U-value PEX-PEX [W/(mK)]
U4=1/R4;%U-value PEX-PEX [W/(mK)]
U5=1/R5;%U-value PEX-PEX [W/(mK)]
Upexpur=1/Rpexpur; %U-value PEX-PUR [W/(mK)]
U7=1/R7; %U-value PUR-PUR [W/(mK)]
U8=1/R8; %U-value PUR-PUR [W/(mK)]
U9=1/R9; %U-value PUR-PUR [W/(mK)]
U10=1/R10; %U-value PUR-PUR [W/(mK)]

% Element mass
d_l=L/n; % Length of the pipe element
d_time=d_l/v; % Computational time step
d_v= d_l*A; % Volume of the water in one pipe element

%Mass of the PEX element 1-5
pipe_mass1 = pi/4*((d+thickness_pex*2/5)^2 - d^2)*d_l*rho_pex;
pipe_mass2 = pi/4*((d+thickness_pex*4/5)^2 -
(d+thickness_pex*2/5)^2);
pipe_mass3 = pi/4*((d+thickness_pex*6/5)^2 -
(d+thickness_pex*4/5)^2)*...
d_l*rho_pex;
pipe_mass4 = pi/4*((d+thickness_pex*8/5)^2 -
(d+thickness_pex*6/5)^2)*...
d_l*rho_pex;
pipe_mass5 = pi/4*(D^2 - (d+thickness_pex*8/5)^2)*d_l*rho_pex;

%Mass of the PUR element 1-5
pur_mass1 = pi/4*((D+thickness_pur*2/5)^2 - D^2)*d_l*rho_pur;
pur_mass2 = pi/4*((D+thickness_pur*4/5)^2 -
(D+thickness_pur*2/5)^2)*...
d_l*rho_pur;
pur_mass3 = pi/4*((D+thickness_pur*6/5)^2 -
(D+thickness_pur*4/5)^2)*...
d_l*rho_pur*rho_pur;
pur_mass4 = pi/4*((D+thickness_pur*8/5)^2 -
(D+thickness_pur*6/5)^2)*...
d_l*rho_pur;
pur_mass5 = pi/4*(D_pur^2 - (D+thickness_pur*8/5)^2)*d_l*rho_pur;
% Other
time=0; %Start time
% Array for storing the by-pass duration at each cycle (by-pass +
stand-by)

```

```

time_bp = ones(1,n)*0;

% array pre-allocation of output variables, for calculation speed
purposes
x = ones (1,n-1); % spatial coordinate of each node,excluding the
first one
y2 = ones (1,n-1); % Variable that stores the T along the pipe length
y3 = ones (1,n-1); % Variable that stores the T along the pipe length
t_water_out = ones(1,n)*t0; % Toutlet

jj=1;
eps=20;
% The programme stops when the duration of 2 consequent by-pass
periods is
% <0.1 s or when the number of cycles exceeds 200
while (eps > 0.1 && jj<200)

% BYPASS:
% The temperature profile along the pipe is equal to the Twater at
time=0
% or, in case of stand-by, to the Twater after the stand-by period.
% In the first time step Toutlet is equal to the water
% temperature after stand-by in the element n
t_water_out(1) = tw(n);

% Twater=Tsupply for each by-pass cicle
tw(1) = tsupply;

%Calculation time-step by time-step
p=1;
while t_water_out(p)<t_set_bypass

    for i=1:n %Calculation pipe element by pipe element along the

        Q(i)=U1*d_l*(tw(i) - t1(i)); % Heat transfer water-PEX
        d_tw(i)=Q(i)/(mass_flow*cp_w); % dt water temperature
        d_t1(i)=Q(i)*d_time/(cp_pex*pipe_mass1); % dt pex1
temperature

        Q(i)=U2*d_l*( t1(i) - t2(i)); % Heat transfer PEX-PEX
        d_t(i)=Q(i)*d_time/(cp_pex*pipe_mass1); % dt pipe1
temperature

        t1(i) = t1(i) - d_t(i); % New pex1 temperature
distribution

        d_t2(i)=Q(i)*d_time/(cp_pex*pipe_mass2); % dt pex2
temperature

        Q(i)=U3*d_l*( t2(i) - t3(i)); % Heat transfer PEX-PEX
        d_t(i)=Q(i)*d_time/(cp_pex*pipe_mass2); % dt pipe2
temperature

        t2(i) = t2(i) - d_t(i); % New pex2 temperature
        d_t3(i)=Q(i)*d_time/(cp_pex*pipe_mass3); % dt pex3
temperature

