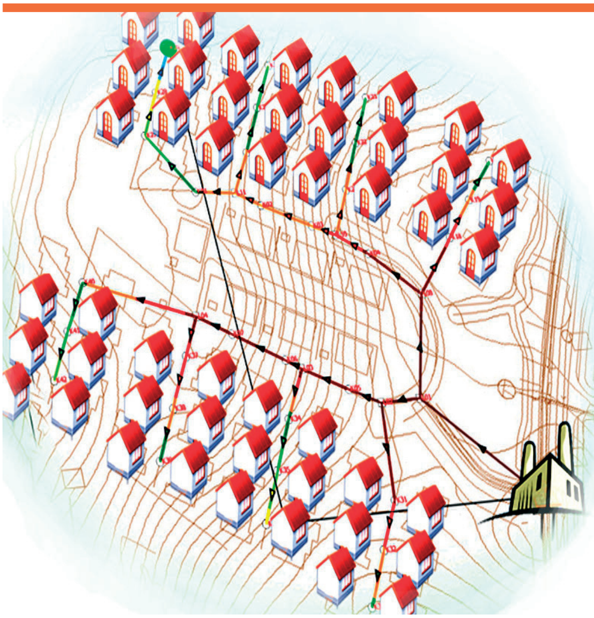
District Heating in Areas with Low Energy Houses

Detailed Analysis of District Heating Systems based on Low Temperature Operation and Use of Renewable Energy



Hakan ibrahim Tol

PhD Thesis

Department of Civil Engineering

2015

DTU Civil Engineering Report R-283 (UK)
February 2015

DTU Civil Engineering
Department of Civil Engineering

DISTRICT HEATING IN AREAS WITH LOW ENERGY HOUSES

DETAILED ANALYSIS OF DISTRICT HEATING SYSTEMS BASED ON LOW TEMPERATURE OPERATION AND USE OF RENEWABLE ENERGY

Thesis for the Degree of Doctor of Philosophy

Hakan İbrahim Tol

BYG•DTU - Department of Civil Engineering

Technical University of Denmark

2015

Supervisors:

Professor Dr. Svend Svendsen	Technical University of Denmark	Denmark
Associate Professor Dr. Susanne Balslev Nielsen	Technical University of Denmark	Denmark

Assessment Committee:

Associate Professor Dr. Brian Elmegaard	Technical University of Denmark	Denmark
Associate Professor Dr. Janusz Wollerstrand	Lund University	Sweden
Associate Professor Jens Brusgaard Vestergaard	Aarhus University	Denmark

بِسْمِ اللّٰـهِ الرَّحْمَـٰنِ الرَّحِيمِ

Koruyan ve Bağışlayan Allah'ın Adıyla

I Allahs den Nådiges den Barmhjertiges Navn

In the name of Allah, the Merciful, the Compassionate

“ *Read!*

In the Name of your Rabb Who has created ”

Sura ‘Alaq (The Clot): Verse 1

The Holy Qur’an

PREFACE

The Danish energy scheme aims at the use of renewable energy for the heating of all buildings by 2035. A new generation of district heating systems operating at low temperatures and employing renewable energy sources is seen as being able to accomplish this. The intention is to integrate low-energy district heating systems operating at very low temperatures, such as 55°C for supply and 25°C for return. The basic aim of the PhD project reported on here was to find optimal solutions to this involving use of renewable-energy-based low-energy district heating systems at the municipal and the regional level. The detailed analysis of several cases, each representing a unique infrastructural municipal heating task, can provide a rational basis for innovative transformations and developments in adapting whole regions to the use of the low-energy district heating systems. Attention is also directed at intensive efforts that have been directed at a comprehensive integration of renewable energy sources in meeting the energy requirements of portions of the Danish energy supply, research questions there being formulated in terms of efforts to solve two major tasks: (i) the proper dimensioning of district heating networks and (ii) the economic exploitation of locally-available renewable energy sources, as examined in three case studies, each being carried out in collaboration with Danish municipalities.

The first case study, conducted in collaboration with Roskilde Municipality, was concerned with the designing of low-energy DH networks for new settlements, for which the building of low-energy houses was planned, in particular matters of the network dimensioning method to be employed, the substation type, the network layout, and the hydrostatic pressure level that was best considered. The second case study, carried out in collaboration with Gladsaxe Municipality, was directed at replacing existing heating infrastructures, such as natural gas grids and high-temperature district heating systems, with low-energy district heating systems for the existing areas, in which it is planned that the houses presently located there will be renovated so as to achieve a high degree of energy savings. The third case study involved research question aimed at investigating possibilities of exploiting the locally available non-fossil fuel sources to be supplied to low-energy district heating systems.

This doctoral thesis is submitted in partial fulfilment of the requirements for the PhD degree based on the Danish PhD project entitled "District Heating in Areas with Low Energy Houses".

Hakan İbrahim Tol

19th of January 2013, Kongens Lyngby

ABSTRACT

This PhD thesis presents a summary of a three-year PhD project involving three case studies, each pertaining to a typical regional Danish energy planning scheme with regard to the extensive use of low-energy district heating systems, operating at temperatures as low as 55°C for supply and 25°C for return, and with the aim of intensive exploitation of renewable energy sources. The hypothesis is that a detailed analysis of energy performance and cost of construction and operation of low energy district heating systems can be used as a rational basis for planning use of district heating in areas with low energy houses.

The first case study focus was concerned with developing a method for the designing of low-energy district heating systems for new settlements in which low-energy houses were to be built. The method involved primarily the development of a novel pipe dimensioning method based on optimization of the pipe diameters rather than use of rule-of-thumb methods, through consideration of a certain value of a maximum pressure gradient or a maximum velocity, or both. In addition, attention was directed at the assessment of (i) substation types considered for use in connection with the low-energy houses involved, together with the idea of utilizing booster pumps in the district heating network and (ii) use of network layouts of either a branched (tree-like) or a looped type. The methods developed were applied in a case study, the data of which was provided by the municipality of Roskilde in Denmark.

The second case study was aimed at solving another regional energy planning scheme, one concerned with already existing houses, the heat requirements of which were currently being met by use of a natural gas grid or a conventional high-temperature district heating network. The idea considered for employing a low-energy district heating system here involved use of an operational control approach of boosting the supply temperature during the peak winter months due to their shorter durations when compared to a year period. This approach can be considered in two different respects: (i) in the municipal infrastructure, transforming the current heating systems into low-energy district heating systems and (ii) in the operation of low-energy district heating systems. The building settlement in question, one located in the municipality of Gladsaxe, was chosen for the case study carried out, due to the existing houses there being considered for renovation to houses of a low-energy class, and due to the existing heat-supply energy infrastructure there being a natural gas grid.

The third case study carried out aimed at developing energy conversion systems based on use of renewable energy sources that were available locally. This was carried out in an external stay at the University of Ontario Institute of Technology (UOIT) in Oshawa, ON, Canada under the supervision of Prof. İbrahim Dinçer. In this colleborative study, a novel method was developed to serve as the basis of a decision

support tool in investigating the optimal use of renewable energy sources, particular consideration being given to the following:

(i) the monthly satisfaction of energy requirements of various types: heating (including the demands of space heating and of domestic hot water production), electricity, and cooling, in order to study the improvement in efficiency achieved by use of multi-generation systems,

(ii) various types of energy conversion systems, such as single-generation, co-generation, and multi-generation systems,

(iii) the long-term storage of heat energy to cope with the mismatch between the energy production from renewable energy sources and the heat energy requirements, both in terms of the variations involved, such through the excessive production of heat by means of solar based systems, heat that cannot be used immediately but can be stored in borehole storage systems, to be used then in the cold winter period,

(iv) an extensive economic assessment of the technologies involved, taking several different parameters into account, each unique for the technology in question, such as the specific investmet costs based on an economy-of-scale, operation and maintenance costs, the lifetime of the technology, the capacity factor, and the salvage value of the energy conversion system at the end of its lifetime,

(v) seasonal variation in the generation of energy, in line with the availability of the renewable source in question,

(vi) on a limited scale, aimed at gaining as much insight as possible into the complexities of the questions involved, examining the environmental concerns possible to encounter during the operations of each conversion system, the security of supply being figured on the basis of the optimal solutions obtained.

In summary, the methods developed in the case studies concern the technical framework for establishing an integrated energy supply scheme involving the use of renewable energy sources for meeting the energy needs of low-energy houses by means of a city-wide low-energy district heating system.

Keywords: low-energy; district heating; energy efficiency; optimization; pipe dimensioning; network layout; control philosophy; substation; renewable energy; decision support tool.

RESUMÉ

Denne ph.d.-afhandling er en sammenfatning af det treårige ph.d.-projektet vedrørende tre casestudier, som hver er unik med henvisning til en typisk regional dansk energiplanlægning med hensyn til omfattende brug af lavenergi-fjernvarmesystemer, der opererer med lave temperaturer såsom som 55 °C i fremløbet og 25 °C i returløbet og med en intensiv udnyttelse af de vedvarende energikilder.Hypotesen er at en detaljeret analyse af lavenergifjernvarmesystemers energimæssige egenskaber samt anlægs- og driftsudgifter kan benyttes som et rationelt grundlag for planlægningen af brugen af fjernvarme i områder med lavenergibygninger

I det første case study, blev fokus rettet mod valg af designmetode til lavenergi-fjernvarmesystemer for nye bebyggelser af lavenergihuse. Designmetoden indeholdt hovedsageligt fastlæggelsen af en ny rør-dimensioneringsmetode baseret på optimering af diametre i stedet for at bruge tommelfingerregler, der er baseret på den maksimale trykgradient, maksimal hastighed og/eller samtidig behandling af begge. Et andet designelement omhandlede de vurderinger af (i) typer af fjernvarmeunits i bygningerne, der kunne benyttes i lavenergihusene sammen med ideen om udnyttelse af boosterpumper i fjernvarmenettet og (ii) udformningen af fjervarmenettet enten som forgrenede (træ- lignende) eller som ringe. De udviklede metoder blev afprøvet i et casestudie baseret på data leveret af Roskilde Kommune.

I det andet case study blev fokus rettet mod løsning af en anden regional energiplanlægningsopgave, der vedrører eksisterende huse, der er tilsluttet et naturgasnet eller et konventionelt højtemperatur fjernvarmenet. Den forskningsmæssige idé til løsning af dette problem var ved anvendelsen af et lavtemperatur fjernvarmenet med en styringsstrategi baseret på en forøgelse af fremløbstemperaturen i kolde vinter-spidslastperioder af kort varighed sammenlignet med hele året.

Det blev overvejet at anvende denne løsning i to situationer, den første (i) som led i ændringen af den kommunale varmeplan fra de nuværende naturgasnet til lavenergi-fjernvarmesystemer og den anden (ii) i forbindelse med driften af lavenergifjernvarmesystemer. Den eksisterende bebyggelse i Gladsaxe kommune blev valgt til casestudiet, fordi den repræsenterer bygninger med behov for energirenovering og ændring i forsyningsløsning fra det nuværende naturgasnet.

I det tredje case study var fokus på bestemmelse af lokalt tilgængelige vedvarende energikilder til brug i energiforsyningssystemer. En undersøgelse af dette skete under det eksterne ophold på University of Ontario Institute of Technology (UOIT), Oshawa, ON, Canada under vejledning af professor Ibrahim Dincer. I denne fælles undersøgelse blev en ny metode udviklet til at være grundlaget for et beslutningsstøtteværktøj vedrørende en optimal udnyttelse af vedvarende energikilder med omfattende analyser med hensyn til:

(i) den månedlige opfyldelse af forskellige typer af energibehov dvs. opvarmning, herunder krav til rumopvarmning og varmt vand, el og køling med henblik på at inddrage effektivisering af multi-generationssystemer,

(ii) forskellige typer af energikonverteringssystemer såsom 'single-generation', 'co-generation', og 'multi-generationssystemer',

(iii) den langsigtede lagring af varme til at klare den manglende overensstemmelse mellem produktion af varme fra vedvarende energikilder og behovet for varme, som begge følger forskellige variationer f.eks. kan den overproduktion af varme ved hjælp af sol-baserede systemer ikke anvendes, men kan opbevares i borehulslagersystemer og anvendes i den kolde vinterperiode,

(iv) en omfattende økonomisk vurdering af teknologierne ved at tage hensyn til en række parametre for hver teknologi, såsom de specifikke udgifter til investering, drift og vedligeholdelse, levetid, kapacitetsfaktoren, og restværdi af energiforsyningssystemet,

(v) den sæsonmæssige variation af energiproduktionen afhængigt af den vedvarende energikildes ydelse

(vi) og, i begrænset omfang de miljømæssige hensyn, der er mulige at opfylde under driften af hvert konverteringssystem samt forsyningssikkerheden for de optimale løsninger.

Metoderne, der er opnået ved case-studierne, har samlet set givet de tekniske rammer for etablering af et integreret energiforsyningssystem baseret på anvendelse af vedvarende energikilder til forsyning af lavenergihuse ved hjælp af lavenergifjernvarmeanlæg.

Nøgleord: lavenergi; fjernvarme; energi effektivitet; optimering; rør dimensionering; netværk layout; kontrol filosofi; substation; vedvarende energi; beslutningsstøtteværktøj.

LIST OF PUBLICATIONS

The thesis is based on the following three ISI articles, one non-ISI article, and two book chapters, all of which have been prepared by Hakan İbrahim Tol as the main author, under the supervision of Prof. Svend Svendsen, who has contributed to development of the research topics and of the theoretical considerations taken that are dealt with, and to a review of the reports documenting the research studies. The co-supervisor, Ass. Prof. Susanne Balslev Nielsen, has aided to a considerable degree in several development steps undertaken during the PhD project, by means of which considerable improvements were achieved in the research conducted and in the reporting of the results. The book chapters had the assistance to a considerable extent of Prof. İbrahim Dinçer in the external study carried out at University of Ontario Institute of Technology, Oshawa, ON, Canada.

ISI Articles

I. Tol, Hakan İbrahim, Svendsen, Svend, *Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark*. Energy 38 (2012) 276 – 290.

II. Tol, Hakan İbrahim, Svendsen, Svend, *A comparative study on substation types and network layouts in connection with low-energy district heating systems*. Energy Conversion and Management 64 (2012) 551–561.

III. Tol, Hakan İbrahim, Svendsen, Svend, *Effects of boosting the supply temperature on pipe dimensions of low-energy district heating networks: A case study in Gladsaxe, Denmark*. Energy and Buildings 88 (2015) 324-334.

Non-ISI Article (Peer-Reviewed)

I. Tol, Hakan İbrahim, Svendsen, Svend, *The exergetic, environmental and economic effect of the hydrostatic design static pressure level on the pipe dimensions of low-energy district heating networks*. Challanges 4 (2013) 1-16, doi:10.3390/challe4010001.

Book Chapters

I. Tol Hakan İbrahim, Dincer Ibrahim, Svendsen Svend (2013) Determining the Optimal Capacities of Renewable-Energy-Based Energy Conversion Systems for Meeting the Demands of Low-Energy District Heating, Electricity and District Cooling - Case Studies in Copenhagen and Toronto. In: Ibrahim Dincer et al (eds.), Progress in Clean Energy. Submitted to Springer (Accepted to be Published).

II. Tol Hakan İbrahim, Dincer Ibrahim, Svendsen Svend (2013) Regional Energy Planning Tool for Renewable Integrated Low-Energy District Heating Systems: Environmental Assessment. In: Ibrahim Dincer, Can Ozgur Colpan, Fethi Kadioglu (eds). Causes, Impacts and Solutions to Global Warming, Springer, New York.

Peer-Reviewed Conference Articles

The following peer-reviewed conference articles have also been published by the main author Hakan İbrahim Tol on the basis of research topics with which the doctoral study is concerned. The results taken up in each of them were taken account of in writing the ISI articles, which were based on the conference articles i and ii, the ISI article II being based on the conference articles i and ii, the non-ISI article I being based on the conference article v, the ISI article III being based on the conference articles iii and vi, and the book chapters I and II being based on the conference articles iv and vii. The conference articles were not included in the dissertation due to the detailed presentation of them provided already in the ISI articles and the book chapters.

i. Tol, Hakan İbrahim, Svendsen, Svend, *Design of low-energy district heating system for a settlement with low-energy buildings*, 3rd International Symposium on Environmental Management, Oct 26 – 28, 2011, Zagreb, Croatia, pp. 166 – 171.

ii. Tol, Hakan İbrahim, Svendsen, Svend, *Determination of optimum network layout for low-energy district heating systems with different substation types*, The Third International Renewable Energy Congress, Dec 20 – 22, 2011, Hammamet, Tunisia, pp. 179 – 184.

iii. Tol, Hakan İbrahim, Svendsen, Svend, *Operational planning of low-energy district heating systems connected to existing buildings*, International Conference on Renewable Energy: Generation and Applications, Mar 4 – 7, 2012, Al-Ain, United Arab Emirates.

iv. Tol, Hakan İbrahim, Nielsen, Susanne Balslev, Svendsen, Svend, *Case studies in low-energy district heating systems: Determination of dimensioning methods for planning the future heating infrastructure*, IFME World Congress on Municipal Engineering – Sustainable Communities, Jun 4 – 10, 2012, Helsinki, Finland.

v. Tol, Hakan İbrahim, Svendsen, Svend, *Effect of design static pressure level on energy efficiency at low energy district heating systems*, Pacific Rim Energy and Sustainability Congress, Aug 6 – 9, 2012, Hiroshima, Japan, pp. 130 - 137.

vi. Tol, Hakan İbrahim, Svendsen, Svend, *Optimal dimensioning of low-energy district heating networks with operational planning - Case study for existing buildings*, 11th International Conference on Sustainable Energy Technologies, Sep 2 – 5, 2012, Vancouver, Canada, pp. 113 - 122.

vii. Tol, Hakan İbrahim, Dinçer, İbrahim, Svendsen, Svend, *Potential District Heating Systems with Non-Fossil Fuel Heat Sources For Low-Temperature Applications* (As Abstract), 11th International Conference on Sustainable Energy Technologies, Sep 2 – 5, 2012, Vancouver, Canada.

ACKNOWLEDGEMENTS

This PhD thesis is dedicated, first of all, to our Creator, Allâh (Subḥānahu Wa Ta'Ala) Who created me and guided me to the Straight Path (of İslam) and, also, to my parents Yaşar Esma and Bekir, for always being there for me. I am indebted to my sister Esra and niece Işıl, for their being like a bright sun with their sincere interest in me as their brother, which has helped giving me the power to cope with the stress of my PhD studies.

I would like to express my deep gratitude to my main supervisor Professor Svend Svendsen for his inspiration, patient guidance, and useful criticisms of and comments on my research work. Despite his busy schedule, his answers to my questions often became long discussions of technical details and of energy policies, all of this helping very much to improve the quality of my research work. My deep gratitude is also extended to my co-supervisor Associate Professor Susanne Balslev Nielsen, for her tolerant advice and assistance in keeping my progress on schedule, and her encouragement and inspiration to my work, and her practical suggestions and comments concerning my PhD work.

I wish to gratefully acknowledge the help provided by the Roskilde Municipality and the Gladsaxe Municipality for their financial support of this PhD project and in their providing the geographical data for use in the case studies.

I would like to express my very great appreciation to Professor İbrahim Dinçer, for his valuable and constructive suggestions during the planning and development of the external study carried out at the University of Ontario Institute of Technology (UOIT), Oshawa, ON, Canada. The financial support provided this external study by COWIfonden, Marie & MB Richters Fond, and Oticon Fonden is extremely appreciated. My sincere gratitude is also extended to my colleagues in the UOIT, Sadi Halil Hamut, Ahmet Özbilen, and Nader Javani, for their help in my very quick adaptation to my new working environment there.

I wish to thank my colleagues in the Section of Building Physics and Services. My special thanks are extended to Alessandro Dalla Rosa, who shared his experiences in his PhD work that sped up my accomplishment of my PhD, to Lies Vanhoutteghem, not only for her support in the office but also for not leaving me alone in most, and to Martin Morelli, for his enthusiastic supports above all. I wish also to thank my colleagues in the same field, in particular Hongwei Li, Marek Brand, and Maria Harrestrup, whose knowledge improved the quality of my research studies. The enjoyable times spent in the breaks with my young-hearted Danish colleagues Anne Damgaard Rasmussen, and Jesper Engelmark are sincerely appreciated.

TABLE OF CONTENTS

GLOSSARY

Low-Temperature	Excessively low temperature supply of about 50°C.
Low-Energy	Used for district heating systems operating at low temperatures.
Low grade	Surplus heat at low temperatures which it is hard to exploit.
Heat carrier medium	A medium consisting of a fluid used to transport heat in such a way that a change in enthalpy occurs through an endothermic reaction that takes place, for example at the heat source, and an exothermic reaction, for example one of positive effect for consumers.
Pipe Network	A closed circuit of several pipes connected to each other hydraulically for the purpose of circulating a heat carrier medium from a heat source to consumers.
Node	A junction of several pipes or a sign for heat consumers.
Leaf node	A node without any successor node (also used as end-node).
Root node	A node without any predecessor node, in reference to a heat source.
Pipe segment	A short segment of pipe that connects a node to a succeeding node, in the order from root node to leaf node.
Route	A sequence of pipe segments extending from a root node to a respective leaf node.
End-user connection	A service pipe that provides the means of circulation taking place within a district heating network, used for in-house installation.
Network layout	The shape of a pipe network with respect to the interconnections between the pipes.
Branched network	The tree-like formation of a network providing a unidirectional flow from the root node to the leaf nodes.
Looped network	The looped formation of a network shaped in the form of closed paths composed of pipe segments, in which each heat-demanding-node has a number of alternative paths for the flow to be supplied by one of the neighboring nodes.
Supply line	A pipe line employed to deliver the heat carrier medium after its enthalpy has increased at the heat source (Also known as feed line).
Return line	A pipe line employed to transfer the medium back to the heat carrier medium after its enthalpy has been released through heat consumption by the in-house installations of consumers.
Single pipe	An insulated type of pipe used in district heating networks, the pipe being protected or shielded by an insulating casing.
Twin pipe	An insulated type of pipe used especially in district heating networks, involving two pipes, both of the same diameter, protected over-shielded by an insulating casing.

Pump Station	A major facility in a district heating network, one that provides the difference in pressure difference required to circulate a heat carrier medium.
Pressure drop	A loss in pressure during circulation of the heat carrier medium through the pipe network involved, one due to frictional forces (also termed as pressure loss).
Head lift	The maximum amount of pressure the pump can provide, the measure of it being given as the vertical lift of the medium.
Booster pump	A small-scale facility a network is equipped with, one located close to the consumers, for the purpose of providing an increase in the pressure of the supply line, in addition to the residual pressure capacity from the main pump station.
Holding pressure	A certain minimum amount of pressure maintained in the heat carrier medium during its circulation, in order to prevent the risk of cavitation.
Pressure gradient	A physical quantity representing the rate of change in pressure with respect to the length of the pipe segment or segments to which it is applied.
Substation	An in-house installation at a consumer site that conveys the heat content to be used in the space heating of a house and in the production of domestic hot water
Buffer tank	A small-scale tank used for the storage of heat in a substation, one that stores heat content from the district heating network during off-peak times of day for it to be used for in-house heat needs at peak times (also termed as storage tank).
Thermostatic valve	A self-regulating valve used in connection with in-house heating systems, one that regulates the flow of an in-house heat carrier medium in accordance with the heat demand rate.
Bypass valve	A self-regulating valve used in connection with a district heating network, its transmitting the supply-heat carrier medium, when its temperature be degraded, to the return line, to then be circulated to the heat source.
Heat Demand	The heat energy requirement of a consumer site.
Heat load	The heat energy that needs to be conducted by a district heating pipe network.
Simultaneity factor	A factor reducing the effect on the estimated heat load through taking advantage of the asynchronous heat use by multiple consumers, since use of heat by different consumers involved occurs neither all at the same time nor at the same rate.
Heat load duration	A decrescent way of showing heat loads together with their duration of occurrence during the period of a year with respect to a given district.
Heat load factor	The ratio of any particular heat load to the peak heat load rate.
Heat density	A physical quantity representing the unit of overall heat load per area of the land on which the district heating network is employed.

"Be a scholar, a science-lerner, or a science-listener; or a lover of them.

Don't be the fifth, then you'll be perished."

Prophet Muhammed

(Peace&Blessings Upon Him)

1 INTRODUCTION

District heating systems, supplying the heat produced from a central heat production plant/s to consumers by way of heat carrier medium circulating in a distribution network involving use of pre-insulated pipes, has been found to be highly useful. Their usefulness can be listed as (i) their being energy efficient, (ii) their being easy to exploit energy sources of virtually any type (even renewable electricity by means of electrically-driven heat pump), and (iii) their being able to recover low-grade waste heat that otherwise would be lost.

In the early stages of the use of district heating systems, the distribution of heat took place through the use of steam as the heat-carrying medium. In the course of time, the drawbacks in basing heat carrying here on the use of steam became increasingly evident. However, such systems were found (i) to be expensive in their construction and maintenance, (ii) to require condensation of the steam after its heat content had been utilized by consumers, (iii) to cause enormous heat losses, and (iv) to require excessive safety measures. In the wake of these defects being noted, the newly built systems that evolved were based on super-heated (pressurized) water, its temperature at about 120°C, and afterwards on hot water, at a temperature of about 90°C [1,2]. Further reduction in the supply temperature was achieved by pertaining trials of decreasing 5°C of the supply temperature each week from 85°C to 70°C in an operating Danish district heating system. In studying the effects of this practically on an operatin district heating system, a significant reduction in the heat loss from the district heating network was found as a decline from 460 TJ/year to 375 TJ/year when the supply temperature was reduced from 85°C to 70°C, respectively. However the pumping power was obtained without any change. The temperature difference was obtained with a decrease from 35°C to 28°C [3]. The article [3] provided further benefits of lowering temperatures as (i) improved efficiency of CHP plants, (ii) ease in using of heat storage tanks, (iii) upgraded exploitation of industrial surplus heat, (iv) possibilty of utilizing a condenser as a boiler and (v) simplified design of network. In more recent developments (details described in [4,5]), low-energy district heating systems operating at very low temperatures, 55°C in the case of supply and 25°C in the case of return, were found to satisfy the heating demands of low-energy houses when control of the substations was adequate. In case of a traditional district heating network when equipped to supply low-energy buildings, the low level of heat demand by consumers was obtained to cause the heat loss from the network being the major proportion in comparison to the overall heat load of the district. The solution to this issue was found with focus given on minimizing the heat loss from the network, and, thus, the investment cost. As given in [4], the socio-economic analysis resulted in economic superiority of low-energy district heating systems in comparison to cases of utilizing heat pumps (for two different configurations one as ground coil and the other as air-to-water).

Successful examples of employing such extremely low supply temperatures in low-energy DH systems have been demonstrated in various case projects, their descriptions given below:

I) Lystrup, Denmark as summarized from the articles [6,7],

The district heating system was designed with a high level of differential pressure so that small pipe dimensions can be ensured. A minimum supply temperature was defined as 50°C at the consumer site, its design return temperature being defined as 25°C. Both initiatives were the reason for having minimum heat loss from the district heating network. The key design criterias can be given as (i) maximum velocity of 2 m/s, (ii) maximum static pressure of 10 bar, (iii) holding pressure of 2 bar, (iv) minimum differential pressure of 0.5 bar, (v) supply temperature range of 50°C - 70°C, and (vi) by-pass valves equipped at the end of each street. The Lystrup district heating supplies to a heating space area of 4115 m^2 with 40 terraced houses and one community building. The terraced houses there was established in accordance to low-energy class standards with radiators for rooms and a floor heating for the bathroom, their overall heat demand given as 31.4 kWh/(m^2.year). The performance of this pilot low-energy district heating system was observed to be rewarding for the development of low temperature operation. Heat loss from the district heating network was obtained to be 25% lesser than the conventional district heating network that was considered with temperature scheme of 80°C – 40°C, as supply and return, respectively.

II) SSE Greenwatt Way development project in Slough in the UK, as summarized from the article [8],

This district heating system there was designed to be operated at a supply temperature of 55°C and its heat source being ground source heat pumps, air source heat pumps, solar thermal collectors, and a biomass boiler. The substation of each house was equipped with a plate heat exchanger providing heat supply as domestic hot water and space heating. The project highlights reducing the return temperature from the consumer-site by means of serial connection of the radiators, which, in return, improves the efficiency of heat production units while reduces (i) pipe sizes in the pipe dimensioning stage, (ii) the heat loss from the district heating network, and (iii) the pumping energy. Besides, a large stratified heat storage system was coupled to the district heating network. The benefits were achieved with (i) overcoming of the mismatch between heat supply and heat consumption by the consumers, (ii) flexibility and efficiency achieved in renewable heat production.

III) Drake Landing Solar Community development project in Okotoks, Alberta, Canada, as summarized from the article [9]

This district heating system was designed to supply at a temperature level of 55°C (for an outdoor temperature of -40°C) to 52 detached houses with high insulation properties, its source based on a solar thermal system (having 2293 m^2 gross area of plate collector) and a borehole seasonal storage system (having 34000 m^3 of earth space with a grid of 144 boreholes). Two heat storage systems were also equipped for short duration of use with a tank capacity of 240 m^3 to overcome the mismatch between heat supply and heat demand. The discharge rate of these heat storage systems were defined to be as in higher rate than the borehole seasonal storage system. Hence, the heat storage systems were used as buffer between the borehole storage system and the district heating system.

IV) The minewater development project in Heerlen, the Netherlands, as summarized from the article [10]

The minewater taken out from four different wells, each having different levels of temperature, has been used as source for a heat production plant that is supplying buildings there of (i) heat in low temperature as 35°C – 45°C and (ii) cooling in high temperature as 16°C – 18°C. The return temperature as combined of both heating and cooling is observed to be as 20°C - 25°C. As safety concerns, the low-energy district heating system was designed to be in couple with a polygeneration energy production system involving of electricity-driven heat pumps and of gas-fired high-efficient boilers. Besides the use of the underground spaces (of the abadoned mines) there as geothermal sources, they were also utilized as borehole storage systems. Hence, the unused heat from the low-energy district heating system was designed to be re-injected to the minewater volumes for storage purposes. The paper [10] states that as soon as the building insulation properties are excessively efficient, the supply of heating and cooling can be with low-grade energy (i.e. its level of supply temperature can be close to the room temperature). Another statement of the same study is regarding the high investment costs of such systems which, however, can become profitable by preventing additional cooling systems, by use of an integrated design approach, and by management also of the heat source by the investors. The integrated design approach here refers to the comprehensive optimization of one whole system imvolving of its sub-sections with their interactions to each other. In the paper [10], the sub-sections of one whole system were considered with (i) the building-site (focus given on its sustainability), (ii) determining the capacities of the sources, (iii) heat production site (focus given on technologies such as heat pumps, cogeneration, and storage of heat and of cooling mean), and (iv) emissions.

V) Operating low-energy district heating system in Kırşehir, Türkiye, as summarized from the article [11]

A successful example of employing low-temperature operations is also to be found in the district heating system in Kırşehir, Turkey, which has been supplying heat to 1,800 dwellings in high-rise multi-family buildings since 1994. The driving force for having low temperature operation in the municipal heat infrastructure there originated in the availability of a local geothermal source, having a temperature of about 57°C. In the design stage of this low-energy district heating system, some complaints arose regarding the practicability of using low-temperature operation in such a cold climate with outdoor design temperature of -12°C. However, any complaints were delated by the consumers so far. In the Kırşehir district heating network, the pipe type of polyester fiber-glass was used, its supply line being designed as pre-insulated while the return line without insulation, both buried at a depth of 1.5 – 2 km below ground. The operating temperatures were defined as 56 °C and 40 °C in terms of, respectively, supply and return. The heat loss from the supply line was observed as 0.4 °C/km. The idea of not using insulation in the return line can be interpreted as due to low investment together with the fact of utilizing free renewable source that is geothermal energy. The control of each of two distinct networks (one having the circulation of geothermal brine and the other having the circulation of heat carrier medium) was based on the control philosophy of pump flow rate control. The pump was determined as adjusting the flow rate dependent on the outside temperature and pressure regulation through the district heating network. Hence, three pumps were established as coupled to each network. The first stage pump was defined to be used in situations of the low-demand conditions (equivalent to 15.6% of the peak demand) during winter and in summer months. In case the overall demand increases, the second stage pump was defined to be activated to satisfy the overall heat demand equivalent to 39% of the peak demand. Then, the third stage pump was defined to be activated to satisfy the overall heat demand equivalent to 78% of the peak heat demand. Each in-house system was based on the control philosophy of “priority of domestic hot water heating”. The domestic hot water production unit was designed with an instantaneous heat exchanger units –with surface area in the range of 3 - 38.2 m^2–, its heat source being defined as the supply line of radiator system. The reason behind this was that the house thermal comfort condition was considered not be depreciated due to lack of space heating supply in 10 minutes of domestic hot water consumption. The radiator system installed at each house has a capacity, being obtained with operation temperatures of 54 °C in terms of supply temperature, and 38 °C in terms of return temperature. The temperature of domestic hot water was found to be 48°C in case the domestic water temperature coming to the production unit has the temperature at around 15°C. Various benefits of utilizing low operating temperatures have become evident through the experience gained from the demonstration projects and through different studies in this field [3,12,13], which have shown the following:

(i) reduction in the overall heat loss (a) from piping networks and equipments, such as heat exchanger stations, valves, etc. with which district heating systems became equipped and (b) through leakages of the heat carrier medium,

(ii) increased efficiency in heat extraction at heat production plants,

(iii) ease in the exploitation of (a) low-grade energy sources such as geothermal sources and solar energy and (b) waste heat from industry, which would otherwise be lost,

(iv) improved thermal comfort achieved by means of (a) low indoor air circulation speeds, (b) prevention of the dehydration of indoor air and of dust burning on radiators, as well as of skin burns, all of which are possible in the case of high temperature operations.

(v) decrease in the axial forces and stress that district heating piping networks can be subjected to.

(vi) reduced risk of encountering cavitation in the pipes in the network through reduction in the minimum cavitation pressure.

On the basis in particular of the advantages just referred to, low-energy district heating systems are rewarded as being able to utilize renewable energy sources in a satisfactory way to low-energy houses, doing so being a long-term goal of energy policies in Denmark [15].

1.1 Aim and Hypotheses

A major aim of this PhD thesis was defined as developing a method for using sustainable and energy efficient low-energy district heating systems both (i) in areas where low-energy houses have been built and (ii) in areas in which houses of a more conventional type are located. This method was conceived in particular as providing a framework for Danish municipalities being able to make an innovative and sustainable transformation of their energy infrastructures so as to have sustainable, energy efficient and environment friendly district heating systems (able to supply heat to low-energy buildings as well as to existing buildings with lacking or poor insulation). This is seen as facilitating an infrastructural transformation process involved in (i) developing a method for designing low-energy district heating systems considered for new settlements, (ii) developing a method for designing low-energy district heating systems for already existing settlements involving existing buildings in use of existing old in-house heating systems and (iii) developing a decision support tool in planning for the use of renewable energy sources as heat sources for low-energy district heating systems. Regarding the heat supply, strong emphasis is placed on matters of sustainability, security of supply and reliability.

It is hypothesized that a detailed analysis of energy performance and of overall costs – including the costs of investment and of operating and maintenance – of low-energy district heating systems can be used as a rational basis for planning the use of low-energy district heating in areas in particular in which low energy houses are built.

1.2 Purpose and Scope

The PhD research reported on here has been concerned with three main quantitative research questions (Figure 1.1).

The first research question is that of what method or methods can best be used to determine the most energy-efficient and sustainable optimal dimensioning of a low-energy district-heating piping network, together with the substation types and the network layouts that can most fruitfully be employed.

The second research question concerns the technical possibilities of integrating the use of low-energy district heating systems in already existing settlements with the existing in-house heating systems houses there are equipped with.

The third research question concerns that of how a decision support tool can be developed for determining the optimal capacities of renewable-energy-based energy conversion systems for supplying heat to low-energy district heating systems and the technical specifications such a tool should meet.

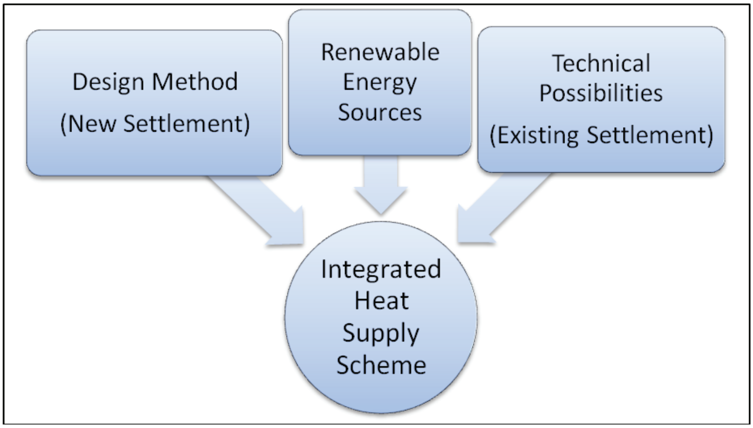


Figure 1.1. *The research questions concerned with the rational basis for developing future energy schemes*

In order to evaluate the applicability of the methods developed to the research questions posed, the methods were employed in three case studies; (i) a case study carried out in a suburban area of Trekroner, Denmark, the data and the maps involved being provided by the municipality of Roskilde, (ii) a case study carried out in an already existing settlement in which the buildings are currently being supplied by a natural gas grid, the data for the study and the map of the area needed being provided by the municipality of Gladsaxe, and (iii) a case study carried out for the Greater Copenhagen Area and for the Greater Toronto Area in which the low-energy district heating systems employed there were studied, the research questions referred to above being posed.

1.3 Disposition of the Thesis

The PhD thesis which is based on article-based dissertation consisted of six publications involving of three ISI articles, of one non-ISI article, and of two book chapters, all being referred in the section of "List of Publications".

The major aim of this PhD thesis was defined as 'the development of a method for use of sustainable and energy efficient low-energy district heating systems both for new settlements and existing settlements with existing buildings'. This major aim was formulated with three research questions, their detials being described in Section 1.2.

The first research question concerned the energy efficiency of the low-energy district heating networks for new settlements, considering the first part of the major aim of the PhD thesis. The beginning of the PhD study has the first inception task of developing a novel method for designing the low-energy district heating networks for a new settlement considering in particular sub-focus points: (i) pipe dimensioning methods, (ii) substation types, (iii) network layouts, and (iv) maximum levels of hydrostatic pressure involved. Following the aforementioned numbering here; the ISI articles I, and II, both, presented the results of the sub-focus points (i), (ii), and (iii); and the non-ISI article presented the results of the sub-focus point (iv) (Details given in Section 2.1.1).

The second research question concerned the energy efficiency of the low-energy district heating networks for existing settlements, in focus on the second part of the major aim of the PhD thesis. The investigation results of the first research question was utilized as the basis knowledge in addressing the second research question. Special focus was directed to develop a control philosophy of boosting the supply temperature in the peak cold winter periods for low-energy district heating systems. Here the low-energy district heating systems were considered to be replaced from the current heating infrastructures which can be a high-temperature district heating system or a natural gas heating system, both being expected to end their service life soon. Two areas of application of the control philosophy 'boosting the supply temperature in the peak cold winter periods' were studied, (i) one satisfying the current heat demands (which are of a higher level than that foreseen for the future) during the transition period of improving the insulation property of the existing buildings, and (ii) the other being the control philosophy for the future low-energy district heating systems as operational philosophy to overcome the short-lasting peak demand conditions. The ISI article III has the description of the technical solution involving of the control philosophy in question (Details given in Section 2.1.2).

The third research question concerned the sustainability, security of supply and reliability of the low-energy district heating systems, as third part of the major aim of the PhD thesis. Hence, focus was given on investigation of locally available renewable-based heat sources in order to supply to low-energy district heating systems (for new or existing settlements, both of which were investigated by addressing the first two research questions). Low-energy district heating systems were considered with single heat-production plants and also with multi-enegry generation plants which has better efficiency than single-generation ones. A decision support tool was developed for determining the capacities of renewable-energy-based energy conversion systems, together with the satisfaction of the monthly energy requirements, along with economic considerations in connection with the energy conversion system or systems being employed. Here, the monthly energy requirements were considered as heat for low-energy district heating systems, cooling for low-energy district cooling systems operating in high-temperatures, and electricty. The book chapters I and II provided a decision support tool for determining the capacities of renewable-energy-based energy conversion systems, together with (i) the satisfaction of the monthly energy requirements and (ii) economic considerations in connection with the energy conversion system or systems being employed. The book chapter I presented specifically the environmental improvement gained by use of renewable-sourced energy production systems in comparison to non-renewable sources regarding the decision support tool in question (Details given in Section 2.1.3).

Aforementioned descriptions of all methods as result of the three research questions show, in particular, their inter-complementary connection to each and, as whole, the achievement of the major aim of the PhD thesis. All of the methods obtained together with their results in the cases studies (each of which was observed as solution to one of three research questions), together, constituted the rational basis in response to the hypothesis of the PhD thesis, involving both of energy performance and of overall costs of low-energy district heating systems. The containment relationship of the research questions to one other can be seen in Figure 1.2.

It is hypothesized that a detailed analysis of energy performance and of overall costs – including the costs of investment and of operating and maintenance – of low-energy district heating systems can be used as a rational basis for planning the use of low-energy district heating in areas in particular in which low energy houses are built.

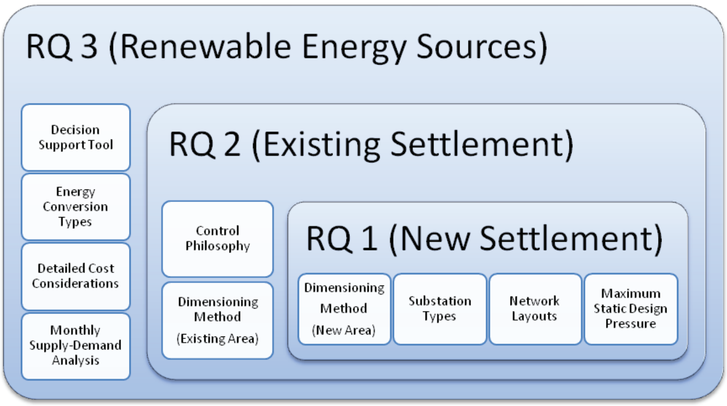


Figure 1.2. *Illustration of containment relations between the different research questions (RQ refers to Research Questions in the context named)*

"*Seek knowledge even in (as far as) China.*
Because seeking knowledge is religious duty upon every Muslim"
Prophet Muhammed (Peace&Blessings Upon Him)

2 METHODS

The first part of the method section deals with how the hypothesis of the PhD thesis is answered by means of adressing the research questions, their detail being given in Section 1.3 (Figure 1.2).

The solution to the first research question is described in Section 2.1.1 in which dimensioning of low-energy district heating networks considered for new settlements is presented. In particular, the consideration is given to the determination of (i) pipe dimensioning methods, (ii) substation types, (iii) network layouts, and (iv) maximum levels of hydrostatic pressure involved.
The solution to the second research question is described in Section 2.1.2 in which the use of the control philosophy "boosting the supply temperature in the peak cold winter periods for existing settlements is demonstrated. The design method developed as a response to the first question was re-considered with the operational control philosophy in solving the second research question.
As sum, the pipe determination methods were developed for new settlements and existing settlements (with existing city-wide heating infrastructure) in response to the research questions 1 and 2, respectively. Afterwards, the solution to the research question 3 is presented in Section 2.1.3 in which the determination method of the optimal capacities for renewable-based energy sources, supplying low-temperature heat to low-energy district heating systems is presented.

The second part of the methods section is concerned with the commercial software programs that have been utilized in connection with the research studies involved in the thesis.

2.1 Integrated Design for the Low-Energy Future

Various matters taken up in the ISI articles are dealt with in this section. Each sub-section concerns the methods developed to answer the research questions involved in the part referred to. The first two sub-sections, both concerned with dimensioning of low-energy district heating network, together with the last sub-section, concerned with the energy supply scheme intended to be applied to the renewable energy supply. Readers shall keep in mind that all of these sub-sections must be seen as constituting an integrated whole as the answer to the proposed hypothesis.

2.1.1 Design of Low-Energy District Heating Systems

This section presents a new method for the designing of low-energy district heating systems involving use of a pipe dimensioning method and the analysis of different substation types, of the effect of any booster pumps employed in the network, different network layouts, and the static pressure levels employed. The section also summarizes the methods described in the ISI articles I, and II; and in the non-ISI article I, all of which are concerned with providing an answer to the first research question.

Pipe-Dimensioning Method

The major aim here was to develop a pipe dimensioning method appropriate for the low-energy district heating systems to be employed in new settlements. The goal was to develop a dimensioning method providing greater energy savings and involving lesser construction costs for the piping network than achievable by use of a rule-of-thumb methods. These rule-of-thumbs methods are based on reducing the pipe dimensions of the network until the satisfaction of a certain criteria such as that of maximum velocity, maximum pressure gradient, or both [16]. Several approaches were considered for each of the different forms of a district heating networks.

The first approach was directed at modelling of a district heating network (i) with use of list of nodes, each indicating a consumer or conjunction point of multiple pipe segments, and (ii) with use of list of pipe segments, each indicating a continuous line of pipes of the same diameter connecting two nodes (this research concept being based on the study [17]). Here the use of a partite model of the network involved considering each pipe segment separately. The purpose as taken within this PhD thesis was to consider each pipe segment in accordance with the consumer load (the number of consumers) that the pipe segment is exposed to.

The next approach then was directed at determination of the heat load on the pipe segments involving use of simultaneity factor, its effect decreasing in accordance with the consumer load considered. The basic idea behind the use of simultaneity factor comes from the asynchronous behavior of heat consumption by consumers as whole [18]. Use of the simultaneity factor shows differences in the level of accordance with the type of heating demand involved, what was considered in the study being both space heating and heating of domestic hot water [19]. Various simultaneity factors, each of them unique for the demand type in question, either space heating demand or demand for domestic hot water production, were employed in each pipe segment. Simultaneity factor shows also difference in according to the substation type equipped as in-house installation. Two different types of the substation was involved in the PhD research studies, one with substation equipped with storage tank and the other with direct heat exchanger, both as the production unit of domestic hot water.After determining the heat load on each pipe segment involved, with use of the simultaneity factor, as a function of the consumer load, use was made of the pipe dimensioning method to be employed. The main idea here was to exploit the head (pressure) lift provided by the main pump station as much as possible in each route of the district heating network (the AluFlex type pipe has the limitation of the maximum static pressure being 10 bar – the absolute pressure). The argument behind this is that once the pump head lift can overcome the pressure loss in the critical route, which may be the longest route in the network (though this is not necessarily the case) it can overcome the pressure losses occurring in the other routes [20]. The idea was thus to develop an optimization model appraising each pipe segment of the DH network separately with dimensioning of it, while at the same time assessing the pressure loss occurring in each route for the purpose of maximising use of the head lift provided by the pump station. In line with the optimization flowchart shown in Figure 2.2, the objective function was formulated so as to minimize the heat loss from the district heating network, the constraint function being devised to maximise the exploitation of the allowable head lift in each route through decreasing the pipe dimensions appropriately.

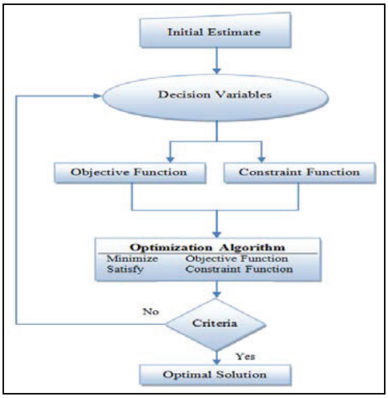


Figure 2.1. *General diagram of the optimization flowchart*

The optimization method developed was compared with the rule-of-thumb methods, one based on the 'Maximum pressure gradient – critical route method' in which one pressure gradient limit is taken as maximum, defined in terms of the critical route, for each route and the other being based on the 'Maximum pressure gradient – multi-route method', in which the maximum pressure gradient limit was determined for each route separately. The expressions used in application of the different dimensioning methods are given in Table 2.1.

There are several arguments against use of the optimization method in question, their being derived from consideration of the substation types in the in-house systems of the consumers, when including booster pumps in the network layouts, and employing the maximum static pressure for the design, all of which is described in detail in the following sections.

Table 2.1 *The expressions used in the different dimensioning methods*

Goals	Maximum pressure gradient		Optimization Method
	Critical route method	Multi-route method	
Objective of Minimization	$D(p_{i-1,i}) \quad \forall i = 1, \dots, n_i$	$D(p_{i-1,i}) \quad \forall i = 1, \dots, n_i$	$\dot{Q}_{Loss}$
Constraints	$\nabla P(p_{i-1,i}) \le \nabla P_{\mathrm{Max_{CR}}}$ $D(p_{i-1,i}) \in \boldsymbol{TPD}$	$\nabla P(p_{i-1,i}) \le \nabla P_{\mathrm{Max_l}} \quad \forall l; p_{i-1,i} \in l$ $D(p_{i-1,i}) \in \boldsymbol{TPD}$	$\Delta P(R_l) = \Delta P_{Max} \quad \forall l = 1, \dots, n_l$ $D(p_{i-1,i}) \in \boldsymbol{TPD}$
Equations Employed	$\nabla P(p_{i-1,i}) = \dfrac{\Delta P(P_{i-1,i})}{L(P_{i-1,i})}$ $\nabla P_{\mathrm{Max_{CR}}} = \dfrac{\Delta P_{Max}}{L(R_{CR})}$	$\nabla P_{\mathrm{Max_l}} = \dfrac{\Delta P_{Max}}{L(R_l)} \quad \forall l = 1, \dots, n_l$	$\dot{Q}_{Loss} = \sum_{i=1}^{n_i} \{L(p_{i-1,i}) \times [U_S(D^*(p_{i-1,i})) \times (T_S - T_G)$ $+ U_R(D^*(p_{i-1,i})) \times (T_R - T_G)]\}$ $D(p_{i-1,i}) = \lceil D^*(p_{i-1,i}) \rceil$ $D^*(p_{i-1,i}) \in \mathbb{R} \wedge D(p_{i-1,i}) \in \boldsymbol{TPD}$

where $p_{i-1,i}$ refers to the pipe segments that connect the node *i-1* to the node *i*, in the order from root node to leaf node. The affiliations with respect to pipe segments, indicated prior to the pipe segment by the notations *D*, *∇P*, *ΔP*, and *L* refer to the diameter, pressure gradient, pressure drop, and length of the pipe, respectively. *R* is the route constituted by the sequential pipe segments, starting from the root node and extending to the respective leaf nodes. The diameters of the pipe segments have their size in relation to the pipe diameter sets defined, either as **TPD,** representing commercially available pipe diameters, or as $\mathbb{R}$, so as to allow the optimization algorithm to find continuous (not commercially available) values for the diameters, which are later rounded up to the upper values of the diameters given in the set of **TPD**. In its sole form, the subscript *Max* refers to the maximum size of the parameter where it applied, additional subscripts being given next to *Max*, where CR and l, refer, respectively, to critical route, and to route label. The superscript * refers to generated values of decision variables for “the pipe diameters” as obtained by use of the optimization algorithm. The details can be found in ISI article I.

Substation Types

The properties of the substation the houses are equipped with have a considerable effect in various ways on the network dimensions, due to different levels of heat found in the district heating network and changes in the simultaneity effect in accordance with the heat consumption profile. In the present study, the aim was to investigate the effects of the storage (buffer) tank, which has a capacity of 120 litres, as taken from the studies [6,7,19,21,22]. Figure 2.3 shows the configurations of different substation types considered in the study. Another point concerned employing of booster pumps in the network with the aim of increasing the maximum allowable pressure loss, this being aimed in turn at being able to decrease the pipe dimensions further by use of the optimization algorithm. Employing booster pumps in the network, as shown in Figure 2.4 – (c), was considered, with use of the substation type not equipped with a storage tank in the houses of the consumers.

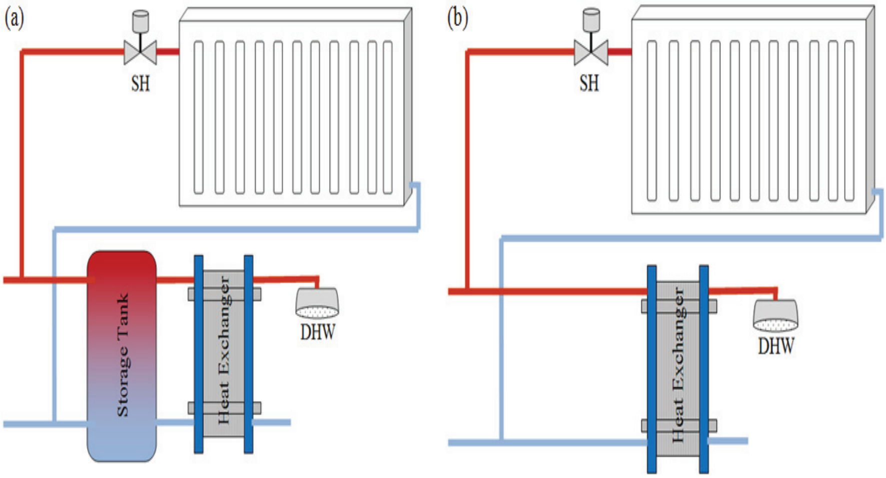


Figure 2.2. *Diagram of the two substation types employed: (a) with a storage tank and (b) without a storage tank, as taken from the ISI article II.*

Optimal pipe dimensions were obtained by use of the optimization method in question for three cases, (i) the one having a substation with a storage tank being located in each house, (ii) another having a substation without any storage tanks being used, and (iii) a third employing booster pumps in the network under the conditions applying to the second case. The reliability of the optimal pipe dimensions was later evaluated by use of the hydraulic and thermal simulation software Termis, using several scenarios as input data. The scenarios was formed with the heat consumption profiles of consumers representing the periods of the cold peak winter. Here the heat consumption profiles took, also, account of the degree of simultaneity of the heat demands.

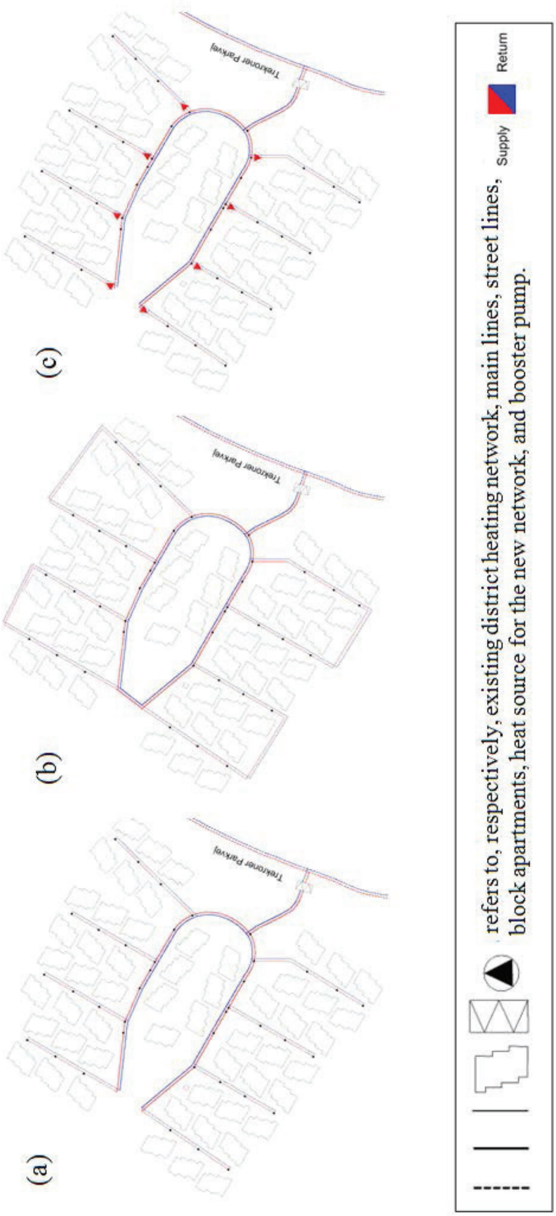


Figure 2.3. *Network layouts: (a) branched layout, (b) looped layout, and (c) branched layout involving use of booster pumps, illustrations taken from the ISI article II.*

Network Layouts

Another matter investigated was that of the layout of the distribution network, the one layout being in the form of a branched (tree-like) and the other a looped layout, as shown in - Figure 2.4 (a) and Figure 2.4 - (b), respectively [23,24]. The aim here was to measure the drops in temperature of the supply heat carrier medium when delivered to consumers during the summer period. This is because of the extreme scarcity of heat consumption then, due to the lack of any need for space heating, and reduced use of domestic hot water because of many consumers not being at home [25].