        Q(i)=U4*d_l*( t3(i) - t4(i)); % Heat transfer PEX-PEX
        d_t(i)=Q(i)*d_time/(cp_pex*pipe_mass3); % dt pex3
temperature

        t3(i) = t3(i) - d_t(i); % New pex3 temperature
        d_t4(i)=Q(i)*d_time/(cp_pex*pipe_mass4); % dt pex4
temperature
    end
end

```

```

Q(i)=U5*d_l*(t4(i)-t5(i)); % Heat transfer PEX-PEX
d_t(i)=Q(i)*d_time/(cp_pex*pipe_mass4); % dt pex4
temperature
t4(i)=t4(i)-d_t(i); % New pex4 temperature
d_t5(i)=Q(i)*d_time/(cp_pex*pipe_mass5); % dt pex5
temperature

Q(i)=U_pexpur*d_l*(t5(i)-t6(i)); % Heat transfer PEX-
PUR
d_t(i)=Q(i)*d_time/(cp_pex*pipe_mass5); % dt pex5
temperature
t5(i)=t5(i)-d_t(i); % New pex5 temperature
d_t6(i)=Q(i)*d_time/(cp_pur*pur_mass1); % dt pur1
temperature

Q(i)=U7*d_l*(t6(i)-t7(i)); % Heat transfer PUR-PUR
d_t(i)=Q(i)*d_time/(cp_pur*pur_mass1); % dt pur1
temperature
t6(i)=t6(i)-d_t(i); % New pur1 temperature
d_t7(i)=Q(i)*d_time/(cp_pur*pur_mass2); % dt pur2
temperature

Q(i)=U8*d_l*(t7(i)-t8(i)); % Heat transfer PUR-PUR
d_t(i)=Q(i)*d_time/(cp_pur*pur_mass2); % dt pur2
temperature
t7(i)=t7(i)-d_t(i); % New pur2 temperature
d_t8(i)=Q(i)*d_time/(cp_pur*pur_mass3); % dt pur3
temperature

Q(i)=U9*d_l*(t8(i)-t9(i)); % Heat transfer PUR-PUR
d_t(i)=Q(i)*d_time/(cp_pur*pur_mass3); % dt pur3
temperature
t8(i)=t8(i)-d_t(i); % New pur3 temperature
d_t9(i)=Q(i)*d_time/(cp_pur*pur_mass4); % dt pur4
temperature

Q(i)=U10*d_l*(t9(i)-t10(i)); % Heat transfer PUR-PUR
d_t(i)=Q(i)*d_time/(cp_pur*pur_mass4); % dt pur4
temperature
t9(i)=t9(i)-d_t(i); % New pur4 temperature
d_t10(i)=Q(i)*d_time/(cp_pur*pur_mass5); % dt pur5
temperature
end

% New node temperatures
for i=2:n % tw(1) is excluded because it is constant
(=Tsupply)
    tw(i)=tw(i)-d_tw(i); % water temperatures along the
pipe
end
t1=t1+d_t1;
t2=t2+d_t2;
t3=t3+d_t3;
t4=t4+d_t4;
t5=t5+d_t5;
t6=t6+d_t6;
t7=t7+d_t7;
t8=t8+d_t8;
t9=t9+d_t9;
t10=t10+d_t10;

```

```

%Twater for each element for next time step; tw_t(n+1) refers to
Toutlet
    for i=n+1:-1:2
        tw(i)=tw(i-1);
    end
% Twater at the outlet, for the considered time step
    t_water_out(p+1)=tw(n+1);
% Increase of one unit the variable counting the number of time steps
    p=p+1;

    % RE-calculation of the convective transfer with the new average
    Twater
    % Thermal properties water at the average Twater
    Tmean = mean(tw); % Average Twater along the pipe
    rho_w=rho(Tmean); %Density of water [kg/m3]
    lambda_w=lambda(Tmean); %water thermal conductivity
    cp_w=cp(Tmean); %Cp [J/(kg*K)]
    vis_w=vis(Tmean); % cinematic visc.
    Pr_w=Pr(Tmean); %Prandtl Number
    v=mass_flow/A/rho_w; %water velocity inside the pipe [m/s]
    Re=(v*d)/(vis_w); %Reynolds Number (N.B.: Cinematic viscosity)
    if Re > 10000
        Nu=0.023*(Re^0.8)*Pr_w^0.3; % Dittus-Boelter eq.
    elseif Re < 2300
        Nu=1.86*(Re^0.33)*Pr_w^0.33*(d/L)^0.33; % Sieder-Tate eq.
    else
        Nu=0.0033*Re*Pr_w^0.37; % Bohm eq.
    end
    alfa=(Nu*lambda_w)/d; % Convective heat transfer coefficient
    [W/(m2*K)]
    Rconv=1/(pi*alfa*d); % Convective linear thermal resistance
    water-PEX
    U1=1/(Rconv+R1); %U-value water-PEX [W/(mK)]