Several scenarios, generated with use of different domestic hot water consumption profiles, distinct for each consumer, in accordance with there being different occupancy patterns of consumers as a result of many people being on vacation, aimed at including as wide a range as possible of the urban heat consumption profiles involved, and obtained with consideration of a simultaneity factor effect for each pipe segment, were used as input to dynamic simulations that were carried out with use of the commercial software Termis.

Maximum Design Static Pressure

Dilemma originated when there was an excessive reduction in the pipe dimensions until the maximum allowable pressure loss in terms of the aforementioned optimization algorithm occurred. Accordingly, the effect of maximum design static pressure during the design stage on the dimensions of the piping network was investigated. In what was a comparative study of the optimal solutions found in connection with various input values for the maximum static pressure, the values obtained indicated, as shown in Table 2.2, that the maximum allowable pressure losses occurred at the points of maximal (i) overall costs – consisting of the investment costs and the levelized O&M costs caused by the heat loss and by the electricity consumption caused by pumping, (ii) exergy losses, and (iii) environmental impact. A sensitivity analysis was also performed in order to assess the uncertainty of the economic considerations taken account of in the study [26].

Table 2.2 *Maximum static pressure values appointed in the design stage of low-energy district heating network*

	Maximum Static Pressure Values [bara]					
	MSP 1	MSP 2	MSP 3	MSP 4	MSP 5	MSP 6
P_{MS}	4	6	8	10	15	25

2.1.2 Boosting of the Supply Temperature

After developing the optimization algorithm for dimensioning the pipes to be used in the case of a new settlement, the second research question aimed then at investigating the technical possibilities of employing a new low-energy district heating system in an existing housing area equipped with existing in-house heating systems [14,27], the details of which were taken up in ISI article III. The aim was to employ the control philosophy involving a boosting of the supply temperature in the cold winter periods that represent a very short part of the year. The expectation was to make use of the existing over-dimensions of the radiators (assumed here to represent the in-house heating systems employed), in the studies [14,28], consideration being given to the fact that energy saving measures are planned to be undertaken for the existing houses there in the near-future. The mass flow requirements were derived as being equivalent to the heat demand for (i) space heating, with consideration being given to the over-dimensioning of the radiators there, as well as the temperature level of the heat carrier medium temperature the consumers were supplied with, and (ii) domestic hot water, as assessed on the basis of the thermal response of the substation, configured as shown in Figure 2.4 (a). Various limits to the maximum mass flow values, as given in Table 2.3, were analyzed in order to evaluate the sensitivity of employing the control philosophy in question.

Table 2.3 *Various maximum mass flow values, analyzed as representing limits to the control philosophy investigated*

	Mass Flow Limits [kg/s]				
	MFL 1	MFL 2	MFL 3	MFL 4	MFL 5
$\dot{m}_{Max}$	107.7	80.0	50.0	20.0	15.3

Two areas of application for using the control philosophy in question were considered;

(i) the one area of application being for the transition period of the district from the use of a current heating infrastructure such as a natural gas grid and a traditional high-temperature district heating system, to use of a low-energy district heating system, avoiding the need of having an over-dimensioned network that could possibly be called for because of the high heat demand levels in the existing houses,

(ii) the other area of application being for the operation of a low-energy district heating network with the idea of boosting the supply temperature during the peak winter period, and the rest of the year having a low supply temperature, one of 55°C, in the case of having low-energy houses and a heat source available for producing the heat carrier medium at high temperatures.

Both areas of involved the same expectation that use of an over-dimensioned piping network in predominantly low-heating-demand situations in off-peak periods can be prevented by designing a network with the idea of increasing the temperature of the supply during the peak period. Sensitivity analysis was carried out in order to evaluate the limitations of applying the control philosophy in question, with the aim of determining, the supply temperature level required in the case of various configurations of the nominal capacity of in-house radiator heating systems and the current heat demand of the houses [29]. The decision concering variables of the sensitivity analaysis were determined as current heat demand, original radiator capacity and former radiator dimensioning standards, all of which were chosen due to their effects on the mass flow requirement for a low-energy district heating network designed in an existing settlement.

2.1.3Renewable Energy Supply

The third research question was concerned with the investigation of a decision support tool for determining the optimal capacities of the renewable energy based energy conversion systems the low-energy district heating systems were to be provided with. Efficiency gains are possible with use of such multi-generation technologies as cogeneration, trigeneration, and integrated multi-input multi-output generation systems [30,31]. Hence, the investigation planned was extended to encompass other types of energy requirements of the district involved in terms of the supply of electricity and of cooling. An optimization method was developed with the aim of minimizing the overall lifecycle costs of a group of different energy conversion technologies, each based on generation forms involving use of single-, co-, or tri-generation technologies, through determining their capacities and the degree to which the monthly requirements of each energy type were satisfied. Monthly evaluation was carried out due to the variation in energy demands of the houses being discordant with the variation in the energy production rates of some of the technologies (such as systems based on solar and on wind energy, and due to the long-term energy storage options that borehole storage systems provide in connection with heat (supply-demand) management). A detailed analysis of economic considerations was needed in order to have a basis for comparing different technologies, one taking account of several different parameters, such as (i) the specific investment costs involved with the economy-of-scale achieved, (ii) the levelized values with respect to the O&M cost, (iii) as well as the salvage costs on a lifetime basis, depending upon the technology involved. Also, the performance of each technology was studied, the parameters considered including (i) a capacity factor, (ii) energy efficiency, and (iii) the heat-to-electricity ratio in the case of being equipped with a cogeneration system to be employed in the constraint function of the optimization algorithm. Optimal solutions were assessed later from the standpoint of the exergoeconomic costs, and of the savings achieved in terms of environmental impact (in comparison to fossil-fuel based energy conversion technologies).

2.2 Commercial Softwares Utilized

The methods described in the section 2.1 were of considerable aid in the developmental work carried out, the observations made, and the evaluation of them, various details of which are taken up below.

The *Optimization Toolbox™*, which provided a wide variety of optimization algorithms using *MATLAB®*, was used very much in developing the methods employed. The nonlinear constrained multivariable models, each formulated differently when used to find the solution to the different research questions, were optimized by use of two different solvers, the one being a “fmincon” solver utilized extensively in connection with the first and the second research questions, details regarding this being presented in the ISI articles I, II, and III; and in the non-ISI article I, the other being the “genetic algorithm” solver utilized in connection with the third research question, details regarding it being provided in the book chapter I.

The *Visual Basic for Applications (VBA)* software together with Excel from Microsoft© were used in dealing with the large amount of data obtained regarding the nodes and the pipe segments involved in a district heating network, the codes employed being programmed to carry out the calculations involved in sequence over the routes and in each of the pipe segments involved, appropriate functions being employed to ease the integration of various expressions in the programming code, such as the simultaneity factor and simple (yet powerful) sub-codes for studying the relations between the pipe segments and the nodes.

Termis®, a hydraulic and thermal simulation program, was used in simulating the optimal district heating networks (obtained by use of the methods developed in the research works)with use of various generated-heat-demand scenarios during the peak winter period (to assess the reliability of the optimal dimensions), and for the summer period (to assess the drops in temperature of the heat supply carrier medium with use of different network layouts). Termis, as its state-of-the-art, is based on quasi-dynamic assumption, which deals with hydraulic and thermal analyses by use of continuity equations in terms of mass, impulse and energy on the basis of static flow model.

MapInfo®, a Geographic Information System (GIS) tool, was utilized for retrieving the data of the case studies, the spatial information involved being provided by the municipalities in collaboration with the author.

In the PhD work, the following software programs aided the work to a great extent.

XSteam provided the steam and water properties based on the International Association for Properties of Water and Steam Industrial Formulation 1997 (IAPWS IF-97), which was used as an add-on utility in connection with Excel and Matlab.

TeamViewer© was used to control the optimization simulations remotely from home, which enabled me to save a great deal of time in the PhD work as a whole.

"*Observations always involve theory.*" - Edwin Hubble

3 KEY RESULTS

The results obtained in the research studies carried out provide answers to the research questions posed, which are taken up in Section 1.2, the major results will be summarized here. A more detailed account of them can be found in the ISI articles referred to in the sub-sections that follow.

3.1 Optimal Design of Low-Energy District Heating Systems

In the ISI articles I, and II; and in the non-ISI article I, four aspects of the design of a low-energy district heating system intended for a new housing development were presented: (i) development of a pipe dimensioning method, (ii) effects of the substation type on the pipe dimensions employed, (iii) avoiding excessive drops in temperature in the network during the summer periods, and (iv) the effects on the pipe dimensions of the maximum design static pressures as foreseen in the design.

The methods developed, as presented in the aforementioned ISI articles, were employed in a case study concerning the suburban area of Trekroner in the municipality of Roskilde in Denmark, in which extensive building construction involving 165 low-energy houses is planned. The piping network is to have a total length of about 1.2 km in the layouts of the branched type, eight routes and 1.4 km in the layout being of the looped type, the lengths referred to excluding the end-user connections. Each in-house substation, supplied by the low-energy district heating system there, was assumed to have a unique peak heat demand of 2.9 kW in terms of space heating demand, and a unique heat demand of 32 kW, and of 3 kW in terms of heat demand in connection with domestic hot water production, respectively, in cases in which a substation is equipped with only an (instantaneous) heat exchanger or with a 120 liter storage tank installed before the heat exchanger.

Table 3.1 shows the pipe dimensions as obtained by use of three different dimensioning methods, the pressure drop values over each of eight different routes and the heat loss values being given in Table 3.2 (the substation type involves use of a storage tank).

A further investigation was carried out regarding the effects of various maximum design static pressure levels on the pipe dimensions called for. Each of the maximum static pressure levels was taken as a limit for the optimization method in question, their results for each being given for the overall length of the pipes for each of the pipe diameters involved, equipped as indicated in Table 3.3.

Table 3.1 *The overall pipe lengths as obtained for the different pipe diameters for each of three different dimensioning methods*

Pipe Type	Nominal Diameter	Pipe Length [m]		
		Pressure Gradient Critical Route	Pressure Gradient Multi Route	Optimization
AluFlex Twin Pipe	14/14	-	-	141.9
AluFlex Twin Pipe	16/16	-	-	22.8
AluFlex Twin Pipe	20/20	-	163.4	181.8
AluFlex Twin Pipe	26/26	369.5	206.1	263.6
AluFlex Twin Pipe	32/32	343.1	343.1	-
Steel Twin Pipe	32/32	214.7	250.4	471.4
Steel Twin Pipe	40/40	154.2	118.5	-
Steel Twin Pipe	50/50	66	66	-
Steel Twin Pipe	65/65	-	-	66
Steel Twin Pipe	80/80	-	-	-

Table 3.2 *Pressure drop values, as obtained over the routes involved on the basis of each of three different dimensioning methods and overall heat loss values*

Routes	Pressure drop through the routes [bar] and overall heat loss [kW]		
	Pressure Gradient Critical Route	Pressure Gradient Multi Route	Optimization
Route 1	1.91	2.26	6.56
Route 2	2.60	3.24	7.05
Route 3	3.17	3.82	7.64
Route 4	3.66	4.29	5.51
Route 5	1.98	2.32	6.53
Route 6	2.50	2.85	7.64
Route 7	3.15	3.48	6.40
Route 8	3.87	3.87	7.73
$\dot{Q}_{Loss}$	6.6	6.4	5.6

Table 3.3 *The overall pipe length as obtained for the pipe diameters listed, for each of six maximum static pressure values*

Pipe Type	Nominal Diameter	Pipe Length [m]					
		MSP 1	MSP 2	MSP 3	MSP 4	MSP 5	MSP 6
AluFlex Twin Pipe	14/14	-	-	-	141.9	-	-
AluFlex Twin Pipe	16/16	-	-	-	22.8	-	-
AluFlex Twin Pipe	20/20	-	94.7	162.9	181.8	-	-
AluFlex Twin Pipe	26/26	231.4	349.2	343.4	263.6	-	-
AluFlex Twin Pipe	32/32	296.9	235.1	206.3	-	-	-
Steel Twin Pipe	20/20	-	-	-	-	418.5	507.4
Steel Twin Pipe	25/25	-	-	-	-	377.9	574.1
Steel Twin Pipe	32/32	184.3	210.9	250.4	471.4	285.1	66
Steel Twin Pipe	40/40	177.3	144.1	118.5	-	66	-
Steel Twin Pipe	50/50	191.6	47.5	66	-	-	-
Steel Twin Pipe	65/65	66	66		66	-	-
Steel Twin Pipe	80/80	-	-	-	-	-	-

Figure 3.1 shows the exergy values of annual pump power and of annual heat loss for the Gladsaxe district heating network, its diameters being obtained by the optimization method (its description given in ISI Article I) with various levels of maximum static pressure levels. The details are presented in non-ISI Article I.

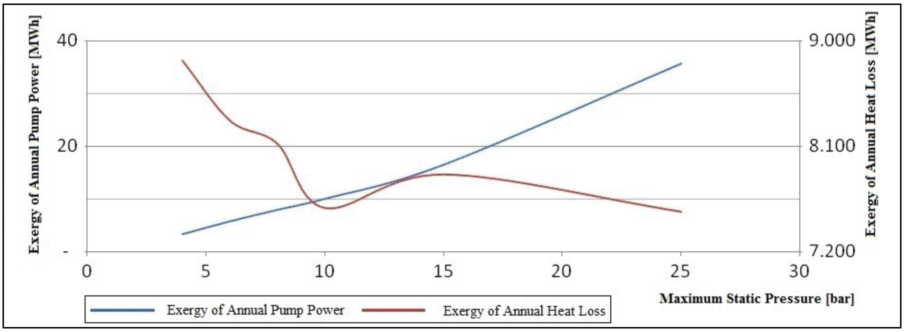


Figure 3.1. *Exergy values as obtained for the annual pump electricity consumption and for the overall heat loss from the DH network*

The effects of each of two different substation types and of the additional booster pumps installed in the district heating network on the pipe dimensions involved were examined with use of a dimensioning based on optimization, the results together with the heat loss values obtained in being shown in Table 3.4.

Table 3.4 *The overall length as obtained for different pipe diameters, for each of three different configurations of substation types, together with a booster pump employed.*

Pipe Type	Nominal Diameter	Pipe Length [m] and Overall Heat Loss [kW]		
		Substation (Storage Tank)	Substation (Heat Exchanger)*	Substation (Heat Exchanger) & Booster Pump*
AluFlex Twin Pipe	14/14	141.9	-	-
AluFlex Twin Pipe	16/16	22.8	-	-
AluFlex Twin Pipe	20/20	181.8	70.7	163.8
AluFlex Twin Pipe	26/26	263.6	92.4	156.2
AluFlex Twin Pipe	32/32	-	108.8	46.4
Steel Twin Pipe	32/32	471.4	762.1	667.6
Steel Twin Pipe	40/40	-	-	-
Steel Twin Pipe	50/50	-	-	47.5
Steel Twin Pipe	65/65	66	113.5	66
Steel Twin Pipe	80/80	-	-	-
$\dot{Q}_{Loss}$		5.6	6.1	6.0

* The order of the last two columns was given wrongly in the ISI article I, the correct order given here.

Drops in temperature were also evaluated in terms of the network layout involved, the one being a branched network and the other a looped layout, the loops being obtained by linking the end nodes of the branched network, as shown in Figure 2.4 – (b).

Table 3.5 shows the results of the dynamic analysis conducted, for a time period of 8 h, the heat demand profiles of consumers being generated on the basis of their presence ratio in 75%, 50%, and 25%.

Table 3.5 *Average values and standard deviations for different parameters, as obtained on the basis of observations made for each of two network layouts.*

Parameters	Presence Ratio	Network Layouts	
		Branched Network	Looped Network
Ratio of Heat Loss to Heat Supply [-]	25%	7.9% ± 0.03%	8.8% ± 0.21%
	50%	4.5% ± 0.01%	5.2% ± 0.03%
	75%	3.1% ± 0.02%	3.6% ± 0.03%
Return Temperature at Heat Source [°C]	25%	28 ± 0.48	25 ± 0.00
	50%	26 ± 0.14	25 ± 0.00
	75%	25 ± 0.03	25 ± 0.00
Degree-Minutes [°C-min]	25%	995 ± 435	20016 ± 11300
	50%	501 ± 144	2966 ± 1192
	75%	376 ± 101	987 ± 298

3.2 Control Philosophy of Boosting the Supply Temperature

The ISI article III presents a design method based on a control philosophy involving an increase in (a boosting of) the supply temperature during the peak winter periods in the case of low-energy district heating systems considered for use in connection with existing settlements. The method developed method was employed in a case study concerning an already existing housing district in the municipality of Gladsaxe in Denmark. At present, the district has a heating infrastructure involving use of a natural gas grid supplying the 783 houses there. In the case study regarding it, each flat’s demand for space heating was assumed to be 5.1 kW for the current situation and 2.9 kW for the future situation. The nominal capacity of the radiator systems currently used was assumed to be 9 kW for each house. The heat demand for domestic hot water production was considered to be 3 kW (in connection with use of a 120 litre storage tank) for the current and the future situation since the existing natural gas grid is assumed to have been replaced by a low-energy district heating system from the start of the period the study concerned. Table 3.6 shows the levels of the supply temperature and the maximum mass flow load required for the district in question in two different cases, the one without use of the control philosophy and the other with use of it, the maximum limit employed with use of the control philosophy being 15.5 kg/s. The return temperatures are also given in the table, the values for them being dependent upon the performance of the in-house radiators, in accordance with the supply temperature and with the maximum mass flow requirements involved.

Table 3.6 *Supply temperatures, the associated return temperatures, and the maximum flow loads observed, as obtained both for current and for future situations*

	WITHOUT CONTROL PHILOSOPHY			WITH CONTROL PHILOSOPHY		
	T_S [°C]	T_R [°C]	$\dot{m}_{DH}$ [kg/s]	T_S [°C]	T_R [°C]	$\dot{m}_{DH}$ [kg/s]
Current Situation	55	46.0	103.3	95	29.3	15.4
	55	39.3	53.4	87	26.1	15.5
	55	32.1	31.3	77	23.1	15.5
	55	24.6	19.3	63	22.8	15.5
	55	21.4	14.5	55	21.4	14.5
	55	19.6	8.6	55	19.6	8.6
	55	18.5	9.6	55	18.5	9.6
	55	18.0	7.7	55	18.0	7.7
Future Situation	55	26.0	20.8	65	22.5	15.5
	55	23.8	18.4	62	22.2	15.5
	55	21.6	15.5	55	21.6	15.5
	55	19.7	12.6	55	19.7	12.6
	55	18.7	10.6	55	18.7	10.6
	55	18.5	9.7	55	18.5	9.7
	55	18.1	8.2	55	18.1	8.2
	55	17.9	7.3	55	17.9	7.3

The overall lengths of the pipes and their diameters are given in Table 3.7, their being obtained by optimizing the district heating network under the limits of six different maximum flow rate values (Table 2.3). The annual heat losses from the district heating network are shown in Table 3.8.

Table 3.7 *The overall length of the pipes as obtained for different pipe diameters considered and for each of five mass flow limits*

Pipe Type	Nominal Diameter	Pipe Length [m]				
		MFL 1	MFL 2	MFL 3	MFL 4	MFL 5
AluFlex Twin Pipe	14/14	-	-	-	128	128
AluFlex Twin Pipe	16/16	-	-	-	410	530
AluFlex Twin Pipe	20/20	-	128	411	939	1049
AluFlex Twin Pipe	26/26	214	410	487	727	1753
AluFlex Twin Pipe	32/32	684	1169	1306	2188	1368
Steel Twin Pipe	32/32	809	210	1256	436	2248
Steel Twin Pipe	40/40	1385	1543	932	3301	1053
Steel Twin Pipe	50/50	1300	1368	2684	417	541
Steel Twin Pipe	65/65	919	2248	1053	419	295
Steel Twin Pipe	80/80	2818	1470	541	-	120
Steel Single Pipe	100	417	124	295	320	200
Steel Single Pipe	125	419	295	-	-	-
Steel Single Pipe	150	320	320	320	-	-

Table 3.8 *The annual heat loss values as obtained for the current and for future situations*

Situations	Annual Heat Losses [MWh]				
	MFL 1	MFL 2	MFL 3	MFL 4	MFL 5
Current Situation	44.7	30.8	17.1	5.5	4.0
Future Situation	43.8	30.1	16.6	5.3	3.8

Figure 3.2 shows the sensitivity measures of the supply temperature as function of nominal capacities and the current heat demands of the in-house radiators and Figure 3.3 shows the required mass flow rates and the levels of boosted supply temperature for the Gladsaxe DH network both for current and future scenarios..

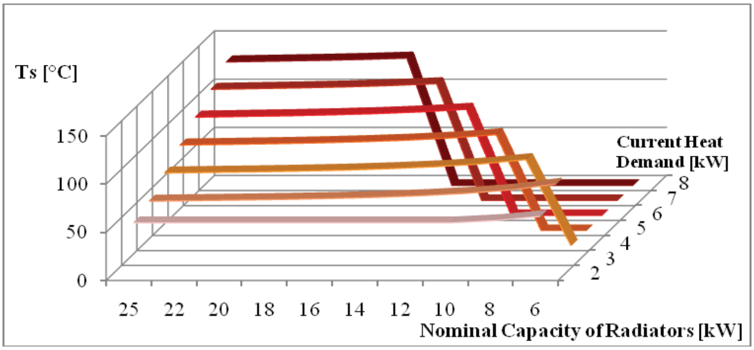


Figure 3.2. *Sensitivity analysis of the supply temperature*

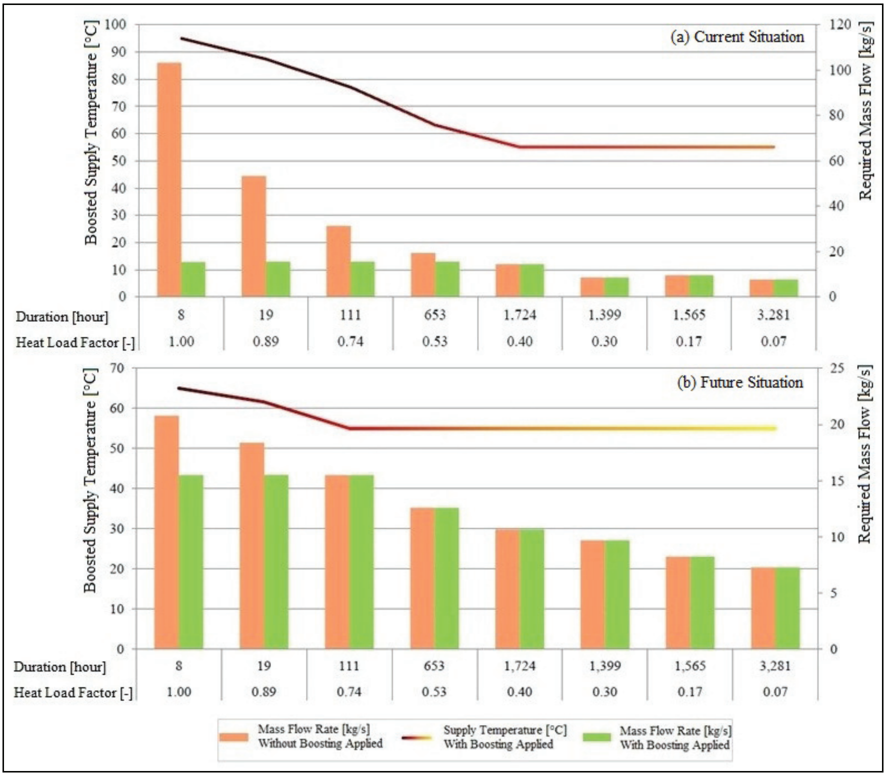


Figure 3.3. *Required mass flow rates, as taken from ISI Article III*

3.3 Optimal Renewable Energy Supply

The book chapter I presents the optimization method that was developed, which minimizes the nominal capacities of the renewable-energy-based energy conversion systems to satisfy the monthly energy requirements for electricity, heat, and cooling, each considered using of a distribution network, respectively, as electricity grid, as a low-energy district heating network, and as district cooling network. The method was employed in two case studies, the one for the Greater Copenhagen Area (GCA), and the other for the Greater Toronto Area (GTA), with their distinctive annual variations in their energy requirements, as shown in Table 3.9.

Table 3.9 *Monthly residential energy requirements for the case of GCA and of GTA, as taken from book chapter I*

		Monthly Energy Requirement Values [GWh]											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GCA	Heat	1392	1308	1274	771	536	386	352	268	402	754	1107	1358
	Electricity	850	767	787	661	680	636	630	685	689	726	751	786
	Cooling	0.77	0.72	0.80	0.99	0.99	1.27	1.65	1.65	1.10	0.69	0.69	0.69
CTA	Heat	3652	3369	1872	1419	961	869	861	883	861	2158	3072	3502
	Electricity	553	502	502	470	486	482	573	541	478	478	474	514
	Cooling	214	199	222	275	343	252	458	281	306	191	191	191

The optimal solutions are given in Figure 3.4, Figure 3.5, and Figure 3.6, for the annual production of the energy forms of electric energy, heating, and cooling, respectively.

The emission impacts of four different traditional fossil fuel-based energy conversion technologies are shown in Table 3.10 in which each of the observed data is given as emission saving for comparison to the case with supply of renewable-energy based energy conversion technologies, details given in book chapter II.

Table 3.10 *Emission impacts of four different traditional fossil fuel-based energy conversion technologies, as taken from book chapter II*

Technologies	η^*	Emissions (CO_2) [M tons] GCA	GTA
Coal-based back-pressure steam turbine	%88	703	1,118
Coal-based extraction-condensing steam turbine	%70	883	1,406
Natural gas-based gas turbine	%80	420	668
Propane-based reciprocating engine	%80	499	794

* Thermal efficiency of the power plant technologies indicated as assumed for the research work presented in the book chapter I and II.

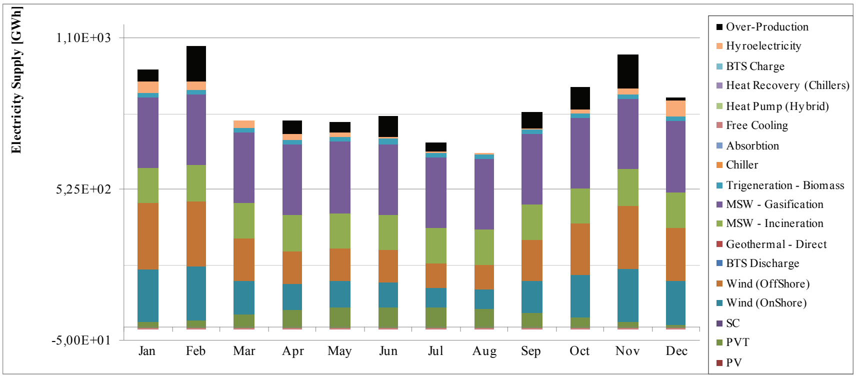


Figure 3.4. *The monthly electricity production in the case of GCA [Book Chapter I]*

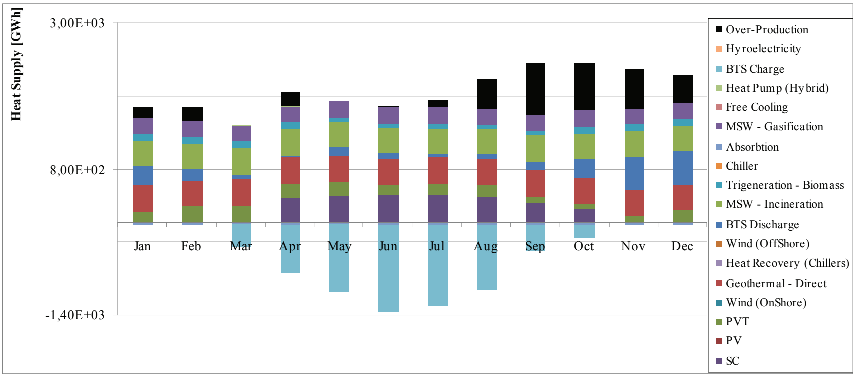


Figure 3.5. *The monthly heat production in the case of GCA [Book Chapter I]*

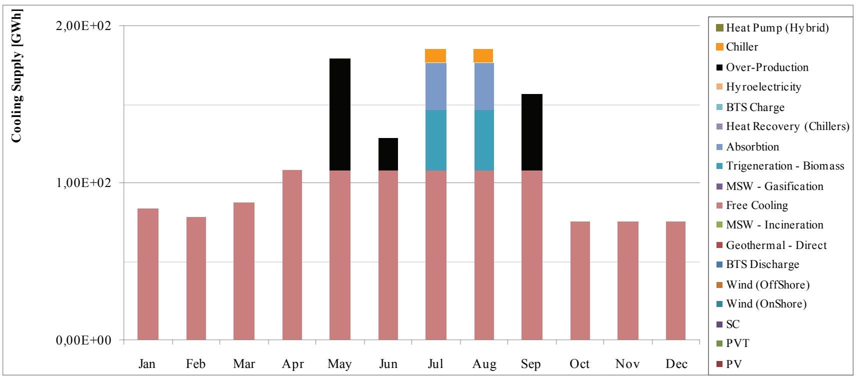


Figure 3.6. *The monthly cooling production in the case of GCA [Book Chapter I]*

The optimal solutions are given in Figure 3.7, Figure 3.8, and Figure 3.9 for the annual production of the energy forms electricity, heating, and cooling, respectively.

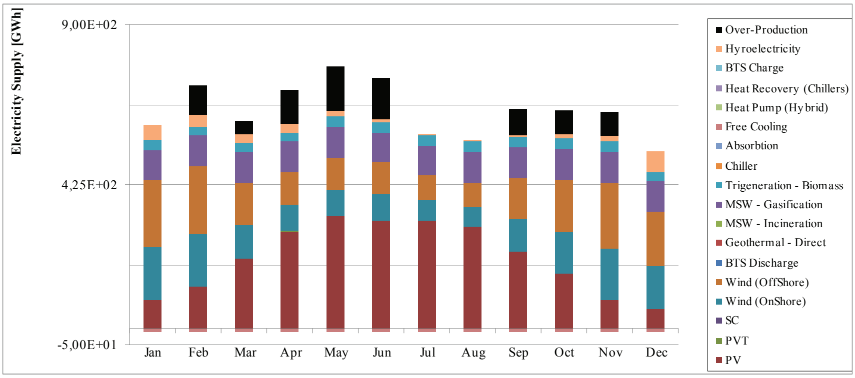


Figure 3.7. *The monthly electricity production in the case of GTA [Book Chapter I]*

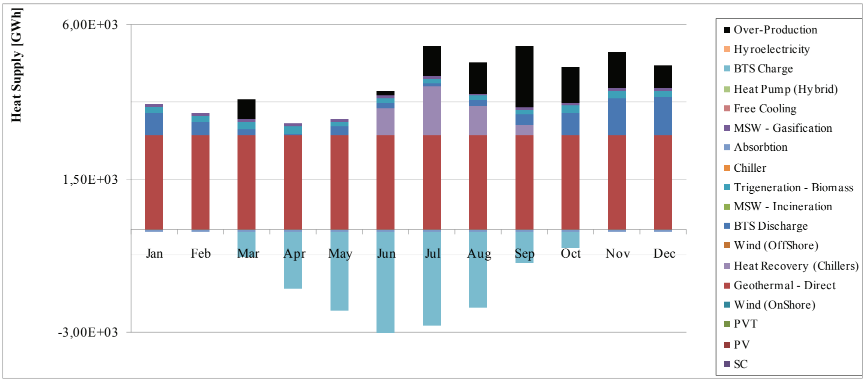


Figure 3.8. *The monthly heat production in the case of GTA [Book Chapter I]*

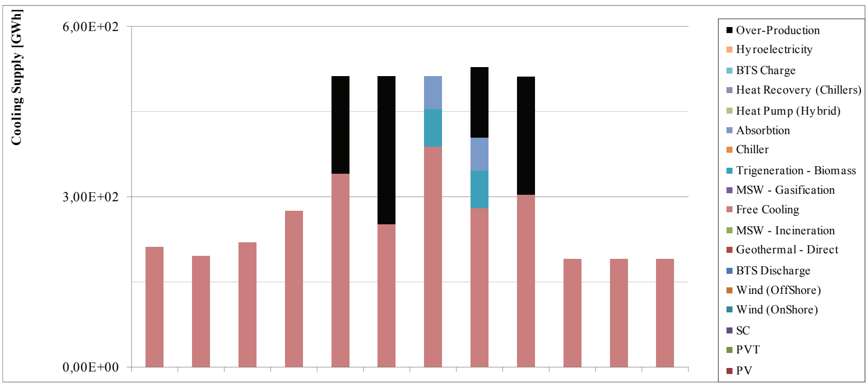


Figure 3.9. *The monthly cooling production in the case of GTA [Book Chapter I]*

"*In life, the truest guide is science*" – Mustafa Kemal Atatürk

4 DISCUSSION

The present PhD thesis documents various aspects of the design of low-energy district heating systems operating at very low temperatures, those of 55°C for supply and 25°C for return, the research questions of major interest concerning (i) the design of district heating networks for new settlements, (ii) the design of district heating networks for already existing communities, and (iii) renewable energy sources that can be used supplying heat to low-energy district heating systems. The methods developed, each designed for the detailed analysis of several dimensions of relevance here, such as energy performance measures and measures stemming from lifecycle cost analyses, represent the main topics of the thesis. Since start of the doctoral research work reported on here, the author's aim has been to develop methods of a type applicable to conditions such as those encountered in the planning of district heating systems in Denmark. The major observations made and results obtained, and how they can be interpreted will be briefly discussed here.

The **ISI articles I**, and **II** and; the **non-ISI article I** document the results that apply to the first research question considered in regard to the designing of district heating networks for new housing areas.

The heat requirement of a consumer can be met as soon as the substation equipped in the consumer site is provided with adequate levels of supply temperature and of pressure difference between the supply and the return line. In the project work for the first research question the focus mostly given to the pressure considerations in a district heating network due to its being determinative design criteria as most among the others. Any district heating network, both in the formation of layout as branched (tree-like) or as looped, is, in fact, a closed piping loop due to circulating of its heat carrier medium in the order as a heat exchanger in a heat production plant, a supply network line, a consumer installation (substation), a return network line, and again, (back to the first order) the heat production plant. Each consumer follows this order with division of each to other by another pipe branch, hence all of the consumers are in the formation of being parallel to each other. In detail, setting aside of a district heating network, it can be interpreted as paralel piping lines (each involving a consumer) one within the other (with focus given to the layout of branched network). For any piping network (independent of its being a district heating network), when considering parallel piping systems, the pressure loss is equal in each of the parallel piping lines. The critical route of a district heating network is always parallel to the other routes of the district heating network. The critical route always holds a pressure difference as the highest when considering between the supply and the return line near the location of the heat production plant. According to the principle of "equal pressure loss in each of the parallel piping lines", the routes rather than the critical one holds the pressure head which is determined by the critical route.

One of the most central research findings concerned the importance of exploiting the head lift provided by the pump station as much as possible (that is due to the aforementioned description of the research idea regarding pressure loss considerations) throughout the various routes of a district heating network, within the framework of the limits imposed by the maximum static pressure permitted. The optimization method based on this research idea was found to result in greater savings of energy than those that conventional pipe dimensioning methods based on consideration of the maximum pressure gradient along the critical route provided.

Results concerning the effects of the maximum static pressure on the optimal pipe diameters (reported in detail in **non-ISI article I**) showed that large energy savings can be achieved with use of pipes of the AluFlex type for districts in which variations in elevation permit the use of low levels of maximum static pressure (of 10 bar as obtained by this research work). Exergetic assessment was in need for comparing different energy types, as typical for district heating systems, the heat loss from the network and the consumption of electricity by the pump station. The exergetic values of the heat loss from the district heating network was found to be of greater weight than the consumption of electricity by the pump for each level of maximum static pressures (as its value being defined as between the limits of 4 bar and 25 bar) (Figure 7). However, another focus was directed to how the heat loss and pump power consumption being obtained for various levels of the maximum static pressure. The increase in the pump power requirement was observed to be significantly lower than the overall heat loss value with the increasing maximum static pressure below the maximum static pressure level of 10 bar. However, in high levels of the allowable pressure loss as defined 23 bar, a significant reduction of pipe dimensions were obtained, as can be seen in Table 3.3. Another discussion can be directed to the cost components. One major outcome of this research work was obtained regarding the cost components of the district heating network. That is obvious to indicate that the highest impact being the pipe investment cost. One can note the correlation of the pipe investment cost with the heat loss from the district heating network since both are dependent on the pipe dimensions. Hence, the objective function of the optimization algorithm can be formulated as a function, either, of the heat loss from the district heating network or of the overall pipe investment cost. It should be kept in mind that the sensitivity of the optimization results may differ according to the selected formulation (either pipe investment cost or heat loss from the district heating network).

Results of the investigations concerned with the types of substations employed (taken up in detail in **ISI article II**) show the heat load values to have a strong effect on the diameters that are optimal for the different pipe segments, when the optimization methods in question are applied to the networks for each substation type. Employing a storage tank in a substation reduces the load on the network appreciably, permitting a marked reduction in the pipe diameters involved. Other results of relevance here are that the preponderance of the end branches (the pipe segments close to the end-users) as opposed to the main transmission pipe segments (close to the heat source). It is obvious to indicate that the large amount of the end branches significantly contributes to the overall heat loss from the network more than the other branches of the network in the other sections. This occurs because of less amount of consumers being connected to the end branches and, as a consequence, lower reduction in the heat load by the simultaneity factor (since it is a function of consumer numbers) than the main transmission pipe segments having large amount of consumer load. Also, one should note that excessive reduction of the heat loss can be achieved by reducing the heat demand of the consumers, i.e. by means of equipping a storage tank in the substation and/or by means of improving the heat insulation of the consumer site together with savings in the domestic hot water consumption. .

It is rewarding to point out the discussion of the method described in ISI paper II. Another concept in designing low-energy district heating networks was involved in the research work with use of booster pumps in the network. Besides the head lift provided by the main pump station in the network, additional boost of head lift can be provided by a booster pump which, as its purpose of use (considered in this research work), is to be located in the mid-sections of a district heating network (i.e. between the main pump station and the end-users). In this research work, the concept of using booster pump was considered in the design stage of district heating network to reduce the pipe dimensions further than the reduced dimensions achieved by use of the optimization method (described in ISI paper I). It is rewarding to remind the reader that the dimensioning of the pipe segments (by use of the optimization method in question) of a network was defined as dependent upon the head lift provided (by the main pump station), its maximum limit being determined as below the maximum static pressure. The concept of the booster pump was considered with the idea of splitting the head lift on the route into two different parts. Additional booster pumps are equipped in the locations where the head lift provided by the main pump station reaches to its minimum level (below, there is a risk of cavitation). Hence, installing booster pumps there in the network provides an increase in head lift. The splitting of the network (with respect to the head lift), therefore, provides short sequences of pipe segments (such as (i) on sequences of pipe segments extending from the heat source to the booster pumps and (ii) from each booster pump to the leaf node of each route in question) that is in connection with the optimization method. Hence, with this concept (of utilizing booster pumps in the mid-sections of the network), the optimization algorithm makes use of the head lifts splitted by use of the booster pumps as the constraints. The additional head lift potential was utilized as excess space to be used in the constraints of the optimization. As a result further reduction of the pipe diameters were obtained more than the reduction achieved by the optimization itself.

Nevertheless, use of what in the case study carried out were found to be optimal pipe dimensions was not shown to increase the energy savings achieved as compared with the case of the substations being without storage tanks and the network being without booster pumps. Rather, installing booster pumps in the network can be considered to be best for districts that have large differences in elevation and/or that require large-scale networks having excessively long routes.

The dynamic simulations carried out to assess the drops in temperature drops in the various network layouts and the consequent heat loss from the network indicated the heat demand profiles of the consumers to have strong effects on the operation of the network. The presence of fewer consumers affects operations of the DH system by its increasing the variance obtained through the overall dynamic responses to differing scenarios caused by differences in heat demand profiles being more pronounced than when a greater number of consumers are involved. The results presented in **ISI article II** indicated use of a looped layout to result in longer waiting times than use of a branched layout equipped with bypass valves at the end-nodes of the network does. On the basis of observations made in connection with a degree-minutes evaluation, use of a looped layout results in larger drops in the temperature of the heat carrier medium than when a branched layout formation is employed, since the heat loss produced is greater.

ISI article III documents observations made pertaining to the second research question concerning the designing of district heating networks for existing housing areas. Details of the method obtained is rewarding to be described here in order to show the superiority of the research observations. The existing in-house radiator systems in existing settments was found to be with over-dimensions. This is because of the lower temperature differences as appointed in the design stage of the existing in-house radiator systems. Hence, in this research work, an operational control philosophy was considered with boosting of the supply temperature in the peak cold winter periods. The aim, here, was given to decrease the overall mass flow requirements of the low-energy district heating network, considering the performance of existing in-house radiator systems. In a pre-investigation of this research work, a dynamic analysis was carried out for an existing house with a certain level of heat demand with a radiator system having a certain capacity, (here the term certain being given to indicate no change during the dynamic analysis). As a result of this pre-investigation with the dynamic analysis, the mass flow requirement of the radiator system was obtained to be reduced with the increasing supply temperature. This is due to the difference between the nominal capacity of the radiators and the brought on heat demands of the house present at the time (reduced due to the improved insulation equipped there). The outcome of the pre-investigation formed the basis behind the use of the control philosophy of boosting supply temperature in the peak cold winter periods. The challenging point here can be the increase in the heat loss from the network that can be expected when the supply temperature level increases. However, the fact is that the cold periods last relatively short in durations as compared with the rest of the year period. Hence, the optimal pipe diameters, as obtained with use of the operational control philosophy of boosting the supply temperature, resulted in lesser heat loss from the network than the optimal pipe diameters without considering of the control philosophy.

Figure 9 shows the superiority of the control philosophy with boosting of supply temperature levels in the peak cold winter periods. With the control philosophy the supply temperature was observed with various upper levels (each level varies in different periods) than the low-temperature of 55 °C for short durations. Hence, an excessive reduction of the overall mass flow requirement was obtained, which is obvious to be rewarding in excessive reduction of the pipe dimensions of the district heating network in the design stage. This has to be interpreted as designing a future district heating network with for an existing settlement despite high heat demand of existing buildings. More in detail, the unnecessarily over-requirement of mass flow (when considering non-boosting of supply temperature case) can be leaped by increment of supply temperature levels in the transition period of replacement of an existing heating infrastructure with low-energy district heating system. Also, the control philosophy can still be utilized for saving any excessive mass flow requirements in the future operation of the low-energy district heating systems when the existing buildings will be renovated to low-energy-class.

The **book chapter I and II** document observations made pertaining to the third research question concerning the designing of a decision support tool for determining the optimal capacities of different energy conversion systems based on use of regional sources that are renewable. It was found that different aspects of assessing what solutions are optimal can influence decision making here. In comparison to the other similar research studies, the optimization method presented in the book chapters are superior due to detailed considerations, being taken into account in the economy calculations of the energy conversion plants. Besides the deficient considerations taken in the optimization methods of the other similar research studies, the considerations (all of which are essential together) were involved for each of the energy conversion system (plant). The list of the considerations are given here: (A) For each of the plants (i) the economy-of-scale (of the investment cost) as a function of the nominal capacity, (ii) the maximum capacity limit, (iii) the life time, (iv) the salvage cost in a period which was considered as the period for comparing all of the plants with various life times, and (v) capacity factor; and (B) For the district (i) various energy requirements (heating, domestic hot water, cooling, electricity as most essential necessasities) of most districts, and (ii) multi-generating energy conversion systems due to their superior efficiencies. Also, It was noted that the overproduction of heat that can readily occur during the summer due to the reduction in the heat requirements then and the ready availability of solar heat and of waste heat from supermarket cooling systems can be exploited by use of borehole storage systems.

Several optimal solutions were obtained with different capacity and with different overall lifecycle costs in both of the case studies. Some of the optimal solutions employed here had to be eliminated in accordance with various considerations, such as the variation of the energy sources (that is to satisfy the sustainability), overproduction, and the security of supply (which can be interpreted as shortcomings of the optimization method of this research work, to be considered in further studies).

Another major discussion point can be given to the domination of the energy conversion systems as obtained with the optimization. When considering the exergetic costs, the borehole thermal storage systems, the direct utilization of geothermal sources, and the free-cooling technologies employed resulted in a significant reduction in exergetic costs (being dominant in the point of nominal capacity) in all optimization solutions obtained. This is due to the very low specific costs assigned to the energy conversion systems in question.

"*Whoever follows a path to seek knowledge,*

Allah (The Creator, Subḥānahu Wa Ta'Ala) will ease their path to Paradise"

Prophet Muhammed

(Peace&Blessings Upon Him)

5 CONCLUSIONS

The prevailing use of low-energy district heating systems can be seen as being able to provide a win-win-solution to energy needs through locally available and renewable or low-grade energy sources being used to supply the energy for low-energy houses. Thus far, district heating systems generally have proved to be energy-efficient, environmentally friendly and convenient from the standpoint of consumers. From the municipal standpoint, the district heating systems have also proved to be superior due to its being sustainable, high secure in energy supply, local-energy-source-friendly, efficient in supply management and efficient in pollution control. The preliminary focus, as given in most, to sustainability, can easily be ensured with renewable energy sources that can be found locally such as geothermal energy, solar energy, hydroelectricity, wind energy, wave power, geothermal energy, bioenergy, biomass, waste fuel (from residuals of renewable consumptions), tidal power etc. Although most renewable sources are to produce electricity solely, the produced electricity can be used by heat pumps to produce heat supply for district heating systems. One should note that the supply temperature of the circulating heat carrier medium can be boosted with any type of heat source and/or any type of heat production plant. In terms of security of supply, district heating systems can be called as best among the other municipal-wide heating energy systems. Vast various renewable energy sources with their ease to produce hot water with several available technologies guarantee the security of supply when a mixture of heat production from several energy sources is considered. Another leading feature of district heating systems can be directed to ease of connecting any local energy sources (that can be referred as being local-energy-source-friendly). Also, exploiting of the municipal solid waste as waste fuel in the incineration plants can be referred as win-win-solution, providing benefit both as depleting the municipal waste and as production of heat. When considered with local biomass sources, cogeneration plants can also provide improvements in efficiency through their use of waste heat produced during the plant cycle. It is obvious is that most of the citizens are uneducated in heating appliances when considering the individual heating systems. Use of district heating systems ease management of heat supply, which eliminates the defficiencies of user-oriented individual heat production by the uneducated citizens. The management become superior with purchasement of economic fuel or of utilizing economic heat production plant, with supplying heat in accordance with the weather conditions, and with improved efficiency in heat production.

In the case of exploiting fossil-fuel energy sources, district heating systems can still be known as exclusive when compared to individual heating systems. This is because of the ease of controlling the pollution in the centralized heat production plants.

What applies to district heating systems generally applies still more to low-energy district heating systems. It is because of the ability of low-energy operation which provide the low temperature operation with use of virtually any type of heat source, including waste heat sources that would otherwise be unavailable. Besides, low-energy district heating systems provide improved energy efficiency, decreased environmental impact and better indoor thermal comfort than any traditional district heating systems.

The design methods were developed in the thesis work as response to various research questions. Employing of the methods in different case studies, and analysis of their results led to various conclusions regarding how to design low-energy district heating systems. All of the conclusions together related to the hypothesis that was investigated in this PhD thesis. It was concluded that concerns regarding the environmental impact of the production and consumption of the energy needed can be coped with through the use of low-energy district heating systems which can serve as a bridge between the use of renewable sources available regionally and the low-energy houses. It is indicated in the conclusion of all publications, stating as "a district heating system should always be designed in accordance with what works best within the district itself". It should be noted that the main aim of the research works carried out here has been to develop the design method in question, without assuming to provide the best solution for the cases considered. It has seemed reasonable to aim at this, since each district heating network needs to be designed in accordance with the geographical and climatic conditions that apply to the district in question. Thus, the methods proposed would need to be redesigned somewhat from case to case as new districts are dealt with. However, the obtained results can still be interpreted in the conclusion of this PhD thesis as the rewarding superiority of low-energy district heating systems.

A number of general conclusions not yet taken up can be drawn with respect to the first research question of this PhD thesis. One can note that the heat load from the consumer site has the dominant effect on the pipe dimensions in the design stage of district heating systems (regardless of the operational level of temperature). The heat load has to be considered with two parts, one being, as obvious, the heat demands of consumers and the simultaneity of the heat demands for the pipe segments having supply to multiple consumers. Another effect on the pipe dimensions can be considered by the operational control philosophy. In regard to the network-site of district heating system, one of the important recommendations arrived at in the thesis work is that of employing suitable storage tanks in the substations of the houses. The reason is due to the reducing effect on the heat demand of the consumer-site with the equipped storage tank and thus of the pipe dimensions. The storage tank has a significant effect on reducing the heat demand of domestic hot water, which is more than the heat demand of space heating. However, small houses can be provided with substations equipped only with a heat exchanger for domestic hot water production because of the limited space available in them.

One of the major promoting conclusion is given of using simultaneity factors in determination of the heat load in each pipe segment. It is because making adequate use of simultaneity measures was obtained to be important for their preventing overestimates of the heat load due to the admittedly rather infrequent occurrence of concurrent heat consumption when multiple consumers are involved. Obtaining the most accurate estimates of the heat load possible – neither over nor underestimated – for all parts of a district heating network can help providing improvements in the energy efficiency.

After determination of the heat load on the pipe segments, as indicated – neither over nor underestimated –,the optimization algorithm (the one given in **ISI article I**) can be utilized to lead to further savings in construction cost of the network-site due to reduced diameters of the pipe segments. The optimization algorithm in question was based on taking into consideration particularly of each pipe segment which was considered with reducing effect (on heat load) by simultaneity factor that is determined as a function of the number of consumers connected (to that pipe segment). This allowed making it possible to reduce each pipe diameter in the network to the smallest size possible, in accordance with the unique heat load on each of the pipes (thus unique mass flow requirement there). The unique mass flow obtained (with use of optimization algorithm) on each pipe segment was discovered to has its upper limit with the pressure loss through each route. The limiting effect of the pressure loss through each route was defined as reaching its highest point just below the head lift of the main pump in the optimization algorithm. Considering the equal pressure drops occuring in parallel pipes, once the pressure loss of the critical route is satisfied by the head lift provided by the main pump station, the pressure losses of the other routes can be up to the level of the pressure loss of the critical route. In sum, the optimization algorithm was based on reducing the diameter of pipe segments each of which was considered with reduced heat load involving of simultaneity factor effect, the reduction of the diameters having the upper limit of pressure losses through the routes of the district heating network.

AluFlex twin pipes, which involve of supply and return pipes symmetrically in one outer casing, have the capacity of providing an unsurpassed degree of energy saving. The benefits in use of AluFlex twin pipes can also be listed with (i) its flexibility in installation (thus reduced installation times), (ii) a layer of aluminium foil as a diffusion barrier between the outer casing and the insulation material –providing unchanging insulation property –, and (iii) reduced pressure drop due to low Darcy friction factor and abstention of angled bends. In the districts where high levels of hydrostatic static pressure exist due to variations in elevation, use of AluFlex is still possible by installing booster pumps in the network. In addition to the reduction benefits achieved on pipe diameters with the optimization algorithm itself (aforementioned), further reduction was obtained to be possible by use of booster pumps. Booster pumps can be useful by providing shorter sequences of head lift potential to be considered as the upper limit for the routes of the network with the optimization method. Another conclusion point can be directed to low-demand situations which occur in summer months. Two criterias were investigated for these situations, one being satisfaction of the consumers in terms of supply temperature if it degrades to below a certain base temperature level of 50 °C and the other being the energy efficiency of district network (this time energy efficiency is dependent of stagnation of the heat carrier medium due to low-energy demand by consumers). It should be noticed that the conceptual design of a network (such as equipment of bypass valves, designing of network in looped layout etc.) may result as either satisfactory or unsatisfactory according to the design conditions of the district. However, one outcome of this PhD thesis (the conclusion may change for other networks, its reason given just before) highlights that bypass valves in the end-nodes of a branched network may be best in sparsely-populated districts while a looped layout is best in densely-populated-districts.

A number of general conclusions not yet taken up can be drawn with respect to the second research question of this PhD thesis. An auxiliary reduction in the pipe dimensions employed can also be achieved by utilizing the operational control philosophy as a basis for boosting the supply temperature during peak periods, for those districts in which local renewable energy sources can provide temperatures higher than 55°C. Use of this approach can be considered as applicable in two cases in particular, (i) the one being during the transition period of the heat infrastructure schemes involved, where a replacement of the existing region-wide heating systems present by low-energy district heating systems is planned, and (ii) the other being to use it as the operational strategy of choice for low-energy district heating systems. Considering the future conditions of a district with decreasing heat demand of consumers (due to low-energy class adaptation there), the control philosophy of boosting the supply temperature in short-lasting peak periods in the design stage avoids pipe dimensions that can be infered as over-dimensioned with regard to the future condition. Hence, the district heating network, being dimensioned in accordance with the low-future heat demands, can be sufficient in meeting the current high heat demands with increased supply temperatures. One can note that the significantly reduced mass flow requirements (which refers fundamentally to heat load however is a must-design-criteria – instead of head load – due to the varying supply and return temperatures) can be achieved with the control philosophy of boosting the supply temperature. Any concern about the risk of high heat loss from the network due to the high supply temperature can be inessential. It is because of (i) short duration of peak winter conditions and (ii) savings in heat loss due to the reduced pipe dimensions (that is achieved by the boosted supply temperature) being larger than the deficiency in heat loss by the increment of the supply temperature. Municipal energy planning, hence, can be involved with this control philosophy for existing settlements which (i) are in focus to be replaced from their current heating infrastuctures (their service life being soon over) with low-energy district heating systems and/or (ii) are planned to have renovation on the existing buildings, their energy efficiency being in low level, to upper low-energy class buildings. The control philosophy can be utilized (i) greatly (in high levels of boosting for long durations) in the transition period of replacing the current heating infrastructure to low-energy district heating system and (ii), after the replacement (and the renovation of the existing buildings there), with low levels of boosting with short durations. Some significant benefits can be given as (i) reduced pipe diameters by lowered mass flow requirement with boosting of supply temperature applied, (ii) energy improvements due to reduced pipe diameters, and (iii) ease of boosting the supply temperature for any extreme cases with unexpected over-peak winter conditions in the future operation (when the low-energy district heating systems supplies to renovated low-energy class buildings).