    end
    tw_afterBP = tw;
    time_bypass=(p-1)*d_time; % duration of the by-pass period [s]
    % The duration of the by-pass in each cycle is stored in the array
    t_bp
    time_bp(jj+1)= time_bypass;
    eps = abs( time_bp(jj+1) - time_bp(jj) );
    jj = jj+1; % jj counts the number of cycles. One cycle=bypass+standby
    %
    % STAND-BY
    if time_standby==15
        for k=1:n
            tw(k) = 0.8292*tw(k)+2.6723;
        end
    elseif time_standby==30
        for k=1:n
            tw(k) = 0.7358*tw(k)+3.982;
        end
    elseif time_standby==60
        for k=1:n
            tw(k) = 0.5869*tw(k)+5.8264;
        end
    elseif time_standby==90
        for k=1:n
            tw(k) = 0.4745*tw(k)+7.0186;
        end
    end

```

```

end
t1 = tw;
t2 = tw;
t3 = tw;
t4 = tw;
t5 = tw;
t6 = tw;
t7 = tw;
t8 = tw;
t9 = tw;
t10 = tw;

% Stop the programme, in case the by-pass period is not
considered
if m==1
    break;
end

end

n1 = round(time_bypass/d_time); % total number of iteration

% array pre-allocation of output variables, for calculation speed
purposes
elapsed_time = ones(1,n1)*0; % Variable that stores the elapsed time
z = ones(1,n1)*0; % Variable that stores Toutlet during by-pass

for i=1:n1 %n of iterations
    elapsed_time(i)=d_time*i; %Elapsed time for each calculation
    z(i) = t_water_out (i); % z stores Toutlet during the water flow
end

for j=1:(n-1) %n of iterations
    x(j)=d_l*j+ d_l/2; %longitudinal coordinate of each pipe element
                    %(excluding the first one that has always
T=Tsupply)
end

for j=1:(n-1)
    y2(j) = tw_afterBP(j+1);% y2 stores the T along the service pipe
when
% the by-pass stops (without considering Tinlet=tw(1) and
Toutlet=tw(n+1))
end

for j=1:(n-1)
    y3(j) = tw(j+1);% y3 stores the T along the service pipe after 30
min
% of stan-by (without considering Tinlet=tw(1) and Toutlet=tw(n+1))
end

% OUPUT
% By-pass period: Toutlet [°C] vs.time [s]
% Ouput file 1
data = [elapsed_time;z];
output = fopen ('output.txt', 'w');
fprintf(output,'%s\r\n','Toutlet during by-pass vs. the time:');
fprintf(output,'%s\r\n',' [s] [°C]');
fprintf(output,'%2.3f %2.2f\r\n',data);

% Graph 1

```

```

figure(1);
plot(elapsed_time,z,'-r');
GRID ON;
legend('Toutlet as a function of the time','North');
XLABEL('Time [s]');
YLABEL('Twater outlet[°C]');
AXIS([0 300 5 55]);

% Stand-by period: Twater [°C] vs. x-coordinate [m]
% Ouput file 2: beginning of the stand-by
data2 = [x;y2];
fprintf(output,'%s\r\n','Twater in the pipe before stand-by:');
fprintf(output,'%s\r\n',' [m] [°C]');
fprintf(output,'%2.3f %2.2f\r\n',data2);
% Graph 2
figure(2);
plot(x,y2,'-r');
GRID ON;
legend('Twater in the service pipe, after ',time_standby,...
' minutes after the by-pass has stopped','North');
XLABEL('x [m]');
YLABEL('T water [°C]');
AXIS([0 10 8 55]);
% Ouput file 3: end of the stand-by
data3 = [x;y3];
fprintf(output,'%s\r\n','Twater in the pipe after stand-by:');
fprintf(output,'%s\r\n',' [m] [°C]');
fprintf(output,'%2.3f %2.2f\r\n',data3);
% Graph 3
figure(3);
plot(x,y3,'-r');
GRID ON;
legend('Twater in the service pipe, after ',time_standby,...
' minutes after the by-pass has stopped','North');
XLABEL('x [m]');
YLABEL('T water [°C]');
AXIS([0 10 8 55]);
fprintf(output,'The Re number in case of intermittent by-pass flow
is: ');
fprintf(output,'%2.0f\r\n',Re);
fprintf(output,'The duration of the by-pass is [s]: ');
fprintf(output,'%2.1f\r\n',time_bypass);
fprintf(output,'The duration of the stand-by is [min]: ');
fprintf(output,'%2.0f\r\n',time_standby);
% Calculation of the energy loss during a cycle of by-pass + stand-by
E1=0;
for i=1:n1
    E1 = E1 + mass_flow*cp_w*d_time*(tsupply - z(i));
end