A number of general conclusions not yet taken up can be drawn with respect to the third research question of this PhD thesis. Having low-energy district heating systems that cover an urban area completely can call for concern in focus with searching for the least-costly energy conversion system (energy production plant and/or energy supply) that is locally available. Hence, regional energy planning can be the solution for integrating local renewable sources to low-energy district heating systems. Several different performance measures can be relevant to evaluating the best locally available heat sources here. Each energy conversion system's being unique in its technology results in the need of having a reasonable economic evaluation method that is suitable for comparing all alternatives. Lifecycle cost analysis, if it is used, should be well-defined, special attention being directed at clearly defining of various economic parameters for each of the energy conversion systems. The economic parameters, in this research work of the PhD thesis took account of the specific investment costs considered, together with the economy-of-scale, the lifetime, operating and maintenance cost, and salvage value. The improvements in efficiency with use of multi-generation systems brought the need of including other energy forms in the analysis, such as those of electricity and of cooling, which are most commonly mentioned next to heat energy, although they are outside the scope of the thesis. The integrated consideration of various energy requirements is thus suggested, due to (i) hybrid systems being particularly common in the energy supply infrastructure and (ii) the improved efficiency of multi-generation which if not considered in energy planning tools may cause unrealistic results (for the design capacities to be determined for a mixture of energy conversion systems – e.g. involving of hybrid photovoltaic/thermal cells is neccessary when considering solar energy source besides solely consideration of photovoltaic and/or solar collectors). The long-term energy storage systems that borehole systems represent can be utilized for recuperating the leftover heat produced during the summer period –due to the extreme availability of such sources as renewable solar energy and waste heat from large-scale refrigeration cycles then– that can made use of during the peak winter periods.

One can note that the analysis of energy planning should be carried out on a monthly basis for a period of a year. The reason behind this is because there is a month-to-month variation (i) in the energy production of various energy conversion systems, (ii) in the energy demand of various energy types that are dissimilar with respect to each other, (iii) in the capacity factors with the production of each of the energy types, the analysis given in this paper was carried out, and (iv) in the energy charged or discharged in the borehole storage system.

One should note that the ideal energy supply scheme should involve the integrated use of locally available renewable energy resources to be supplied efficiently to the consumer sites. Attention should be directed at the possibility of using multi-input multi-output energy conversion systems to meet demands and considerations of various types, such as those of electricity, heating, cooling, use of renewable-fuels for transportation, clean water, and cooking. The detailed analysis of this in the thesis with a limited scope (only involving of electricity, heat, and cooling) can be seen as representing a humble step in the direction of providing for the use of an ideal energy supply scheme.

Although there are obvious limitations to the matters taken up in the research reported, the thesis can also be seen as providing a sensible basis for further study. The carrying out of the specific methods employed in the case studies relies on imaginary-but-reasonable data, such as the heat demand values taken and the economic matters considered in connection with the renewable-energy-based conversion systems. One can investigate complex network structures involving both branched and looped network layouts. A further research topic to be mentioned is that of dynamic surveys of the heat consumption in existing districts for cases involving different types of heat-consumption behavior and different types of consumers, different energy supply infrastructures, and different in-house heating systems. This can contribute to still further studies in the area of planning concerning future heating infrastructures. Also, one can investigate the technical possibilities of employing low-temperature operations in district heating networks designed with use of conventional pipe dimensioning methods on the basis of their current high-temperature operations. Moreover, one can investigate using of boosting supply temperature for high-heat-demanding consumers (such as hospitals etc.) in low-energy district heating systems. In addition, research work involved with the designing new low-energy district heating systems for existing housing area could be expanded further to include other indoor heating systems, such as floor heating systems and various layouts for indoor heating systems, installed in the existing house architecture. The decision support tool for developing renewable-energy-based energy conversion systems can be further enhanced by providing it a broader scope than what was studied here, through including (i) further types of renewable sources, such as wave energy and tidal sources, (ii) various technologies in connection with each type of energy conversion system, including large-scale systems such as solar parabolic collectors and heat recovery systems involving cogeneration, and individual systems such as used for installing small-scale heat pumps in houses, and (iii) several different energy outputs. Thermal storage on a medium-scale level (as compared with long-term energy options) could be a topic of investigation of interest in the further development of low-energy district heating systems.

6 REFERENCES

[1] Skagestad B. & Mildenstein P. (2002), *District heating and cooling connection handbook*, Netherlands Agency for Energy and the Environment (NOVEM), The Netherlands.

[2] National District Heating Association (1951), *District heating handbook: a manual of district heating practice, a description of the district heating industry, a guide to modern commercial equipment*, National District Heating Association.

[3] Foged M. (1999), 'Low temperature operation' [News], DBDH [electronic mail on the Internet - cited 2011 Jan], 1, pp. 3-9.

[4] Olsen P.K., Lambertsen H, Hummelshøj R, Bøhm B, Christiansen CH & Svendsen S, et al (2008), 'A new low-temperature district heating system for low-energy buildings', *The 11th International Symposium on District Heating and Cooling*.

[5] Paulsen O., Fan J., Furbo S. & Thorsen J.E. (2008), 'Consumer unit for low energy district heating net', *The 11th International Symposium on District Heating and Cooling*.

[6] Christiansen C.H., Worm J., Jørgensen H., Thorsen J.E., Bennetsen J., & Larsen C.T., et al (2011), *Demonstration of low energy district heating system for low energy building in Ringgårdens Afd. 34 in Lystrup [Demonstration af lavenergifjernvarme til lavenergibyggeri i boligforeningen Ringgårdens afd. 34 i Lystrup]* [in Danish], Report No.: EUDP 2008-II, Teknologisk Institut, Taastrup, Copenhagen.

[7] Thorsen J.E., Christiansen C.H., Brand M., Olesen P.K., & Larsen C.T. (2011), 'Experiences on low-temperature district heating in Lystrup e Denmark', *International Conference on District Energy*.

[8] Wiltshire R. (2011), 'Low temperature district energy systems', *Proceedings of the 16th Building Services, Mechanical and Building Industry Days*.

[9] Sibbitt B., Onno T., McClenahan D., Thronton J., Brunger A., & Kokko J. et al (2007), 'The Drake Landing Solar Community project - Early results', *Proceedings of the 32nd Annual Conference of the Solar Energy Society of Canada*.

[10] Roijen, E., Op 't Veld, P. & Demollin-Schneiders, E. (2007), 'The minewaterproject Heerlen, the Netherlands - low exergy heating and cooling in practice', *28th AIVC and 2nd Palenc Conference "Building Low Energy Cooling and Ventilation Technologies in the 21st Century"*.

[11] Mertoglu O., Bakir N., & Kaya T. (2003), 'Geothermal applications in Turkey', Geothermics **32** (4-6), 419-428.

[12] Østergaard P.A., & Lund H. (2011), 'A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating', Applied Energy **88** (2), 479-487.

[13] Østergaard P.A., Mathiesen B.V., Möller B., & Lund H. (2010), 'A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass', Energy **35** (12), 4892-4901.

[14] Hasan A., Kurnitski J., & Jokiranta K. (2009), 'A combined low temperature water heating system consisting of radiators and floor heating', Energy and Buildings **41** (5), 470-479.

[15] Klima- og Energiministeriet (2012), *Energy policy report 2012*.

[16] Overgaard J., & Knudsen S. (2006), 'District heating networks - choosing the right pipe dimensions' [News], DBDH, [cited 2011 Jan], Link: http://dbdh.dk/images/uploads/pdf-distribution/district-heating-networkschoosing-the-right.pdf.

[17] Benonysson A., Bøhm B., & Ravn H.F. (1995), 'Operational optimization in a district heating system', Energy Conversion and Management **36** (5), 297-314.

[18] Winter W., Haslauer T., & Obernberger I. (2001), 'Simultaneity surveys in district heating networks: Results and project experience [Untersuchungen zur Gleich-zeitigkeit in Nahwärmenetzen : Ergebnisse und Projekterfahrungen] [In German]', Euroheat&Power **30** (10), 42-47.

[19] Thorsen J.E., & Kristjansson H. (2002), *Cost considerations on storage tank versus heat exchanger for hot water preparation*, Report No.: VF.KQ.A2.02, Danfoss A/S, Nordborg.

[20] Sanks R.L (1998) 'Flow in conduits', in: Sanks R.L., Tchobanoglous G., Bosserman B.E, & Jones G.M. (Ed.) *Pumping station design*, Butterworth-Heinemann Boston, USA, 33-39.

[21] Christiansen C.H., Paulsen O., Bøhm B., Thorsen J.E., Ting Larsen C., & Jepsen B.K. et al (2009), *Development and demonstration of low-energy district heating for low-energy buildings. Main report and appendices [Udvikling og demonstration af lavenergi-fjernvarme til lavenergibyggeri. Hovedrapport og bilag]* [In Danish], Report No.: EFP 20072009, Teknologisk Institut, Taastrup, Copenhagen.

[22] Thorsen J.E. (2002), *Dynamic simulation of DH house stations*, Report No.: VF.HB.K2.02, Danfoss A/S, Nordborg, Denmark.

[23] Lejano R.P. (2006), 'Optimizing the layout and design of branched pipeline water distribution systems', Irrigation and Drainage Systems **20** (1), 125-137.

[24] Davidson J.W. (1998), *Learning program for the design of layout geometry of rectilinear looped water distribution networks*, PhD thesis, University of Manitoba, Manitoba, Canada.

[25] Gabrielaitiene I., Bøhm B., & Sunden B. (2007), 'Modelling temperature dynamics of a district heating system in Naestved, Denmark—A case study', Energy Conversion and Management **48** (1), 78-86.

[26] Durmayaz A. (2000), 'An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul', Energy **25** (12), 1245-1256.

[27] Steer K.C.B., Wirth A., & Halgamuge S.K. (2011), 'Control period selection for improved operating performance in district heating networks', Energy and Buildings **43** (2-3), 605-613.

[28] Mertoğlu O., Dokuz İ., Canlan A., & Bakır N. (1999), 'Alternative energy sources and low temperature geothermal district heating [Alternatif enerji kaynakları ve düşük sıcaklıklı jeotermal bölgesel ısıtma]' [In Turkish]. Tesisat Mühendisliği 55, 52-62.

[29] Chinneck J.W. (2006) 'Sensitivity Analysis', in: Chinneck J.W. (Ed.), *Practical optimization: A gentle introduction*, Carleton University, Ottawa, Ontario, Canada.

[30] Dincer I., & Zamfirescu C. (2012) 'Integrated multigeneration energy systems', in: Dincer I., & Zamfirescu C. (Ed.), *Sustainable energy systems and applications*, Springer, New York, USA, 497-517.

[31] Dincer I., & Zamfirescu C. (2012), 'Renewable-energy-based multigeneration systems', International Journal of Energy Research, **36** (15), 1403-1415.

LIST OF SYMBOLS

Sets

$\mathbb{R}$	Set of real numbers
TPD	Set of inner diameters of the commercially available pipes

Roman Letters

D	Inner diameter [mm]
$i\ ,l$	Node indices [-]
i-1	The index for the predecessor node [-]
L	Length [m]
$\dot{m}$	Mass flow [kg/s]
n	Overall amount of the entry type [-]
P	Pressure [bar]
p	Pipe segment entry in the set of pipe segments [-]
$\dot{Q}$	Heat rate [kW]
R	Route [-]
T	Temperature [°C]
U	Linear thermal coefficient [W/(mK)]

Greek Letters

Δ	Difference
φ	Occupancy ratio [%]
∇	Gradient

Subscripts

CR	Critical route
DH	Overall district heating
G	Ground
$Loss$	Loss
Max	Maximum
Min	Minimum
MS	Maximum static pressure
R	Return
S	Supply

Superscripts

*	Continuous (non commercially available) value

LIST OF FIGURES

LIST OF TABLES

APPENDIX

(PUBLICATIONS)

The ISI papers and the book chapters that this thesis is composed of were given in the appendix.

ISI Article I

Tol, Hakan İbrahim, Svendsen, Svend, *Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark*. Energy 38 (2012) 276 – 290.

Abstract

The paper presents a method for the design of a low-energy district heating (DH) system, concerning the studies of different pipe dimensioning methods, substation types and network layouts. Computations were carried out separately on each of the pipe segments of which the DH network consisted. A simultaneity factor was taken account in connection with each of these pipe segments. The applicability of the developed optimization method was investigated with outcomes of its being highly useful in the pipe dimensioning and of its being superior in respect to traditional dimensioning methods. It was shown that an appreciable reduction in heat loss from the DH network could be achieved. The optimal pipe dimensions found were evaluated by use of the commercial software Termis with input of several randomly generated heat demand scenarios involving peak winter conditions. The effects of the network type on the pipe dimensions were investigated for substations of different types containing buffer tanks and heat exchangers and for booster pumps installed at the DH network. Two types of network layouts were compared in terms of satisfaction of customers concerning the supply temperatures and heat loss within the DH network to prevent excessive drops in supply temperature during the summer months.

ISI Article II

Tol, Hakan İbrahim, Svendsen, Svend, *A comparative study on substation types and network layouts in connection with low-energy district heating systems*. Energy Conversion and Management 64 (2012) 551–561.

Abstract

The study deals with low-energy District Heating (DH) networks operating in low temperatures such as 55 °C in terms of supply and 25 °C in terms of return. The network layout, additional booster pumps, and different substation types such as storage tanks either equipped or not equipped in domestic hot water production site were examined. Effects of booster pumps on pipe dimensions in the latter case were investigated. Temperature drops during the summer months due to low heat demands of consumers were explored. Use of approaches such as looped networks and

branched network layouts with bypasses for end-consumers were also studied, heat loss from these networks and the drop in temperature in the heat-carrier-supply medium being compared.

ISI Article III

Tol, Hakan İbrahim, Svendsen, Svend, *Effects of boosting the supply temperature on pipe dimensions of low-energy district heating networks: A case study in Gladsaxe, Denmark*. Submitted to Energy and Buildings (In Review).

Abstract

This paper presents a method for the dimensioning of the low-energy District Heating (DH) piping networks operating with a control philosophy of supplying heat in low-temperature such as 55 °C in supply and 25 °C in return regularly while the supply temperature levels are being boosted in cold winter periods. The performance of the existing radiators that were formerly sized with over-dimensions was analyzed, its results being used as input data for the performance evaluation of the piping network of the low-energy DH system operating with the control philosophy in question. The optimization method was performed under different mass flow limitations that were formed with various temperature configurations. The results showed that reduction in the mass flow rate requirement of a district is possible by increasing the supply temperature in cold periods with significant reduction in heat loss from the DH network. Sensitivity analysis was carried out in order to evaluate the area of applicability of the proposed method. Hence varied values of the original capacity and the current capacity of the existing radiators were evaluated with the design temperature values that were defined by two former radiator sizing standards.

Non-ISI Article I (Peer Reviewed)

Tol, Hakan İbrahim, Svendsen, Svend, *The exergetic, environmental and economic effect of the hydrostatic design static pressure level on the pipe dimensions of low-energy district heating networks*, Challenges 2013, 4(1), 1-16; doi:10.3390/challe4010001.

Abstract

Low-Energy District Heating (DH) systems, having great energy savings by means of very low operating temperatures of 55 °C and 25 °C for supply and return respectively, were considered to be the 4th generation of the DH systems for a low-energy future. Low-temperature operation is considered to be used in a low-energy DH network to carry the heat produced by renewable and/or low grade energy sources to the low-energy Danish buildings. In this study, a comparison of various design considerations with different levels of the maximum design static pressure was performed, their results being evaluated in terms of energetic, exergetic, economical, and environmental perspectives.

Book Chapter I

Tol, Hakan İbrahim, Dinçer, İbrahim, Svendsen, Svend. *Determining the Optimal Capacities of Renewable-Energy-Based Energy Conversion Systems for Meeting the Demands of Low-Energy District Heating, Electricity and District Cooling - Case Studies in Copenhagen and Toronto.* In: Ibrahim Dincer et al (eds.), Progress in Clean Energy. Submitted to Springer (Accepted to be Published).

Abstract

The paper presents a method for determining the optimal capacity of a renewable-energy- based energy conversion systems for meeting the energy requirements of a given district as considered on a monthly basis, with use of a low-energy district heating system operating at a low temperatures, as low as 55 °C for supply and 25 °C for return and with additional considerations being directed to supply electricity and cooling. Several optimal solutions with various nominal capacities of the technologies involved were obtained in each of two case studies, one being for the Greater Copenhagen Area, and the other for the Greater Toronto Area. Various climate conditions of the case areas in question caused different observation of nominal capacities for the energy conversion systems considered with single-production and multi-production based on different renewable energy sources.

Book Chapter II

Tol, Hakan İbrahim, Dinçer, İbrahim, Svendsen, Svend. *Regional Energy Planning Tool for Renewable Integrated Low-Energy District Heating Systems: Environmental*. Chapter 45 In: Ibrahim Dincer et al (eds.), Causes, Impacts and Solutions to Global Warming. Springer, 2013, New York.

Abstract

Low-energy district heating systems, operating at low temperature of 55 °C as supply and 25 °C as return, can be the energy solution as being the prevailing heating infrastructure in urban areas, considering future energy schemes aiming at increased exploitation of renewable energy sources together with low-energy houses in focus with intensified energy efficiency measures. Employing low-temperature operation allows the ease to exploit not only any type of heat source but also low-grade sources, i.e., renewable and industrial waste heat, which would otherwise be lost. In this chapter, a regional energy planning tool is described considered with various energy conversion systems based on renewable energy sources to be supplied to an integrated energy infrastructure involving a low-energy district heating, a district cooling, and an electricity grid. The developed tool is performed for two case studies, one being Greater Copenhagen Area and the other Greater Toronto Area, in accordance with various climate conditions and available resources in these locations, CO2 emission savings obtained with up to 880 and 1,400 M tons, respectively.

ISI ARTICLE I

Energy 38 (2012) 276–290

Contents lists available at SciVerse ScienceDirect

Energy

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

Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark

H.İ. Tol*, S. Svendsen

Technical University of Denmark, Department of Civil Engineering, Section of Building Physics and Services, Brovej, Building 118 DK-2800, Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 17 August 2011
Received in revised form
22 November 2011
Accepted 1 December 2011
Available online 27 January 2012

Keywords:
Low-energy
District heating
Network layout
Pipe dimensioning
Simultaneity factor
Optimization method

ABSTRACT

The paper presents a method for the design of a low-energy district heating (DH) system, concerning the studies of different pipe dimensioning methods, substation types and network layouts. Computations were carried out separately on each of the pipe segments of which the DH network consisted. A simultaneity factor was taken account in connection with each of these pipe segments. The applicability of the developed optimization method was investigated with outcomes of its being highly useful in the pipe dimensioning and of its being superior in respect to traditional dimensioning methods. It was shown that an appreciable reduction in heat loss from the DH network could be achieved. The optimal pipe dimensions found were evaluated by use of the commercial software Termis with input of several randomly generated heat demand scenarios involving peak winter conditions. The effects of the network type on the pipe dimensions were investigated for substations of different types containing buffer tanks and heat exchangers and for booster pumps installed at the DH network. Two types of network layouts were compared in terms of satisfaction of customers concerning the supply temperatures and heat loss within the DH network to prevent excessive drops in supply temperature during the summer months.

1. Introduction

Efforts to reduce energy consumption in European buildings, together with intensified energy efficiency measures that are being undertaken, and the increasing exploitation of renewable energy sources for providing heat have led to the search for a more adequate conception and better network design of new-generation District Heating (DH) systems for low-energy buildings [1–6]. Both the integration of new low-energy buildings and the low-energy renovation of existing buildings increase the percentage of heat loss from the piping network of a traditional DH system. Heat loss from the network has a significant impact on the cost-effectiveness and energy efficiency of a DH system [7–9]. In one project in this area [10] it was found that a low-energy DH system operating at very low temperatures, 55 °C in the case of supply and 25 °C in the case of return, can satisfy the heating demand of consumers through adequate control of the substations [9,11–13]. There are also studies [12,14,15] which have shown that existing indoor heating systems in already existing buildings can continue satisfying the heat demand at low supply temperatures since the existing indoor heating systems were formerly over-dimensioned in their design stage. In addition, certain heat loss can be avoided through operation at low temperatures [11,16], providing savings in heat production as well [9,14,17–21]. The heat loss from a DH network is affected by the diameter of the pipes and the insulation material employed, as well as by the temperature of the supply and by the return heat carrier medium. Accordingly, special attention needs to be directed at the dimensions of the DH piping network so as to take advantage of DH in the best possible way [2,5,22–26]. Traditional methods of DH pipe dimensioning involve use of a size-searching algorithm in which the lowest pipe diameter possible is defined in accordance with the maximum velocity and/or with the maximum pressure gradient, so as to avoid the installation of an over-dimensioned and unnecessarily costly DH network [4,16,23,27]. The risk of obtaining an over-dimensioned piping network can be prevented by optimal design of the DH network [28,29].

It is not expected that each consumer will consume heat at a full demand level or at exactly the same time. This is the basic idea behind the use of simultaneity factor [30]. Special attention was thus directed at determining the heat load in each pipe segment, consideration being given to the consumer load to which each pipe segment is subjected. Three methods for the dimensioning of piping

* Corresponding author. Tel.: +45 45 25 50 27; fax: +45 45 88 32 82.
E-mail addresses: hatol@byg.dtu.dk (H.İ. Tol), ss@byg.dtu.dk (S. Svendsen).

0360-5442/$ – see front matter
doi:10.1016/j.energy.2011.12.002

Nomenclature

Sets

N	Set of nodes
NM	Set of longest nodes
P	Set of pipe segments
$\mathbb{R}$	Set of real numbers
S	Set of scenarios, generated
SN	Set of starting nodes at the street lines
SS_MP	Set of generated heat demand data for main lines
SS_SP	Set of generated heat demand data for street lines
TPD	Set of inner diameters of the commercially available pipes

Roman letters

A, *B*, *C*	Parameters for calculation of heat load in case of DHW, dependent on substation type [-]
C	Number of consumers connected to the node [-]
CC	Cumulative number of consumers at the node [-]
D	Inner diameter [mm]
DM	Degree-minutes [°C-min]
f	Friction coefficient [-]
h_f	Specific enthalpy [kj/kg]
i,j,k,l	Node indices [-]
$i-1$	The index for the predecessor node [-]
L	Length [m]
$\dot{m}$	Mass flow [kg/s]
N	Node entry in the set of nodes [-]
n	Overall amount of the entry type, indicated in the subscript [-]
P	Pressure [bar]
p	Pipe segment entry in the set of pipe segments [-]
PS	Sequences of linked pipe segments [-]
$\dot{Q}$	Heat power [kW]
R	Route [-]
r	Root node [-]
Sc	Label number of scenario [-]
SF	Simultaneity factor [-]
T	Temperature [°C]
t	Time [min]
U	Linear thermal coefficient [W/(mK)]

Greek letters

Δ	Difference
φ	Occupancy ratio [%]
∇	Gradient

Subscripts

Alu	AluFlex twin pipe
B	Base state
BP	Booster pump
CR	Critical route
DHW	Domestic hot water
DHWD	Unique heat demand of domestic hot water
DHWL	Heat load of domestic hot water
f	Final
G	Ground
HD	Unique heat demand
HL	Heat load
Loss	Loss
Max	Maximum
Max_CR	Maximum based on critical route
Max_*l*	Unique, maximum based on each individual route
Min	Minimum
R	Return
S	Supply
SH	Space Heating
SHD	Unique heat demand of space heating
SHL	Heat load of space heating
SS	Scenarios
St	Steel twin pipe
S_t	Supply heat carrier medium at specific time *t*
0	Initial

Superscripts

g	Generated value
*	Continuous (non commercially available) value

networks, two of them based on use of maximum pressure gradient criteria [31] and the other on optimization [11,28,29,32,33], were investigated, their being compared in terms of heat loss from the DH network. Also, DH networks connected to two different substations each containing a buffer tank or a heat exchanger, used for domestic hot water (DHW) production were investigated. In addition, further opportunities for reducing the dimensions involved were studied by installing additional booster pumps in the DH network together with the substations containing heat exchangers for DHW production. The reliability of the DH network with optimal pipe dimensions was evaluated by use of the hydraulic and thermal simulation software Termis, in which peak winter scenarios representing different heat consumption profiles of consumers were compared, these being based on the degree of simultaneity of the heat demands of the different consumers [34]. Supply temperature in the DH network is lowered, in particular through the heat consumption being reduced when there is no need for space heating (SH) and through consumers being absent during holidays and vacation periods. Two types of network layouts were investigated – branched networks with bypasses at leaf nodes and looped networks without bypasses – with the aim of determining how best to prevent marked drops in the supply temperature and at the same time keep heat loss from the DH network at a minimum. The heat consumption profiles of consumers have been found to affect the operation of DH networks [11,36]. Accordingly, different DH network layouts were investigated in terms of energy performance under conditions of low heat demand in the summer, on the basis of time series simulations involving use of the Termis software and of different scenarios.

The objective of this study is to design low-energy DH networks operating in low temperature of 55 °C as supply and 25 °C as return for a new settlement, in which low-energy houses are planned to be built, with focus given on network dimensioning method, substation type, and network layout.

2. Methods

2.1. Description of the site

A case study was carried out concerned with a suburban area of Trekroner in the municipality of Roskilde in Denmark, in which extensive building construction is planned (Fig. 1), the DH system there supplying heat to 165 low-energy houses. The piping network is to have a total length of about 1.2 km in the layout of the branched type and 1.4 km in the layout of the looped type, the

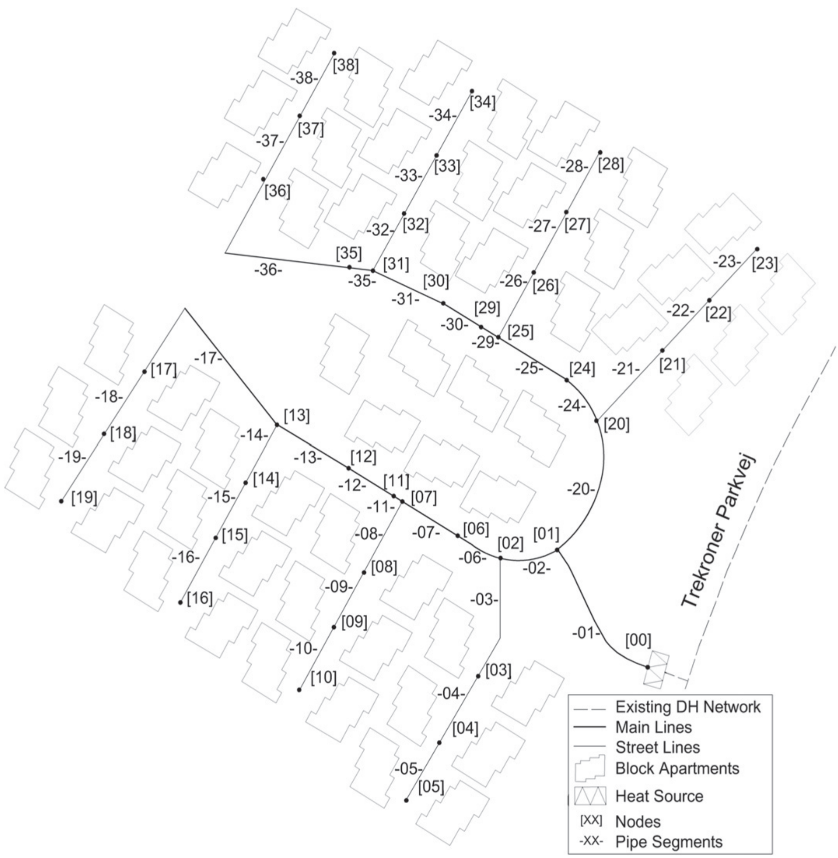


Fig. 1. Diagram of a branched DH network for Trekroner.

length of the end-user connections not being figured in here. Future network extension was assumed to not be required.