%


---


% Comparison with an ideal continous by-pass flow
for i=1:n %n of iterations
    x(i)=d_l*i - d_l/2; %longitudinal coordinate of each pipe element
end
ta = t0; % Tground [°C]
tu = tsupply; % Tupstream
td = ones(1,n); % Tdownstream
U = 0.09; % Average U-value [W/(mK)] of the supply pipe,
% considering 35°C<Twater<52°C, and Treturn=25°C

```

```

        %(adapted from Wallanten's formulas)
K = U/(A*rho_w*cp_w);
% Average T during the stand-by (15, 30, 60, 90 min) in case of
% intermittent by-pass flow, for comparison with continuous by-pass
flow.
t_continuous_bp_15 = 37.4;
t_continuous_bp_30 = 36;
t_continuous_bp_60 = 33.7;
t_continuous_bp_90 = 31.6;
if time_standby==15
    t_bp = t_continuous_bp_15;
elseif time_standby==30
    t_bp = t_continuous_bp_30;
elseif time_standby==60
    t_bp = t_continuous_bp_60;
else
    t_bp = t_continuous_bp_90;
end
Tmean = (tsupply + t_bp)/2; % Average Twater along the pipe
rho_w=rho(Tmean); %Density of water [kg/m3]
% Find the constant, continuous water flow at Tsupply that keeps
Tset_bypass
% at the outlet
equation = @(x)ta*(1-exp(-K*L/x)) + tu*(exp(-K*L/x)) - t_bp;
v_const = fsolve (equation, 0.0001);
for i=1:n
    td(i) = ta*(1-exp(-K*x(i)/v_const)) + tu*(exp(-K*x(i)/v_const));
end
P=0; % Steady-state heat loss for a continuous flow [W]
for i=1:n
    P = P + U*d_l*(td(i) - ta);
end
E2 = P*(time_bypass + time_standby*60);
flow_const = v_const*A*rho_w;
fprintf(output, '%s %2.0f %2.0f\r\n', 'The enegy use in case of
intermittent
                                or continuous by-pass flow is respectively [J]:
', E1, E2);
fclose(output);

```

Code of the functions used in the main code

```
%This function calculate the specific thermal capacity of the water,  
% as function of T [°C]  
function cp_water = cp(T)  
cp_water = 4209.1-132.8*10^-2*T+143.2*10^(-4*T^2); %Cp [J/(kg*K)]  
  
%This function calculate the thermal conductivity of the water,  
% as function of T [°C]  
function lambda_water = lambda(T)  
lambda_water = 0.52+0.0198*T^0.46; %water thermal conductivity  
  
%This function calculate the Pr number of the water, as function of T  
[°C]  
function Pr_water = Pr(T)  
Pr_water=39.5345*T^(-0.144)-18.8396; %Prandtl Number  
  
%This function calculate the density of the water, as function of T  
[°C]  
function rho_water = rho(T)  
rho_water = 1000.6-0.0128*T^1.76; %Density of water [kg/m3]  
  
%This function calculate the viscosity of the water, as function of T  
[°C]  
function vis_water = vis(T)  
vis_water = 1.477*10^-6*2.718281828^(-1.747*10^-2*T); % cinematic  
viscosity
```


This Ph.D. thesis is divided into two parts, which respectively contain an extended synopsis and the collection of five scientific publications. The thesis deals with: the development of a new District Heating (DH) paradigm – namely “low-temperature DH”; the study of its integration to energy-efficient buildings; the investigation of technical options which improve its applicability, in terms of energy performance and socio-economy. The results indicate that the low-temperature DH concept is part of the solution towards an energy-sustainable heating sector.

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