Each individual consumer connected to the low-energy DH network was assumed to have the same type of reference low-energy house. Consumers were assumed to have a unique peak heat demand of 2.9 kW in connection with SH. Also, unique heat demand of each individual consumer in connection with DHW production was assumed to be 32.3 kW in case the substations at each consumer house were equipped with an (instantaneous) heat exchanger employed for DHW production, and 3 kW in case the substations at each consumer house were equipped with a 120 L buffer tank for DHW production. Although instantaneous peak heat consumption power is as high as 32.3 kW from the consumer site, the buffer tank at the substation decreases the peak heat demand power to 3 kW which is actually the charging power of the buffer tank – and stored heat, charged, is later supplied to the consumer from the buffer tank upon request of DHW – (more detailed information regarding this can be found in [37–39]). The heating demand data for SH and for DHW was found to meet the requirements defined for heating demand data by the software Be06, which was updated in 2011 through development of the new version of it, Be10 [40].

Since the heat loss from twin pipes is less than that from single pipes with the same dimensions, and since the cost of installing twin pipes is usually less for dimensions of up to DN 100 [37,41], the network was dimensioned in accordance with the catalogue of commercially available twin pipes within the range of {10, 11.6, 15, 20, 26} for $\mathbf{TPD}_{\mathrm{Alu}}$ and of {37.2, 43.1, 54.5, 70.3, 82.5} for $\mathbf{TPD}_{\mathrm{St}}$ [42,43]. **TPD** refers to the set of inner diameters of the pipes that are commercially available, the subscript “Alu” referring to AluFlex twin pipes and “St” to steel twin pipes. A general set of inner diameters including both AlueFlex twin pipes and steel twin pipes was defined as $\mathbf{TPD} = \mathbf{TPD}_{\mathrm{Alu}} \cup \mathbf{TPD}_{\mathrm{St}}$. The use of higher values for the maximum allowable pressure drop for dimensioning purposes, can result in a sharp decrease in the pipe sizes involved, in heat loss from the DH network and in higher pipe installation costs, at the same time as the operating costs remain constant [28]. The maximum static design pressure for AluFlex twin pipes (10 bara) was considered as a constraint in setting the maximum allowable pressure drop for the dimensioning methods [44]. The overall maximum allowable pressure drop, ΔP_{Max} for the supply and for the return lines was set to 8 bar, for a holding pressure of 1.5 bara on the return line at the heat source. Also, the minimum pressure drop was set to 0.5 bar for the substation of each consumer.

The DH network was dimensioned in the circumstance of peak winter condition at which the ground temperature T_G around the pipe segments was set as 2 °C for the coldest period. In case of dynamic simulations carried out to investigate different network layouts (described in the Section 2.6), the ground temperature was set as 14 °C for the time interval (of the simulations) which regards to a day time occurring during prime holiday times at the summer months [45].

2.2. District heating network model

In the present paper, the calculations were applied mainly to branched networks. The branched network model (Fig. 1) makes use of the node list array **N** and the pipe list array **P** [11,44,46], the end-user connections (also known as the branch pipe) being excluded so as to make calculations easier [27]. In accordance with the DH network model, the heat source at the root node r was defined as supplying heat through the routes R that end at the leaf nodes l (i.e. nodes without any successor node). The pipe list array **P** consists of the pipe segments $p_{i-1,i}$ that connect the node $i-1$ to the node i, in the order of root node r to leaf node l, together with information concerning the number of consumers $C(N_i)$ connected to the node N_i and the length of the pipe segments $L(p_{i-1,i})$. The routes of a network R_l are the branches starting from the root node r and extending to the destination of the leaf node l in question. Accordingly, functions applying to R_l are calculated for the entire route. The path sets PS_l; from the root node r to the respective leaf node l, and PS_{ij_l}; from a node i to the respective node j through the route l were defined as sequences of linked pipe segments. The functions applying both to PS_l and to PS_{ij_l} were put to use on each of the pipe segments separately within the path set in question.

The pipe segments of the branched type DH network were dimensioned according to the peak heat load by including simultaneity factor as a function of the cumulative number of consumers. Each heat-demanding node in the DH network model was defined as supplying heat to six consumers, except for the nodes $i = 6, 11, 12, 24, 29, 30$ and 35, which supply heat to three consumers each. The cumulative number of consumers for each node in the network was calculated using Eq. (1).

$$CC(N_{i-1}) = C(N_{i-1}) + \sum_{k=l}^{k=i} C(N_k) \quad \forall l \text{ where } N_k \in \Gamma^+(N_{i-1}) \subset PS_l \tag{1}$$

where $CC(N_i)$ is the cumulative number of consumers at the node i and $\Gamma^+(N_i)$ denotes the set of all successor nodes in relation to the node i.

The simultaneity factor for space heating was calculated on the basis of the cumulative consumer load on each pipe segment, using Eq. (2). The use of thermostatic control valves coupled to in-house heating systems such as radiators, floor heating systems etc., considering internal and solar heat gains, and good insulation applied at low-energy houses allow us to use simultaneity factor for space heating system [47].

$$SF_{SH}(N_i) = 0.62 + \frac{0.38}{CC(N_i)} \tag{2}$$

where SF_{SH} refers to the simultaneity factor for space heating.

The heat load for SH and for DHW was calculated for each pipe segment, using Eq. (3) and Eq. (4), respectively, and the total heat load by use of Eq. (5).

$$\dot{Q}_{SHL}(N_i) = SF_{SH}(N_i) \times CC(N_i) \times \dot{Q}_{SHD} \tag{3}$$

where $\dot{Q}_{SHL}$ refers to the heat load for SH and $\dot{Q}_{SHD}$ denotes the unique heat demand, which was defined as 3 kW at the Section 2.1, for SH of the individual consumer, both expressed in kW.

The Eq. (4) for the heat load in connection with DHW includes the simultaneity factor integrated to it, depending upon the cumulative number of consumers [37].

$$\dot{Q}_{DHWL}(N_i) = A \times CC(N_i) + B \times CC(N_i)^{0.5} + C \tag{4}$$

where $\dot{Q}_{DHWL}$ refers to the heat load for DHW expressed in kW, where $A = 1.19$, $B = 1.5$ and $C = 0.3$ for a substation having a 120 l buffer tank and where $A = 1.19$, $B = 18$ and $C = 13.1$ for a substation having a heat exchanger.

$$\dot{Q}_{HL}(N_i) = \dot{Q}_{SHL}(N_i) + \dot{Q}_{DHWL}(N_i) \tag{5}$$

where $\dot{Q}_{HL}$ is the total heat load at node N_i both for SH and for DHW, the integrated simultaneity factor depending upon the cumulative number of consumers.

The mass flow was calculated in accordance with the heat load by use of Eq. (6).

$$\dot{m}(N_i) = \frac{\dot{Q}_{HL}(N_i)}{h_f(T_S) - h_f(T_R)} \tag{6}$$

where $\dot{m}$ refers to mass flow in kg/s and $h_f\ (T)$ is the specific enthalpy [kj/kg] of the heat carrier medium at temperature T [°C], the subscripts S and R indicating the temperatures of the supply and the return heat carrier medium, respectively.

The pressure drop in the different pipe segments was calculated using the Darcy–Weisbach equation because of the advantage it has of being strictly dependent upon the kinematic viscosity of water, which is a function of the temperature and is applicable under different flow conditions [44,48]. The friction coefficient f was calculated using the Clamond algorithm, which is simple, fast, accurate and robust for solving the Colebrook equation [49]. Calculation of the pressure drop was carried out for the supply and the return lines separately on the basis of their temperatures.

Heat loss from the DH network was calculated using Eq. (7), which takes account of differences in temperature and of the linear temperature-dependent thermal coefficient between the medium and the ground around it for both the supply and the return lines.

$$\dot{Q}_{Loss} = \sum_{i=1}^{n_i} \Big\{ L\big(p_{i-1,i}\big) \times \Big[U_S\Big(D\big(p_{i-1,i}\big)\Big) \times (T_S - T_G) + U_R\Big(D\big(p_{i-1,i}\big)\Big) \times (T_R - T_G) \Big] \Big\} \tag{7}$$

where $\dot{Q}_{Loss}$ is the total heat loss from the DH network, which has n_i nodes, $U(D)$ being the linear thermal coefficient [W/(mK)] computed as a function of the inner diameter D [mm] and of the ground temperature T_G around the pipe segment [°C]. The subscripts S and R indicate the supply and the return heat carrier medium, respectively.

The linear thermal coefficients were derived from Wallentén's formulations [51] and steady-state heat loss equations given at [45]. The relative error in the heat loss calculated for twin pipes by use of Wallentén's formulations is typically less than 1% and 5% in the perspective of, respectively, symmetrical and anti-symmetrical problem formulation – in the point of temperatures in the supply and return pipes – two of which later were superimposed to form the heat loss formulation for twin pipes in Wallentén's study [51]. The temperature-dependent linear thermal coefficients were derived by dividing the heat loss calculated by use of Wallentén's equation with the temperature difference of the heat carrier medium and ground temperature for each pipe dimensions with consideration given to design supply; return; and ground temperatures defined as, respectively, 55 °C; 25 °C; and 2 °C in case of winter period, and 12 °C in case of summer period.

After the linear thermal coefficients were derived separately for the supply and return line of each commercially available pipe diameter, the regression equations were formed for the linear thermal coefficients as a function of the inner diameter in order to use in the optimization method, described at the Section 2.3.

Temperature drop at the DH network was found as small as 2% in comparison to the temperature difference of supply and return heat carrier medium; hence it was neglected in the heat loss calculations at this paper, except the analyzes carried out for the network layouts which were described at the Section 2.6. Also, the temperature dependency of the thermal conductivity, and the ageing of the PUR (polyurethane) foam were neglected. Also the ground temperature around the pipe segments was assumed to be undisturbed with temperature increase at the soil due to twin pipes, found as small as 0.5 °C based on the study [45] (more detailed information regarding heat loss calculation can be found in [45,50]).

2.3. Dimensioning methods

After determining the basic input data for the DH network, such as geographical information regarding the area as well as the heat source and the heat load on the pipe segments, it is essential that one select an appropriate design method for dimensioning the pipe segments, in order to avoid over-dimensioning of them, which can result in excessively high network installation costs and a high degree of heat loss. The heat loss mainly depends on temperature and pipe size. Therefore, since the temperatures are already as low as possible in low temperature DH networks, minimizing the heat loss means minimizing the size. The following dimensioning methods – the maximum pressure gradient method based on critical route, and multi-route; and optimization method – were employed for the branched DH networks, which were illustrated at Fig. 1, connected to substations having 120 l buffer tanks for DHW production.

2.3.1. Dimensioning Method 1. The maximum pressure gradient, critical route method

The maximum pressure gradient method, involving use of a critical route, has been widely accepted and been traditionally used for the dimensioning of DH networks. In using this method, the maximum pressure gradient is taken as a limit, its being calculated on the basis of the maximum allowable pressure drop for the critical route in the network, using Eq. (8) [31].

$$\nabla P_{Max\_CR} = \frac{\Delta P_{Max}}{L(R_{CR})} \tag{8}$$

where ∇P_{Max_CR} refers to the maximum pressure gradient, defined in terms of the critical route, where $L(R_{CR})$ is the length of longest route for the Trekroner DH network, and ΔP_{Max} refers to the maximum allowable pressure drop of 8 bar, as dealt with in Section 2.1.

Each pipe segment in the network was then dimensioned, using Eq. (9).

$$\text{Minimize } D\left(p_{i-1,i}\right) \quad \forall i = 1, \ldots, n_i \tag{9}$$

Subject to the constraints

$$\nabla P(P_{i-1,i}) = \frac{\Delta P\left(p_{i-1,i}\right)}{L\left(p_{i-1,i}\right)} \le \nabla P_{Max\_CR}$$

$$D\left(p_{i-1,i}\right) \in \mathbf{TPD}$$

where $\nabla P(p_{i-1,i})$ refers to the pressure gradient, calculated according to pressure drop $\Delta P(p_{i-1,i})$ of the pipe segment $p_{i-1,i}$.

2.3.2. Dimensioning Method 2. The maximum pressure gradient, multi-route method

Dimensioning Method 1 leads to over-dimensioning of the pipe segments in the separate routes rather than the critical route of the DH network. If a pump can handle pressure loss in the critical route, it can also handle lesser pressure losses in other routes of the piping network when a closed loop system is involved [48,52]. In accordance with this, the maximum pressure gradient limit was determined for each route separately, using Eq. (10).

$$\nabla P_{Max\_l} = \frac{\Delta P_{Max}}{L(R_l)} \quad \forall l = 1, \ldots, n_l \tag{10}$$

Then, the pipe segments were dimensioned within the limits of the maximum pressure gradient of the route to which they belonged, using Eq. (11). Since the main lines have several routes in common, the lower pressure gradient limits were determined from among the limits defined for the routes.

$$\text{Minimize } D\left(p_{i-1,i}\right) \quad \forall i = 1, \ldots, n_i \tag{11}$$

Subject to the constraints:

$$\nabla P\left(p_{i-1,i}\right) \le \nabla P_{Max\_l} \quad \forall l; p_{i-1,i} \in PS_l$$

$$D\left(p_{i-1,i}\right) \in \mathbf{TPD}$$

2.3.3. Dimensioning Method 3. The optimization method

Another dimensioning method was defined as an optimization algorithm in order to minimize the heat loss from the DH network by means of reducing the dimension of each pipe segment until the potential of the maximum allowable pressure limit was utilised as much as possible in connection with each route of the DH network. Since the reduced heat demand from the consumers will increase the heat loss from the DH network significantly in comparison to the heat supplied to the DH network, and the impact of pumping costs become relatively small than the overall costs in the case of supplying heat to low-energy houses and in the case of using AluFlex twin pipe which has static pressure limit of 10 bara [10], this optimization method mainly focused on reducing the heat loss from the DH network.

Due to the complexity of DH networks, the approach of searching for the minimum value of the objective function is not a particularly effective optimization method in case each combination of available diameters will be tried in all of the pipe segments in the DH network, even if it can provide an accurate global minimum [32]. The use of optimization algorithms saves time in the case of such large and complex DH networks, providing a solution which is close to the global minimum [31]. Optimization was carried out by use of the optimization toolbox of the commercial software Matlab and of the “Active Set” algorithm there [53] and the optimization, which was modelled according to the objective functions and the appropriate constraint functions being obtained using Eq. (12), resulted with continuously variable (though not commercially available) pipe diameters at each pipe segments.

$$\text{Minimize } \dot{Q}_{Loss}\left(D_i^*\right) \tag{12}$$

Subject to the constraints:

$$\Delta P(PS_l) = \Delta P_{Max} \quad \forall l = 1, \ldots, n_l$$

$$D_i^* \in \mathbb{R}$$

$$D_{Min} \le D_i^* \le D_{Max}$$

where D^* is a continuous pipe dimension which is obtained and D_{Min} and D_{Max} are the corresponding minimum and maximum pipe diameters, respectively, of the pipe catalogue set **TPD**. The DH network contains n_l leaf nodes.

The continuous pipe diameters obtained by use of optimization tool of Matlab were rounded upwards by means of Eq. (13) to pipe diameters that were commercially available. Then, the heat loss from the DH network was re-calculated for the optimal – commercially available – pipe diameters by use of the linear thermal coefficients based on Wallentén's formulations (now not regression equation of the thermal coefficients though) and also the pressure drop values were re-calculated according to the final pipe dimensions that were commercially available.

$$D\left(p_{i-1,i}\right) = \left\lceil D^*\left(p_{i-1,i}\right)\right\rceil \; ; D^*\left(p_{i-1,i}\right) \in \mathbb{R} \,\Lambda\, D\left(p_{i-1,i}\right) \in \mathbf{TPD} \tag{13}$$

In order to ensure that the resultant optimal diameters were close to the global minimum in terms of heat loss from the DH network, the optimization was run from several different starting points [32,33,53,54].

2.4. Evaluation of pipe dimensions

The heat consumption profiles of the consumers involved can affect operation of the DH system considerably [11,33]. The optimal pipe dimensions, founded by use of Matlab optimization tool, were later evaluated by means of the commercial software Termis, which in its basic assumption based on mass continuity in all the pipe segments that are linked with one another, i.e. the total mass flow demand from all of the consumers as a whole needs to be equal to the total mass flow supplied by the heat source. The DH piping network was dimensioned in accordance with the peak heat load based on simultaneity factor. The reduced heat load due to simultaneity factor applied in each pipe segment in dimensioning stage brought the need to adjust the heat demand of the consumers as a whole for Termis simulations. Hence, several scenarios, representing - as a whole - the peak heat demand situation in the winter months, were created by means of randomly generated heat demand data based on use of the simultaneity factor. The heat demand data generated for each consumer in the network was created under concurrent consideration of maximum heat load data defined at each pipe segment based on simultaneity factor there i.e. the overall sum of the generated heat demand data at each consumer in the DH network should not exceed the simultaneity factor based heat load defined for the pipe segment connected to the heat source. The scenarios were generated with two fields of application; the first field is the one being that of the junction of several pipe segments in the one by use of Eq. (14) and the second field is for the same predecessor pipe segment by use of Eq. (15):

$$\mathbf{S_{SS\_MP}} = RNG\,\dot{Q}^g_{HL}(N_i) \quad \forall N_i \in \Gamma^+(N_{i-1}) \tag{14}$$

Subject to the constraints:

$$0 \le RNG\,\dot{Q}^g_{HL}(N_i) \le \dot{Q}_{DHWL}(N_i)$$

$$\dot{Q}^g_{HL}(N_{i-1}) = \dot{Q}_{HL}(N_{i-1})$$

$$\dot{Q}^g_{HL}(N_i) \le \dot{Q}_{HL}(N_i)$$

where $\mathbf{S_{SS\_MP}}$ is the array of the heat demand data generated for the main pipe line, *RNG* is a random number generator, and $\dot{Q}^g_{HL}(N_i)$ is the heat load data generated at node *i*.

Table 1
Pump data used in the Termis Model.

	Load profiles			
	1	2	3	4
Flow [kg/s]	1.0	2.1	3.1	4.1
Head [bar]	5.3	6.4	7.5	8.2

The second area of application of the scenarios referred to above is that of adjacent nodes in a given street pipe. Assume in Eq. (15) that follows that N_i is the first node of the street line.

$$\mathbf{S_{SS\_SP}} = RNG\,\dot{Q}^g_{HD}(N_k) \quad \forall N_k \in \Gamma^+(N_i) \,\Lambda\, N_k \subset PS_l \quad \forall l = 1,\ldots,n_l \tag{15}$$

Subject to the constraints:

$$0 \le RNG\,\dot{Q}^g_{HD}(N_i) \le \dot{Q}_{DHWD}(N_i)$$

$$\dot{Q}^g_{HL}(N_i) = \dot{Q}_{HL}(N_i)$$

$$\forall \dot{Q}^g_{HL}(N_k) \le \dot{Q}_{HL}(N_k)$$

where $\mathbf{S_{SS\_SP}}$ is the array of the heat demand values generated for the street line in question.

Let n_{SS} be defined as the number of steady-state scenarios generated. These steady-state scenarios were ones created by the synchronized generation of sub-scenarios for the street and for the main lines by use of Eq. (16).

$$\mathbf{S_{SS}} = \mathbf{S_{SS\_SP}} \cup \mathbf{S_{SS\_MP}} \tag{16}$$

where $\mathbf{S_{SS}}$ is the array of a scenario that contains the random heat demand data for the DH network as a whole.

The random number generator of MS Excel was used to define the seed for random number generation in terms of computer time so the steady-state scenarios were generated in different time configurations so as to avoid duplicate numbers [55]. The optimal pipe dimensions obtained by use of optimization method described at section2.3 were evaluated in the Termis model by use of the generated steady-state scenarios as input data to the simulations, providing the heat demand input pertaining to the consumers in question.

In the Termis model, the temperature of the heat supply from the root node and the return temperature from the consumers were set at $T_S = 55\,°C$ and $T_R = 25\,°C$, respectively. A pressure vessel having a holding pressure of 1.5 bara and a variable-speed pump, with performance being shown at Table 1, were located in the return line at the heat source [44]. In order to avoid a negative or an insufficient pressure difference across the different substations, the pressure difference was fixed at a minimum of 50 kPa in each consumer's substation [27].

The Termis simulations allowed such parameters as the maximum static pressure in the DH network and the minimum pressure difference for the consumers to be checked in terms of the design limits. The confidence interval for the maximum static pressure was determined by means of the bootstrap method, which was used to resample the simulation results for the maximum static pressure reached in the DH network. The reliability of the confidence interval was increased by use of the bootstrap method [56].

2.5. Network types

The energy performance of the DH network was also evaluated for networks of three different types and with substations of

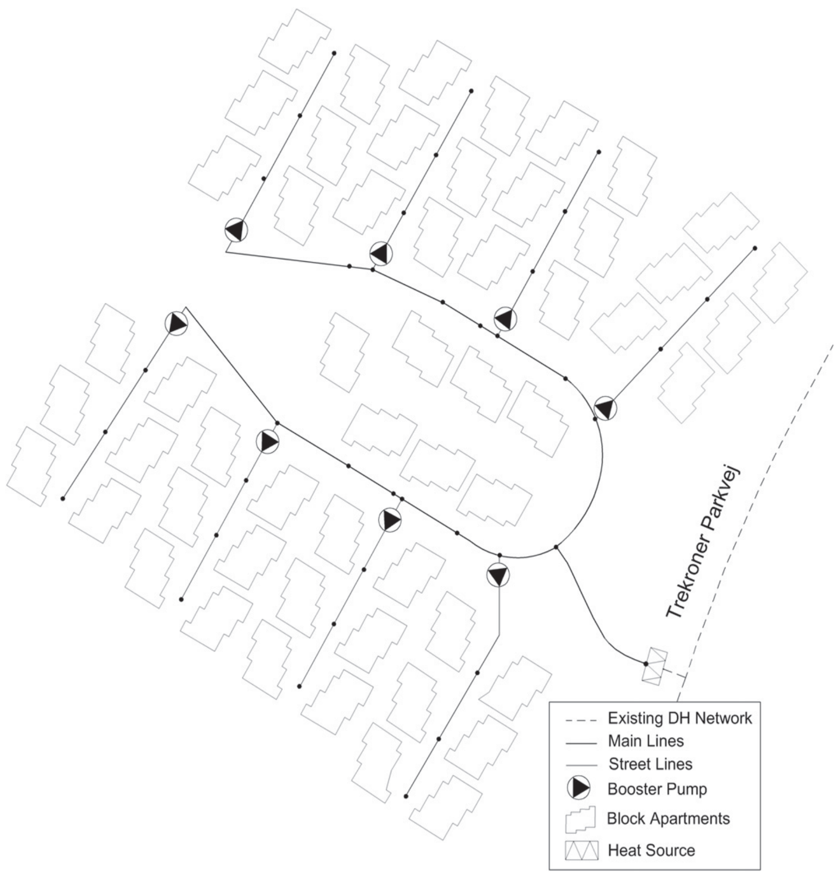


Fig. 2. Diagram of a branched DH network for Trekroner with additional booster pumps.

different types and booster pumps installed in the branched network. The Network Type 1 and 2 was based on the same branched DH network which was illustrated at Fig. 1. However substations which were located in each house differ in DHW production in these network types with the same layout of branched DH network.

Network Type 1. The DH network was connected to substations each one of which were equipped with 120 l buffer tanks for DHW production with unique heat demand of 3 kW from each individual house.

Network Type 2. The DH network was connected to substations each one of which were equipped with heat exchangers for DHW production with unique heat demand of 32.3 kW from each individual house.

Network Type 3. Here the booster pumps were installed at the start of the pipe segments in each street in the case of DH networks of Type 2 (Fig. 2) in addition to the head lift provided from the main pump station which was located in the heat source. The aim here was to have high maximum allowable pressure drop values as a design limit for short sequences of pipe segments, such as for sequences of pipe segments extending from the heat source to the booster pumps and from each booster pump to the leaf node of each route in question. Eq. (12) was revised in accordance with the changed constraints, as shown in Eq. (17). The continuous pipe diameter values obtained were rounded up to the commercially available pipe diameters, by use of Eq. (13).

$$\text{Minimize } \dot{Q}_{\text{Loss}}\left(D_i^*\right) \tag{17}$$

Subject to the constraints:

$$\Delta P\left(PS_{r\_j}\right) = \Delta P_{\text{Max}} \quad \forall N_j \in \mathbf{NM}$$

$$\Delta P\left(PS_{il\_l}\right) = P_s(N_i) - P_r(N_i) + \Delta P_{\text{BP}} \quad \forall N_i \in \mathbf{SN}$$

$$D_i^* \in \mathbb{R}$$

$$D_{\text{Min}} \le D_i^* \le D_{\text{Max}}$$

where PS_{r_j} is the sequence of pipe segments from the heat source to the booster pump in the street that is longest of all, ΔP_{BP} is the additional head lift provided by the booster pump, $P_s(N_i)$ and $P_r(N_i)$ are the values for the static pressure found at node i, **NM** is the set of the longest nodes contained in the main lines, and **SN** is the set of starting nodes for the different street lines.

2.6. Network layouts

During the summer months no use is made of SH and the use of DHW is reduced, due to the absence of many consumers, who are on vacation. The stagnant or low flow observed at the heat carrier medium due to reduction of the overall heat load results in

Fig. 3. Diagram of a looped DH network for Trekroner.

a considerable drop in the temperature of the supply heat carrier medium [35]. A drop in temperature of the heat carrier medium at the supply point can be avoided by use of either of the following two network layouts:

2.6.1. Layout 1. Branched network with a bypass at leaf nodes

Equipping a substation with a bypass allows the cooled supply heat carrier medium to circulate through the return line back to the heat source, resulting in a higher return temperature and as a consequence in greater heat loss from the network and decreased efficiency in the extraction of heat from the heat source [9,16,35]. Installing thermostatic bypasses in substations in leaf nodes is widely accepted as a solution to this problem in traditional DH systems (Fig. 1). When the temperature of the supply water drops below a certain temperature, the thermostatic bypass is activated to direct the supply water to the return line [34,35]. In Layout 1, each of the leaf nodes of a branched DH network layout is equipped with a bypass set to a temperature of 50 °C, and is provided with a dead band of 4 °C and a maximum flow limit of 0.056 kg/s.

2.6.2. Layout 2. Looped network

Another method for preventing a temperature decline of the supply heat carrier medium is to provide the DH system with a looped network layout. Normally, a looped network is used in order to increase the security of supply [29]. In the present case, however, a looped network was employed so as to maintain circulation of the supply heat carrier medium by utilizing the dynamics of heat consumption, without the necessity of using a bypass, preventing in this way an increase both in the return temperature and in heat loss from the return line [57]. This is because the piping network in a looped layout supplies heat to a greater number of consumers in a given district than a branched layout does. This increases the stability of the supply temperature since, for example, when there is no heat demand in one particular location the heat carrier medium is circulated in the supply line to other consumers through the looped DH network [29]. Thus, the dimensions applying to a branched network were used in the looped network, in which external pipe segments are installed in the leaf nodes to form the looped layout (Fig. 3). The diameters of these new external pipe segments were selected on the basis of the maximum diameter of the pipe segments (see Dimensioning Method 3) connected to leaf nodes.

2.7. Dynamics of a DH network

The situation prevailing during the summer months was simulated in Termis for two network layouts with input of different – heat demand – scenarios, generated in connection with DHW consumptions (though no space heating requirement at summer period). Scenarios were generated with different DHW consumption profiles, distinct for each consumer, in accordance with there being

Table 2
List of the pipes and the nodes in the Trekroner DH network.

Pipe [-]	Successor node [-]	Predecessor node [-]	Length [m]
0	1	2	66
1	2	3	19
2	3	4	41
3	4	5	21.6
4	5	6	24.4
5	3	7	35.7
6	7	8	37.4
7	8	9	23.4
8	9	10	23
9	10	11	22.8
10	8	12	31
11	12	13	26.2
12	13	14	31.1
13	14	15	18.5
14	15	16	23.8
15	16	17	23.4
16	14	18	81.8
17	18	19	23
18	19	20	22.5
19	2	21	28.5
20	21	22	32.3
21	22	23	22
22	23	24	23.5
23	21	25	35
24	25	26	36
25	26	27	22.7
26	27	28	23.9
27	28	29	24
28	26	30	34.2
29	30	31	24.9
30	31	32	29.9
31	32	33	20.9
32	33	34	23
33	34	35	22.8
34	32	36	33.6
35	36	37	68.9
36	37	38	22
37	38	39	23.8

Table 3
Pipe diameters, pressure drop values in the different routes, and heat loss from the DH network, as obtained for each of three different dimensioning methods.

		Dimensioning Method 1	Dimensioning Method 2	Dimensioning Method 3
Pipe length [m]	Alu 14/14	–	–	141.9
	Alu 16/16	–	–	22.8
	Alu 20/20	–	163.4	181.8
	Alu 26/26	369.5	206.1	263.6
	Alu 32/32	343.1	343.1	–
	St 32/32	214.7	250.4	471.4
	St 40/40	154.2	118.5	–
	St 50/50	66.0	66.0	–
	St 65/65	–	–	66.0
	St 80/80	–	–	–
Pressure drop through the routes [bar]	R_1	1.9	2.3	6.6
	R_2	2.6	3.2	7.1
	R_3	3.2	3.8	7.6
	R_4	3.7	4.3	5.5
	R_5	2.0	2.3	6.5
	R_6	2.5	2.9	7.6
	R_7	3.2	3.5	6.4
	R_8	3.9	3.9	7.7
Heat loss from the DH network [kW]		6.6	6.4	5.6

different occupancy patterns of consumers then as a result of frequent vacation periods in order to include wide range of possible real urban heat consumption profiles, and on the basis of a simultaneity factor effect on each pipe segment. First, the nodes of consumers present physically and found in the DH network were generated randomly by use of Eq. (18).

$$CC_{\varphi\_Sc}(N_i) = RNG\, C^g(N_i) \quad \forall i = 1, \ldots, n_i \tag{18}$$

Subject to the constraint:

$$0 \le RNG\, C^g(N_i) \le C(N_i)$$

$$CC_{\varphi\_Sc}(N_i) \le CC(N_i)$$

where CC_{φ_Sc} is the node list array that was generated, which includes the consumers currently present, together with subscripts representing the occupancy ratio φ, and the scenario number *Sc*.

Dynamic heat demand scenarios S_{φ_Sc} were then created by generating random heat demand data based on use of a simultaneity factor at each time step *t*, with two Eqs. (14) and (15) applying to each of the predefined occupying consumer nodes (CC_{φ_Sc}). Later, each of the scenarios generated served as the basis for heat demand input data for both of the DH network layouts, so as to maintain the same conditions throughout.

Drops in temperature were also evaluated in terms of the DH network layout. The principle of "heating-degree day" measurement [58,59] was used in assessing the level and the duration of the cooling down of the supply heat carrier medium at heat-demanding nodes during a given time interval. Supply temperatures predicted from time series simulations were evaluated in cases in which the supply temperature falled below a certain base temperature, by use of Eq. (19).

$$DM = \sum_{t=t_o}^{t_f} \sum_{i=1}^{n_i} \left(T_{S,t}(N_i) - T_B\right) \times \Delta t \tag{19}$$

Subject to the constraint:

$$CC_{\varphi\_Sc,t}(N_i) \neq 0$$

where *DM* is degree-minutes in °C-min, Δt is the minimum time step value, $T_{S,t}(N_i)$ is the supply temperature during the time period *t* at the node N_i, T_B is the base temperature, and t_o and t_f refer to the initial and the final time step, respectively, of the time interval.

3. Results and discussion

The pipe-node list for the Trekroner DH network model is shown in Table 2, together with the length of each pipe segment.

3.1. Dimensioning methods

Table 3 shows the resulting pipe diameters, the pressure drop values along the various routes and the heat loss from the DH network for each of three different dimensioning methods that was employed for Network Type 1. As can be seen in the table, for Dimensioning Method 1 the pressure drop values obtained failed to reach the maximum allowable design pressure for the critical route R_8 ($\nabla P_{\mathrm{Max\_CR}}$ = 1617 Pa/m). The same applies to Dimensioning Method 2, the $\nabla P_{\mathrm{Max\_}l}$ values of which are given in Table 4. The residual unused pressure drop potential resulted in both cases in the piping network being over-dimensioned. Dimensioning Method 3 yielded optimal dimensions that were smaller than those provided by the other two dimensioning methods. The pressure drop values obtained were close to the maximum allowable pressure drop, with a 14% reduction in heat loss there compared with Dimensioning Method 1. It was found that the optimization algorithm used in conjunction with Dimensioning Method 1 tended to give results representing an increase in the

Table 4
The maximum pressure gradient values obtained for each of the routes.

	Pressure gradients values [Pa/m]							
	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
∇P_{Max}	4651	3520	2563	2141	4643	3388	2491	1617

diameter of the pipe segments in the main line but a decrease in the diameter of the pipe segments of the street lines. Although the maximum velocity limit was not taken account of in the dimensioning stage, an optimal piping network resulted in a maximum flow velocity of 2.4 m/s in the pipe segments labelled as 5, 10, 16, 23, 28 and 38.

3.2. Evaluation of pipe dimensions with respect to the maximum static pressure

Simulations using steady-state scenarios, in a total number of 100, resulted in different maximum static pressures due to differences in heat consumption profiles within the DH network. The 95% confidence interval for the maximum static pressure computed for the DH network was found to be 1010 ± 3.112 kPa. Re-sampling then, obtaining values 50,000 times with use of the bootstrap method, resulted in 1007.5 ± 0.015 kPa. In terms of this latter confidence interval, the maximum static pressure values obtained were considered to be satisfactory, despite their being slightly higher than the design limit for a static pressure of 10 bara. Peak winter conditions occur very seldom, and the safety factor employed in dimensioning the network equipment provides considerable leeway, virtually assuring that the network will not be damaged [60].

3.3. Network types

Branched DH systems of three different network types were dimensioned by use of the optimization method associated with Dimensioning Method 3. The longest nodes of **NM** {13 and 34} and the starting street-nodes of **SN** {2, 7, 13, 20, 25 and 31} provided boundary conditions for the dimensioning method used for the DH network of Network Type 3. The three types of DH network differed in the degree to which the total length of each dimension of the pipes varied, as shown in Table 5. DH systems of Network Type 1 were found to clearly yield smaller dimensions, providing an 8% reduction in heat loss as compared with Network Type 2, due to a reduction in flow demand brought about by the buffer tanks in the substations. Use of Network Type 3 (which had booster pumps) resulted in a 2% reduction in heat loss (for the DH network) as compared with Network Type 2 (which had no booster pumps). The design limit for the maximum allowable pressure difference for each street was increased after the installation of booster pumps, which provided a head lift of 3.8 bar (Table 6). For the streets belonging to the first and the fifth routes there was already a sufficient pressure difference (7.4 bar) between the supply and the return lines of the main line. Thus, no booster pump was installed in these routes, so as to avoid exceeding the static pressure of 10 bara for the streets in question, in accordance with the design. However the reduction in heat loss in Network Type 3 in comparison to Network Type 2 was not found to correlate with the level of reduction in diameter that comparison of the two revealed, due to the nonlinear characteristics of the heat loss transfer coefficient values obtained, e.g. U(37.2) < U(26) and U(20) < U(15) [W/(mK)].

Table 5
Pipe diameters and heat loss from the DH network, as obtained for each of three different DH network types.

		Network Type 1	Network Type 2	Network Type 3
Pipe length [m]	Alu 14/14	141.9	–	–
	Alu 16/16	22.8	–	–
	Alu 20/20	181.8	163.8	70.7
	Alu 26/26	263.6	156.2	92.4
	Alu 32/32	–	46.4	108.8
	St 32/32	471.4	667.6	762.1
	St 40/40	–	–	–
	St 50/50	–	47.5	–
	St 65/65	66.0	66.0	113.5
	St 80/80	141.9	–	–
Heat loss from the DH network [kW]		5.6	6.0	6.1

3.4. Network layouts

The Termis model, with the optimal pipe dimensions provided with use of Dimensioning Method 3, was employed in connection with both of the network layouts with configuration of Network Type 1 (further information regarding this is provided in Section 3.3). In each time series simulation, heat demand data served as the input data for assessing the heat demand of consumers. The time series were generated for a time range of $t_f–t_o = 8$ h, using a time step of $\Delta t = 10$ min for the scenarios, which were generated five times for each presence ratio considered, those of $\varphi = 75\%$, 50% and 25%. Table 7 presents the frequency distribution of the heat demand in kW at the consumer nodes of the scenarios, as an illustration for occupancy ratios of S_{25_3}, S_{50_2} and S_{75_1}. As can be seen in Table 7, the heat demand at the consumer nodes increased as the occupancy ratio became higher. For an occupancy ratio of 25%, some parts of the DH network contained only one or two occupying consumers, resulting in a low heat demand within the time range of the scenarios.

Table 8 shows the ratio of heat loss to the heat energy supplied within a time range of 8 h, the return temperature being obtained at the heat source and the degree-minutes of the supply temperature obtained in accordance to the base temperature of $T_B = 50$ °C within the DH network. The low heat demand density for $\varphi = 25\%$ was found to affect the operation of DH by producing large variation both in the ratio of heat loss to heat supply in Layout 2 and in the return temperature at the heat source in Layout 1. Scenarios involving high occupancy ratios, such as $\varphi = 50\%$ and $\varphi = 75\%$, resulted in the values for both the ratio of heat loss to heat supply in Layout 1 and for the return temperature at the heat source in both layouts varying only slightly. The operating principles of the looped

Table 6
Pressure changes after installation of a booster pump in the first pipe segment in every street.

Route	Pipe segment[a]	Pressure difference between supply and return lines [bara]	
		Residual pressure difference	Pressure difference with additional head lift
1	3	7.4	11.2
2	8	4.2	8.0
3	14	2.1	5.9
4	17	2.1	5.9
5	21	7.2	11.0
6	26	3.8	7.6
7	32	1.5	5.3
8	35	1.5	5.3

[a] Pipe segments where booster pumps were installed.

Table 7
Frequency distribution of the heat demand in different nodes during a time series, for each of three different scenarios that were generated, S_{75_1}, S_{50_2} and S_{25_3}.

Example scenarios	Bin interval [kW]	Frequency of heat demand during the time series in different nodes [-][a]																														
		N_3	N_4	N_5	N_6	N_8	N_9	N_{10}	N_{11}	N_{12}	N_{14}	N_{15}	N_{16}	N_{17}	N_{18}	N_{19}	N_{21}	N_{22}	N_{23}	N_{24}	N_{26}	N_{27}	N_{28}	N_{29}	N_{30}	N_{32}	N_{33}	N_{34}	N_{35}	N_{36}	N_{37}	N_{38}
S_{75_1}	0	2	8	14	7	15	6	17	10	19	9	13	15	12	9	17	12	14	13	10	11	18	8	15	14	7	13	16	17	6	13	16
	0–6	5	35	7	22	28	12	7	28	22	14	8	17	12	18	10	6	11	11	22	7	6	30	28	29	36	15	27	26	25	14	15
	6–12	12	0	22	14	0	25	19	5	2	20	22	11	13	13	16	8	6	19	11	9	6	5	0	0	0	10	0	0	8	16	12
	12–18	24	0	0	0	0	0	0	0	0	0	0	0	6	3	0	17	12	0	0	16	13	0	0	0	0	5	0	0	4	0	0
S_{50_2}	0	9	12	18	15	13	14	12	12	15	15	17	13	12	8	14	5	15	14	17	15	ND	ND	18	13	10	16	10	15	19	12	12
	0–6	5	12	10	28	30	22	10	31	28	28	26	30	31	35	5	38	12	29	12	5	ND	ND	22	30	33	27	21	28	16	21	18
	6–12	15	12	15	0	0	7	21	0	0	0	0	0	0	0	24	0	8	0	14	10	ND	ND	3	0	0	0	12	0	8	10	13
	12–18	14	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	13	ND	ND	0	0	0	0	0	0	0	0	0
S_{25_3}	0	ND	6	10	21	ND	ND	14	18	19	ND	10	ND	ND	9	16	ND	ND	ND	ND	ND	15	ND	16	ND	14	ND	17	ND	ND	14	12
	0–6	ND	4	22	22	ND	ND	13	25	24	ND	15	ND	ND	16	27	ND	ND	ND	ND	ND	12	ND	27	ND	29	ND	26	ND	ND	29	11
	6–12	ND	16	11	0	ND	ND	16	0	0	ND	17	ND	ND	18	0	ND	ND	ND	ND	ND	16	ND	0	ND	0	ND	0	ND	ND	0	20
	12–18	ND	17	0	0	ND	ND	0	0	0	ND	1	ND	ND	0	0	ND	ND	ND	ND	ND	0	ND	0	ND	0	ND	0	ND	ND	0	0

[a] The numbers indicate the amount of time which heat demand value come true within the bin interval and ND means no head demand due to non-occupying consumers in that node.

Table 8
Ratio of heat loss to heat supply in the DH network, together with the return temperature at the heat source and the degree-minute values obtained, for each of two network layouts.

Scenarios	Ratio of heat loss to heat supply [-]		Average return temperature at heat source [°C]		Degree-minutes of supply temperature at nodes [°C-min]	
	Layout 1	Layout 2	Layout 1[a]	Layout 2	Layout 1	Layout 2
S25_1	7.9%	9.1%	28.6 ± 0.72	24.9	130	2129
S25_2	7.9%	8.6%	28.6 ± 0.92	24.9	11	914
S25_3	7.9%	8.8%	27.9 ± 0.53	24.9	142	1494
S25_4	7.9%	8.6%	29.0 ± 0.81	24.9	198	2635
S25_5	7.9%	8.8%	27.8 ± 0.43	24.9	547	1920
S50_1	4.6%	5.2%	26.1 ± 0.37	24.9	66	454
S50_2	4.5%	5.2%	26.3 ± 0.42	24.9	39	648
S50_3	4.5%	5.2%	26.0 ± 0.46	24.9	127	474
S50_4	4.5%	5.2%	25.9 ± 0.28	24.9	193	323
S50_5	4.5%	5.1%	26.1 ± 0.32	24.9	255	873
S75_1	3.1%	3.6%	25.4 ± 0.28	25.0	134	737
S75_2	3.1%	3.6%	25.3 ± 0.14	25.0	181	379
S75_3	3.1%	3.6%	25.3 ± 0.11	25.0	200	454
S75_4	3.1%	3.6%	25.4 ± 0.29	25.0	102	160
S75_5	3.1%	3.6%	25.3 ± 0.19	25.0	230	540

[a] Average of the return temperature at the heat source with standard deviation through the time series analysis.

network did not allow the return heat carrier medium to circulate before the temperature had fallen to the return design temperature ($T_R = 25$ °C). Thus, Layout 2 was found to maintain virtually the same return temperature, of about $T_R = 25$ °C, at the heat source, regardless of the occupancy ratio and of the degree of variation in the heat demand. In contrast, considerable variation in the return temperatures at the heat source was encountered in Layout 1, due to the mixing of heat carrier mediums of supply and return with each other at return line. As can be seen in Fig. 4, for each scenario the heat loss from the supply line was considerably greater for Layout 2 than for Layout 1, whereas in the return line a small change in heat loss occurred between the layouts, though only for an occupancy ratio of 25%. The latter can be explained as being due to the low heat demand there and, as a consequence, the return temperature being raised by mixture of the return medium with the supply heat carrier medium. The positive correlation of degree-minutes and heat loss here suggests the heat loss to have occurred because of the long waiting time of the supply heat carrier medium at Layout 2. A high density of the heat demand reduces the waiting time of the supply heat carrier medium at Layout 2.

A detailed consideration of heat-demanding nodes with an unsatisfactory supply temperature can be rewarding. In scenario S_{25_1}, it is node 38 which is the most unsatisfactory heat-demanding node, in light of the fact that the supply temperature has a degree-minute value of 686 °C-min. Fig. 5 shows the changes obtained in the supply temperature at node $i = 38$ during an 8 h period and in the heat demands of the nodes $i = 38$ and $i = 37$, the only heat-demanding nodes in the local loop in this scenario. The heat demand patterns of the five consumers at the two nodes resulted in an inadequate supply temperature due to the supply heat carrier medium being overly stable for a long period of time.

In the same scenario S_{25_1}, the heat-demanding node $i = 16$ developed a different dynamic behaviour, one that resulted in a degree-minute value of 419 °C-min (Fig. 6). In this local loop the number of heat-demanding consumers connected to nodes $i = 16$ and $i = 19$ was five, just as in the previous local loop example. However, the heat demand pattern at the heat-demanding nodes did not result in any extreme drop in the supply temperature, as it did at node $i = 38$. The node $i = 16$ was exposed to reductions in the supply temperature, slight in magnitude and of short duration, which is more or less acceptable from an engineering point of view.

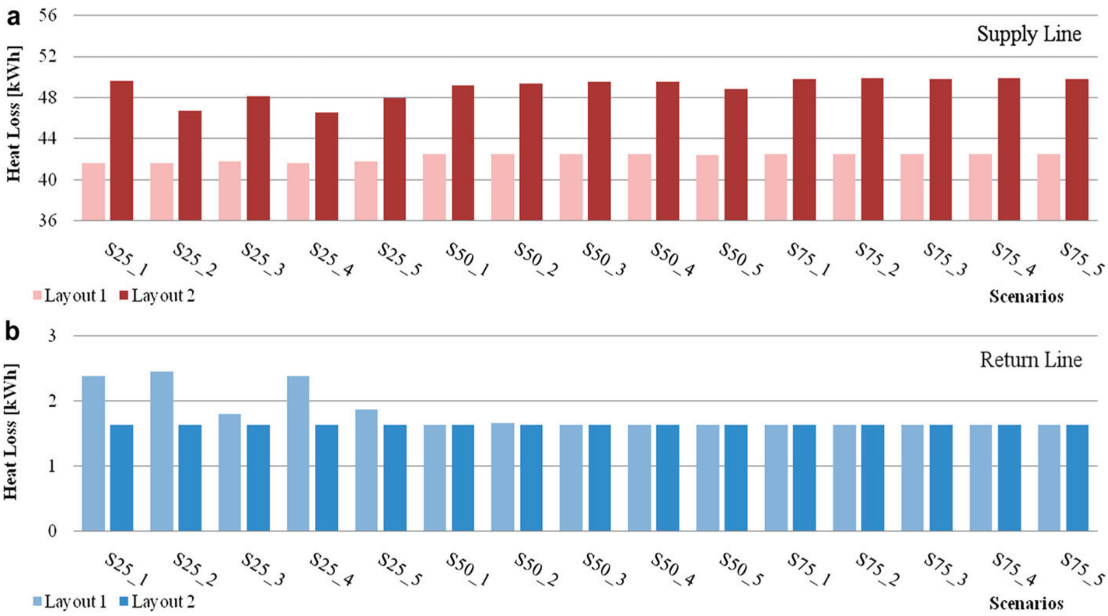


Fig. 4. Overall heat loss from the DH network over a time series, as obtained for (a) supply line and (b) return line.

Fig. 7 shows changes over time in the supply temperature at the node $i = 25$ in Layouts 1 and 2 in the scenario S_{25_4}. In this part of the DH network the only heat-demanding nodes were $i = 25$ and $i = 21$, containing five consumers altogether. Although the same DHW heat-demand patterns were taken as input data for both layouts, the supply temperature profiles of the two layouts differed. The external pipe segment between nodes $i = 23$ and $i = 28$ was also the reason both for the excessive temperature drop in Layout 2 in addition to the reason of the low level of the heat demand of the nodes in question. At the same point in time, the heat consumption by the consumers was sufficient to maintain circulation within the supply line and produce an increase in the supply temperature.

4. Summary

The paper has presented a new method for designing low-energy district heating systems, pipe dimensioning methods, network layout and types of substations being taken up in particular. It was shown that a considerable reduction in heat load in such systems can be achieved through taking account of simultaneity factor in planning of each pipe segment. An optimization method aimed at reducing heat loss in a DH network, also when pressure changes in the various routes through the system are at a maximum, was proposed, a method that can prevent the over-dimensioning of the piping network that readily occurs in the use of traditional dimensioning methods. Comparisons of different dimensioning methods showed that the "Maximum Pressure Gradient" method, when used in conjunction with the optimization method just referred to, was able to provide energy savings of some 14% in preventing heat loss from the DH network. Evaluation of the degree of optimality of a piping network by means of the commercial software Termis was carried out using heat demand scenarios that were randomly generated while at the same time taking account of the simultaneity factor that applied for each pipe segment separately. The results provided strong support for the validity of the optimization method referred to, and also for use of it ensuring that the system is able to withstand conditions of maximum static pressure with sufficient pressure differences obtained in each substation in the DH network. Analysis of different types of networks showed a DH network connected to substations

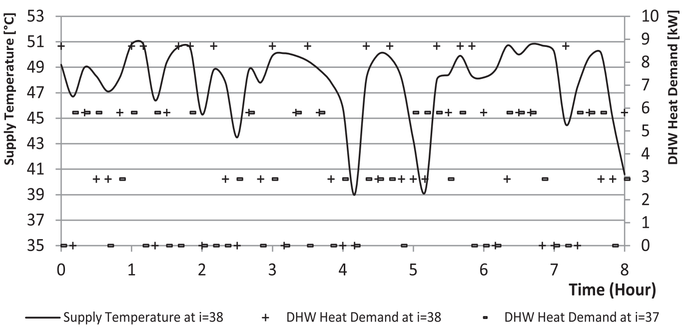


Fig. 5. Changes over time in the supply temperature and the DHW heat demand (S25_1, $i = 38$).

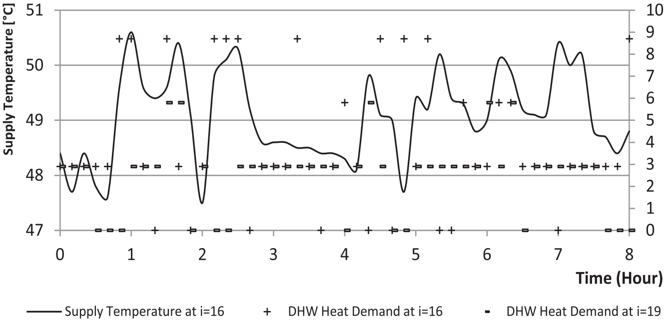


Fig. 6. Changes over time in the supply temperature and the DHW heat demand (S25_1, $i = 16$).

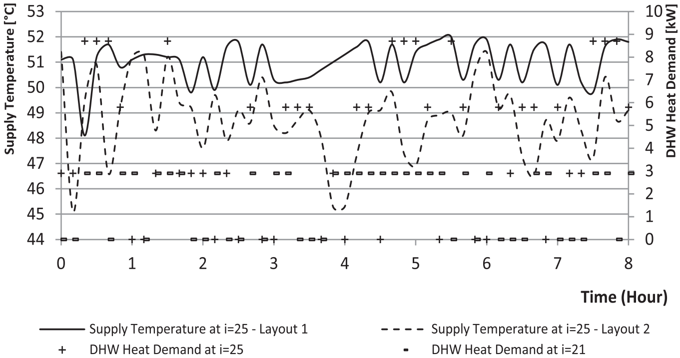


Fig. 7. Changes over time in the supply temperature and the DHW heat demand for each of the two different layouts (S25_4, $i = 25$).

having buffer tanks for DHW production (Network Type 1) to show an 8% lower heat loss from the DH network than a DH network connected to substations having heat exchangers for DHW production (Network Type 2). A Type 3 network, in which booster pumps were installed in a Type 2 network, was found to make a considerable reduction in pipe dimensions possible as a consequence of increased maximum allowable pressure drop at the DH network. At the same time, only about a 2% saving through preventing heat loss by use of a Type 3 network rather than Type 2 network was achieved. The fact that the saving here was so small appears to have been due to the nonlinear characteristics of the heat transfer coefficient. The studies reported on also deal with conditions of low heat demand during summer months when it can be important to prevent low supply temperatures in the DH network from developing. This can be achieved by of either of two different types of network layout, that of a branched DH network having bypass units (Layout 1) and of a looped DH network (Layout 2). Scenarios in which the heat demand patterns of consumers were based on use of simultaneity were generated, the input data thus obtained being analyzed by the Termis software in terms of differing occupancy ratios (25%, 50% and 75%). Under low occupancy ratio conditions (25%, such ratios being common during the summers), a DH network can react sensitively to consumers' heat demand patterns, in the case of Layout 2 in terms of marked variations in heat loss and in the case of Layout 1 in terms of sudden variations in return temperature at heat source in response to different scenarios. One can note that the operational philosophy of Layout 2 is strongly oriented to the heat consumption of consumers. Low demand conditions can also result in the heat carrier medium remaining unused in the supply lines for extended periods of time, which can lead to excessive drops in temperature. In addition, external pipe segments located in looped networks can be a source of considerable heat loss. For occupancy ratios of 25% or less, there also tends to be a clear difference (up to 4 °C) between the return temperature present at the heat source and the return temperature that was planned. Simulation results that were obtained pointed in a general way to Layout 1 being superior to Layout 2 in terms of the supply temperature in the DH network being delivered to consumers with as little loss of heat as possible.

5. Conclusions

A number of general conclusions not yet taken up can be drawn. One is that a district heating system should always be designed in accordance with what works best within the district itself. Another conclusion is that it is highly important to take into consideration, for each pipe segment separately, the degree of simultaneity of the heat consumers involved. In addition, it appears that significant savings can be achieved by use of the proposed optimization method, which makes use of the pumping head lift in all closed loops of a DH network. Buffer tanks for DHW production, installed in each substation, were found to reduce the pipe dimension of the DH network appreciably and the heat loss from it to be reduced as well. One can note too that the mixing of supply and return heat carrier waters that can occur through bypasses being located in leaf nodes does not cause any excessive increase in temperature, except under conditions of extremely low heat demand, the return temperature there also tending to be rather moderate. One should note too that looped DH networks without a bypass tend to contain a considerable amount of supply heat carrier medium, which can lead under certain conditions to considerable drops in temperature and to greater loss of heat from the DH network than from a branched DH network having bypass units in the leaf nodes.

The proposed dimensioning method should be considered in planning for the future energy infrastructures for the low-energy society. However one should develop a design method of low-energy DH system for existing buildings which later will be renovated to low-energy class with consideration given to current and future heat demand of them. The proposed method has the focus on low temperatures but further reduction at the dimensions could be achieved by increasing the supply temperature in the peak winter condition. One future work would be the development of a practical discrete optimization method which deals with commercially available pipe diameters for the dimensioning of DH network.

References

[1] European Parliament legislative resolution of 23 April 2009 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings (recast). Official Journal of the European Union. C 184 E/263. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2010:184E:0263:0291:EN:PDF: [accessed 07.11.2011].

[2] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35(3):1381–90.

[3] 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] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Applied Energy 2011;88(3):568–76.

[5] 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.

[6] 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.

[7] Çomaklı K, Yüksel B, Çomaklı Ö. Evaluation of energy and exergy losses in district heating network. Applied Thermal Engineering 2004;24(7):1009–17.

[8] Torío 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(10):1601–9.

[9] 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. In: The 11th International Symposium on district heating and cooling; 2008. Aug 31–Sep 2, Reykjavik, Iceland.

[10] Christiansen CH, Paulsen O, Bøhm B, Thorsen JE, Ting Larsen C, Jepsen BK et al. Development and demonstration of low-energy district heating for low-energy buildings. Main report and appendices [Udvikling og demonstration af lavenergi-fjernvarme til lavenergibyggeri. Hovedrapport og bilag] [In Danish]. Teknologisk Institut; 2009 March. Report No: EFP 2007. Available from: www.teknologisk.dk/_root/media/34221_EFP%202007.pdf.

[11] Benonysson A, Bøhm B, Ravn HF. Operational optimization in a district heating system. Energy Conversion and Management 1995;36(5):297–314.

[12] Foged M. Low temperature operation [News]. DBDH [electronic mail on the Internet]. 1999 [cited 2011 Jan];1:pp. 3–9.

[13] Paulsen O, Fan J, Furbo S, Thorsen JE. Consumer unit for low energy district heating net. In: The 11th International Symposium on district heating and cooling; 2008. Aug 31-Sep 2, Reykjavik, Iceland.

[14] Hasan A, Kurnitski J, Jokiranta K. A combined low temperature water heating system consisting of radiators and floor heating. Energy and Buildings 2009;41(5):470–9.

[15] Mertoğlu O, Dokuz İ, Canlan A, Bakır N. Alternatif enerji kaynakları ve düşük sıcaklıklı jeotermal bölgesel ısıtma [Alternative energy sources and low temperature geothermal district heating] [In Turkish]. Tesisat Mühendisliği 2000;55. 64–62.

[16] Rämä M, Sipilä K. Challanges on low heat density district heating network design. In: The 12th International Symposium on District Heating and Cooling; 2010. Sep 5-7, Talinn, Estonia. pp. 69–72.

[17] Lund H. Renewable energy systems: the choice and modeling of 100% renewable solutions. Burlington, USA: Academic Press, Elsevier; 2010.

[18] Ren J, Zhu L, Wang Y, Wang C, Xiong W. Very low temperature radiant heating/cooling indoor end system for efficient use of renewable energies. Solar Energy 2010;84(6):1072–83.

[19] Ala-Juusela M, Rautakivi A. Summary report – heating and cooling with focus on increased energy efficiency and improved comfort. VTT. Report No: 2256. Available from: http://www.vtt.fi/inf/pdf/tiedotteet/2004/T2256.pdf; 2004.

[20] Schmidt D. New ways for energy systems in sustainable buildings - increased energy efficiency and indoor comfort through the utilisation of low exergy systems for the heating and cooling of buildings. In: The 21st Conference on Passive and Low Energy Architecture; 2004 Sep 19-22. Eindhoven, The Netherlands. p. 21.

[21] Wasilewski W. The influence of the consumer's installation parameters on district heating systems. Energy and Buildings 1988;12(3):173–7.

[22] Danfoss, 8 steps – control of heating system. Available from: http://heating.danfoss.com/Content/61078BB5-1E17-4CA2-AC49-8A7CAC2BA687_MNU17424997_SIT54.html.

[23] Dincer I, Hepbasli A, editors. District energy systems. Gainesville, USA: CRC Press; 2007. p. 316 (Capehart, BL, editor. Encyclopedia of Energy Engineering and Technology; vol. 3).

[24] Rochas C. The case for district heating: 1000 cities can't be wrong!. DHCAN [Internet]. [cited 2011 Jan]. Available from: http://projects.bre.co.uk/DHCAN/pdf/PolicyGuide.pdf.

[25] Rosada J. Characteristics of district heating - advantages and disadvantages. Energy and Buildings 1988;12(3):163–71.

[26] Dobos L, Abonyi J. Controller tuning of district heating networks using experiment design techniques. Energy 2011;36(8):4633–9.

[27] Overgaard J, Knudsen S. District heating networks - choosing the right pipe dimensions [News]. DBDH [Internet]. 2006 [cited 2011 Jan];1. Available from: http://dbdh.dk/images/uploads/pdf-distribution/district-heating-networks-choosing-the-right.pdf.

[28] Yıldırım N, Toksoy M, Gökçen G. Piping network design of geothermal district heating systems: case study for a university campus. Energy 2010;35(8):3256–62.

[29] Sârbu I. Optimization of water distribution networks. Proceedings of the Romanian Academy, Series A - Mathematics Physics Technical Sciences Information Science 2010;11(4):330–9.

[30] Winter W, Haslauer T, Obernberger I. Untersuchungen zur gleich-zeitigkeit in nahwärmenetzen: Ergebnisse und projekterfahrungen [Simultaneity surveys in district heating networks: results and project experience]. EuroHeat & Power 2001;30(10):42–7 [In German].

[31] González-Cebollada C, Macarulla B, Sallán D. Recursive design of pressurized branched irrigation networks. Journal of Irrigation and Drainage Engineering 2011;137(6):375–82.

[32] Bejan A, Tsatsaronis G, Moran M. Thermal design & optimization. New York: John Wiley & Sons, Inc; 1996 [Chapter 9], Thermoeconomic optimization; pp. 463–510.

[33] Mathews EH, Brenkman HF, Köhler PAJ. Optimization of pipe networks using standardized pipes. R&D Journal 1994;10(2):45–51.

[34] Maunder C, editor. Termis help manual [disk]. Version 2.10. Denmark: Birkerød; 2010. 7-Technologies A/S.

[35] Li H, Dalla Rosa A, Svendsen S. Design of low temperature district heating network with supply water recirculation. In: The 12th International Symposium on District Heating and Cooling; 2010 Sep 5-7. Talinn, Estonia. pp. 73–80.

[36] Peng W, Pinghua Z. Research on network reliability of district heating systems based on the combined planar network model. In: The IEEE international conference on industrial engineering and engineering management; 2009 Dec 8-11. Hong Kong. pp. 233–236.

[37] Thorsen JE, Christiansen CH, Brand M, Olesen PK, Larsen CT. Experiences on low-temperature district heating in Lystrup – Denmark. In: International Conference on district energy; 2011 March 20–22. Portorož, Slovenia.

[38] Brand M, Thorsen JE, Svendsen S, Christiansen CH. A direct heat exchanger unit used for domestic hot water supply in a single-family house supplied by low energy district Heating. In: The 12th International symposium on district heating and cooling; 2010 Sep 5–7. Talinn, Estonia. pp. 60–68.

[39] Brand M, Dalla Rosa A, Svendsen S. Performance of low temperature district heating systems for low energy houses. In: The future for sustainable built Environments with high performance energy systems; 2010 Oct 19–21. Munich, Germany. pp. 174–183.

[40] Erhvervs og Byggestyrelsen, Building class 2020 [Bygningsklasse 2020] [in Danish]. Copenhagen: Erhvervs og Byggestyrelsen; 2011 June 1. p. 33 Available from: www.ebst.dk.

[41] Zinko H, Bøhm B, Sipilä K, Kristjansson H, Ottosson U, Rämä M. District heating distribution in areas with low heat demand density. In: The 11th International Symposium on district heating and cooling; 2008 Aug 31–Sep 2. Reykjavik, Iceland.

[42] Product catalogue of bonded pipe [Internet]. Denmark: Logstor; [modified 2011 July; cited 2011 August]. Available from: http://www.logstor.com/.

[43] Product catalogue of twin pipes [Internet]. Denmark: Logstor; [modified 2009 March; cited 2011 August]. Available from: http://www.logstor.com/.

[44] Steer KCB, Wirth A, Halgamuge SK. Control period selection for improved operating performance in district heating networks. Energy and Buildings 2011;43(2–3):605–13.

[45] Dalla Rosa A, Li H, Svendsen S. Method for optimal design of pipes for low-energy district heating, with focus on heat losses. Energy 2011;36(5):2407–18.

[46] Gabrielaitiene I, Bøhm B, Sunden B. Modelling temperature dynamics of a district heating system in Naestved, Denmark – a case study. Energy Conversion and Management 2007;48(1):78–86.

[47] Vestergaard JB. The distribution network (August). Lecture note presented at Summer School District Energy. Denmark: Århus; 2010.

[48] Sanks RL. Flow in conduits. In: Sanks RL, Tchobanoglous G, Bosserman BE, Jones GM, editors. Pumping station design. Boston, USA: Butterworth-Heinemann; 1998. p. 33–9.

[49] Clamond D. Efficient resolution of the colebrook equation. Industrial & Engineering Chemistry Research 2009;48:3665–71.

[50] Dalla Rosa A, Li H, Svendsen S. Steady state heat losses in pre-insulated pipes for low-energy district heating. In: The 12th International Symposium on district heating and cooling; 2010 Sep 5–7. Talinn, Estonia. pp. 81–89.
[51] Wallentén P. Steady-state heat loss from insulated pipes. Sweden: Lund Institute of Technology; 1991 May. 198 p. Report No: TVBH-3017.
[52] Messina JP. Branch-line pumping systems. In: Karassik IJ, Messina JP, Cooper P, Heald CC, editors. Pump handbook. USA: McGraw-Hill; 2001. pp. 83–90.
[53] The Mathworks Inc. Matlab help manual – optimization toolbox [disk]. Version 7.11.0.584 (R2010b). Massachusetts: Matworks Inc; 2010 August 16.
[54] Leyffer S, Mahajan A. (Mathematics and Computer Science Division, Argonne National Laboratory, Argonne, IL). Nonlinear constrained optimization: methods and software. IL: UChicago Argonne, LLC; 2010 March 17. 30 p. Report No.: ANL/MCS-P1729-0310. Contract No.: DE-AC02-06CH11357.
[55] Microsoft Support. Generating a random number without RAND() in Excel [Internet]. [place unknown]: Microsoft; [modified 2006 Nov 16; cited 2011 Feb]. Available from: http://support.microsoft.com/kb/44738.
[56] Efron B, Tibshirani R. Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. Statistical Science 1986; 1(1):54–75.
[57] Langendries R. Low return temperature (LRT) in district heating. Energy and Buildings 1988;12(3):191–200.
[58] Beggs C. Energy: management, supply and conservation. 2nd ed. Oxford: Butterworth-Heinemann; 2009. Appendix 1, Degree Days; pp. 343–346.
[59] Durmayaz A. An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul. Energy 2000;25(12):1245–56.
[60] Christiansen CH, Worm J, Jørgensen H, Thorsen JE, Bennetsen J, Larsen CT, et al. Demonstration of low energy district heating system for low energy building in Ringgårdens Afd. 34 in Lystrup [Demonstration af lavenergifjernvarme til lavenergibyggeri i boligforeningen Ringgårdens afd. 34 i Lystrup] [in Danish]. Final Report 2011 Maj. Copenhagen: Teknologisk Institut: 2011 Maj. 104 p. Report No.: EUDP 2008-II. Available from: http://www.ibe.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r250.pdf.

ISI ARTICLE II

Energy Conversion and Management 64 (2012) 551–561

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

A comparative study on substation types and network layouts in connection with low-energy district heating systems

Hakan İbrahim Tol *, Svend Svendsen

Technical University of Denmark, Department of Civil Engineering, Section of Building Physics and Services, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Available online 25 August 2012

Keywords:
District heating
Low temperature
Substation type
Branched network
Looped network
Booster pump

ABSTRACT

The study deals with low-energy District Heating (DH) networks operating in low temperatures such as 55 °C in terms of supply and 25 °C in terms of return. The network layout, additional booster pumps, and different substation types such as storage tanks either equipped or not equipped in domestic hot water production site were examined. Effects of booster pumps on pipe dimensions in the latter case were investigated. Temperature drops during the summer months due to low heat demands of consumers were explored. Use of approaches such as looped networks and branched network layouts with bypasses for end-consumers were also studied, heat loss from these networks and the drop in temperature in the heat-carrier-supply medium being compared.

1. Introduction

Energy supply systems based on renewable energy sources have been of considerable interest to policy makers concerned with finding long-term energy solutions, due to such systems being more environmentally friendly than those leading to depletion of fossil-fuels [1–3]. The possibility has been considered of employing District Heating (DH) systems in conjunction with renewable energy sources as a long-term energy solution. This is partly in view of the ease with which DH systems can be connected with any type of heat source [4–7]. Successful examples of employing extremely low supply temperatures in low-energy DH systems, 55 °C for example and 25 °C for return temperatures have been demonstrated in case projects in Lystrup, Denmark [8–10], and in the SSE Greenwatt Way development project in Slough in the UK [11,12]. Various advantages in the use of low operating temperatures have been shown, such as reduction in overall heat loss from the DH network, increased efficiency in heat extraction at the heat source, and the exploitation of low temperature renewable energy sources such as geothermal sources, and solar energy and of waste heat from industry, which otherwise be lost [13–15].

In addition to the benefits achieved by use of low operating temperatures, there are expected to be gains achieved through determining the most energy-efficient dimensioning method or methods to be used in low-energy DH systems. In an earlier study [16], an optimization method was reported, one based in part on earlier studies at our department [17–20]. The method in question aimed at minimizing heat loss from the DH network through reducing the pipe dimensions in each pipe segment of the network. Once the main pump of the DH network is dimensioned so as to provide a certain amount of head lift, as determined on the basis of pressure loss along the critical route, the network can compensate for pressure losses along the other routes in the DH network [21]. An optimization algorithm that was developed facilitated the head lift the pump provided being utilized as much as possible along each route, not simply the critical one [16,22]. The cost impact of pumping was found to be extremely low in comparison both to heat loss from the DH network and to the pipe investment costs when low-energy DH systems using twin pipes [8,10]. The optimization method was, therefore, designed with the aim of minimizing heat losses from the DH network and maximizing the reliability of the system. It also prevented the pressure losses from exceeding the system's upper static pressure limit. In order to supply the heating that consumers needed, the DH network was dimensioned in accordance with the lowest pressure difference that would be viable, one of about 50 kPa, its exact value being unique for the substation of each consumer.

The work presented in the paper addresses two major topics the authors have taken up earlier [16,23]. Emphasis is placed in the present paper on details of the analyses conducted of the effects of the different types of substations and of the network layouts involved. The two major topics considered here are (1) the effects of the substations of different types and of additional booster pumps in the DH network on the pipe dimensions employed and (2) the excessive temperature drop observed in the supply line during the summer months, as viewed in light of the differing heat consumption profiles of consumers during that period.

* Corresponding author. Tel.: +45 45 25 50 27; fax: +45 45 88 32 82.
E-mail addresses: hatol@byg.dtu.dk (H.İ. Tol), ss@byg.dtu.dk (S. Svendsen).

0196-8904/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enconman.2012.04.022

2. Methods

The investigations described were carried out within a genuine case study conducted in Trekroner (a suburban area of the Roskilde Municipality in Denmark) concerned with 165 low-energy houses to be built, for which it was planned that they would be provided with a low-energy DH network. The network was to have an overall length of 1.2 km and of 1.4 km in the case of a branched and of a looped layout, respectively, that were planned to be dimensioned in accordance with twin pipes. The design limit of maximum static pressure was restrained at 10 bara with the use of twin pipes in the DH network. Each consumer was assumed to have the same reference house, appropriate for the low-energy class as defined by the software Be06 [24].

2.1. Effects of the substation types and the booster pump on the pipe dimensions

Studies concerning the substation types and the booster pump were only carried out for the branched DH network layout (Fig. 1). The overall heat load for consumers depended on the consumers' heat consumption profile and Domestic Hot Water (DHW) consumption, as well as on the type of the substation established at each consumer site [25]. Both of the substations considered in the study made use of the same type of heat exchanger and control system in regard to DHW production. Each substation was assumed to supply heat to one consumer only, although in some cases substations can be considered to supply several consumers [26].

The units for space heating (radiators, floor heating, etc.) were assumed to be connected with the DH network directly and for both types of substations to have a fixed heat demand of 3 kW. The substations were considered to be equipped with differential pressure control valves that adjusted the flow on the primary side (where the DH medium is circulated), in accordance with the heat demand requirements that apply which are aimed at achieving a hydraulically balanced distribution throughout the DH network [27,28]. More detailed information regarding the substations with the types involved, given in the following two sub-sections, can be obtained from studies [8–10,14,29,30].

2.1.1. Substation Type 1

This type of substation was equipped with a storage tank having a capacity of 120 l for DHW production (Fig. 2). In this configuration of the substation, the storage tank is located on the primary side, where the DH heat carrier medium is circulated, so as to avoid the risk of legionella growth. The heat supply carrier medium is stored in the storage tank during charging of the tank. When DHW is being used by a consumer, the stored heat carrier medium is considered to be circulating through the heat exchanger of the

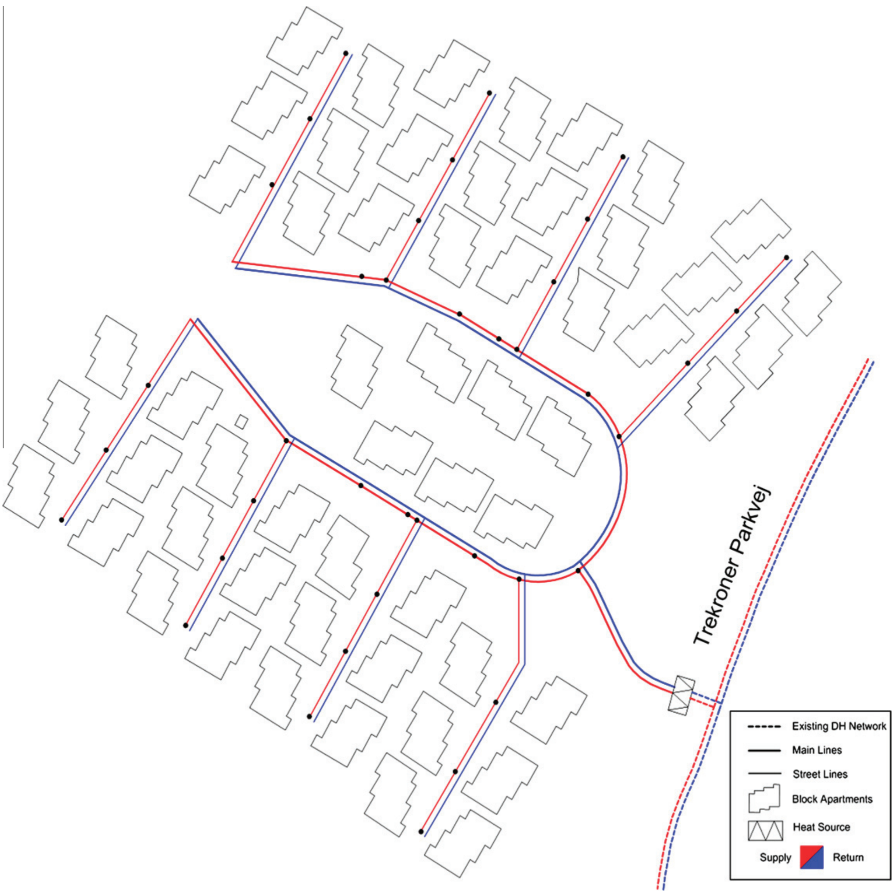


Fig. 1. Branched network layout considered for use in the Trekroner Area.

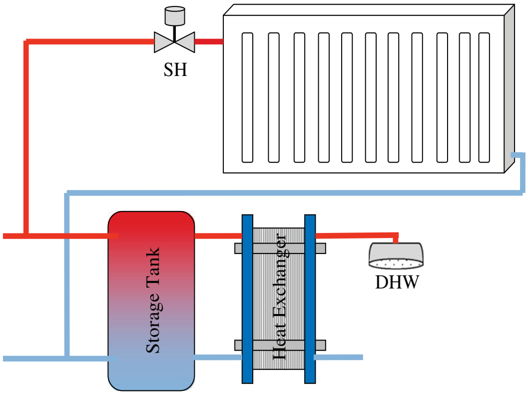


Fig. 2. Diagram of Substation Type 1.

DHW production unit. The flow rate in charging the storage tank is 75 l/h at the most, equivalent for DHW to 3 kW of heat demand, supplied by the DH network [10].

2.1.2. Substation Type 2

In this substation, configuration of the DH network was defined as being connected directly with the heat exchanger of the DHW production unit (though no storage tank, in fact, was installed), as shown in Fig. 3. The heat demand that DHW production created was set to 32 kW, based on data reported in studies.

2.1.3. Booster pump

The degree of utilization of booster pumps varies widely within distribution networks. Traditionally, a booster pump is used to discharge the medium stored in an atmospheric storage tank into a separate, closed and/or high-service distribution network [27]. In the present study, we considered using booster pumps to increase the head lift, designed to be utilized as much as possible in the optimization method employed, with the aim of reducing the pipe dimensions. Increasing the pressure difference between the supply and the return lines by means of the extra head lift that the booster pumps provided made it possible to reduce the pipe dimensions further in a low-energy DH network considered as supplying heat to consumers from a Type 2 Substation. In a closed distribution system, the additional head lift provided needs to be checked regarding whether the overall static pressure at the location where the booster pumps are installed exceeds the maximum allowable static pressure level, the residual pressure level provided by the main pump station also need to be taken into account in connection with this. In this basis of providing extra head lift; the branched network layout was formed with additional booster pumps equipped at the start of the pipe segments in each street, as shown in Fig. 4. The overall static pressure levels, involving the residual and additional head lift provided, respectively, from the main pump station and from the booster pumps established, were checked in each street. No booster pumps were installed in the streets exceeding the overall static pressure beyond the design limit of 10 bara.

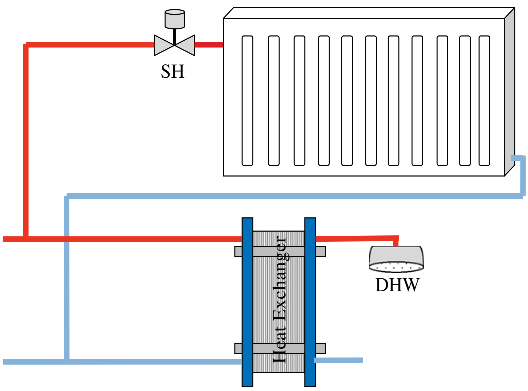


Fig. 3. Diagram of Substation Type 2.

2.2. Preventing temperature drop in the summer months

The consumers do not necessarily need space heating during the summer months. Also, many of them are away on holiday during at least part of that time, reducing the overall DHW consumption. Because of the heat demand being low (no space heating being needed and the reduced DHW needs), the heat carrier medium tends to be exposed to long waiting times before being consumed, leading to the supply heat carrier medium's temperature being markedly reduced [31–33]. Regarding the summer months, there are two matters to be considered in particular: the adequacy of the supply temperature the consumers are provided with, and the heat loss that occurs from the DH network because of the long waiting time of the heat carrier medium. It could be worthwhile to investigate the importance of both matters for maintaining the reliability of supply, so as to avoid excessive temperature drops within the DH network, as regards both (a) the branched portion of the DH network with its bypasses equipped at the end-consumers and (b) the looped portion of it, without bypasses.

2.2.1. Branched DH networks

A branched network layout is widely used in the distribution networks of DH systems as well as in draining and irrigation systems. Such layouts are also observable in natural objects such as blood vessels and trees [34,35]. Branched (also known as tree-like) DH networks are formed in layouts permitting a unidirectional flow from the heat source to the end-consumers (Fig. 1). In a layout of this type there are only two pipe segments connected to each interior node and a unidirectional flow from the root node (the node without any preceding nodes – i.e., the heat source) towards the leaf nodes (the nodes without any successor nodes – i.e. the end consumers) [20,36]. The traditional way of determining the heat load on each pipe segment is to sum all of the heat loads of the successor nodes [37]. In the present study use of a simultaneity factor which is a function of the cumulative number of consumers for each pipe segment was considered. This enables there to be a descending succession of pipe diameters from the heat source to the end consumers, larger diameters being followed by smaller diameters, therefore [38].

In such a branched network layout, thermostatic bypass units were to be inserted at the leaf-nodes in each route of the DH network. Such bypass units become activated when the supply temperature decreases to a certain point, which in the present study was set to 50 °C, there being a dead band at 4 °C and a maximum flow level of 0.056 kg/s, to be used in hydraulic and thermal simulation software Termis software [39]. The supply heat carrier medium, when cooled down, is directed through the bypass units to the return line, to be sent back to the heat source.

2.2.2. Looped DH networks

It was decided that use would be made in part of looped layouts as distribution networks due to their providing greater security of supply than branched layouts do [37,40]. The loops in the pipe seg-

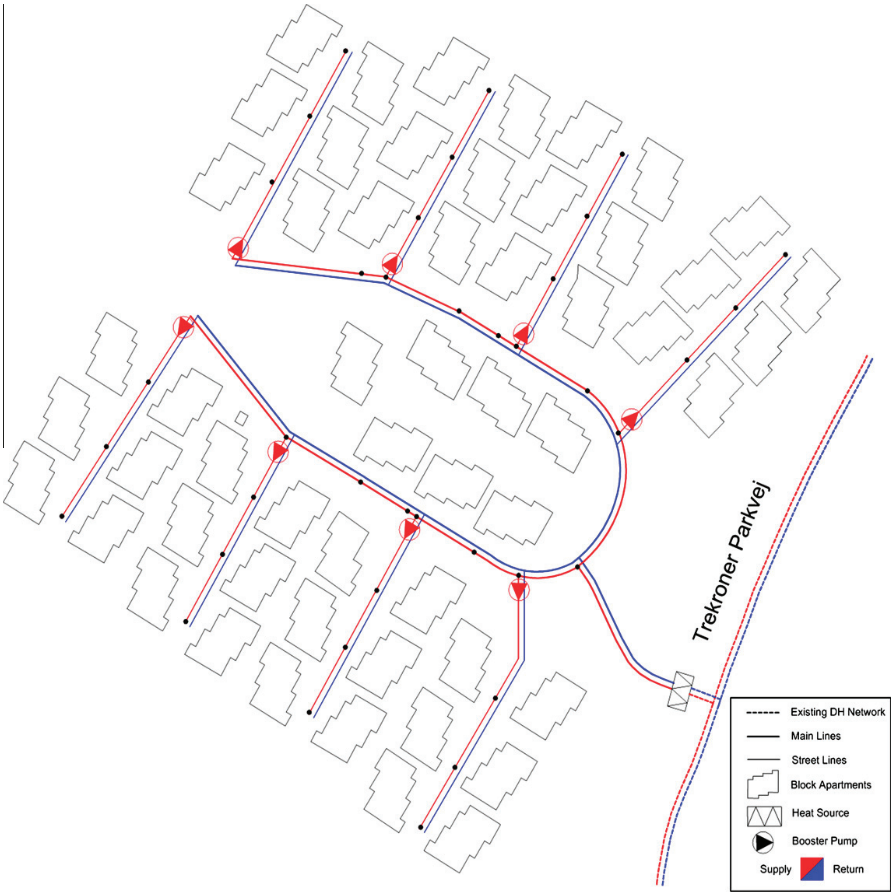


Fig. 4. Branched layout in which booster pumps are located on the supply line at the starting section of each of the streets involved.

ments were in the form of closed paths composed of branches, such that each heat-demanding-node had a number of alternative paths to be supplied by the heat carrier medium of neighboring nodes [38]. Use of a looped layout results in the direction of flow being determined by the shortest (least resistant) path when delivering the heat carrier medium to the heat-demanding-nodes. For a looped layout there is some uncertainty, however, regarding the direction of flow, which is affected by the dynamics of heat consumption in the heat demanding nodes. Since each looped layout is a closed branched path, the piping network in such a looped layout supplies heat to a greater number of consumers in a given district than a branched layout does. Accordingly, supplying a greater number of consumers within such a looped layout can lead to the circulation of the DH heat carrier medium occurring in a completely natural way, through heat consumption by the consumers. In the present study, the DH network was provided with a looped layout without any bypasses (Fig. 5). It should be emphasized that a network being looped can result in its being greater in length than a corresponding branched one, due to the additional pipe segments used to form the closed path of branches there [38,40]. The dimensions of the pipe segments used to link the branches in forming the looped layout were selected on the basis of the maximum diameter of the pipe segments that were to be linked together.

2.3. Dynamic analyses representing summer situations

The dynamics of heat consumption by the consumers affects operation of the DH system considerably through producing variations in critical routes and in the flow conditions present [20,41,42]. Accordingly several scenarios, representing different types of consumer behavior, were generated to investigate the energy efficiency of different network layouts [43]. In generating the scenarios, account was taken of a wide variety of urban heat consumption profiles for the summer months, including lack of need of SH, the vacation-intended absence of some consumers, and the DHW needs of consumers presents in the district (entirely on the basis of the simultaneity factor) [42]. The scenarios generated were used then as input data to the DH model for dynamic analyses, carried out by the Termis software [39], for comparing the energy efficiency of the layouts in terms of heat loss from the DH network and temperature drops that occurred in supplying the heat-demanding nodes.

Also, the basic idea of degree-hours, described in detail in [44], was used in assessing the degree of satisfaction of consumers regarding the supply temperature [44]. A degree–minutes formulation based on degree–hours was defined to investigate the deficiencies in the supply temperature arrived at the heat-demanding consumers through the periods of time covered in dy-

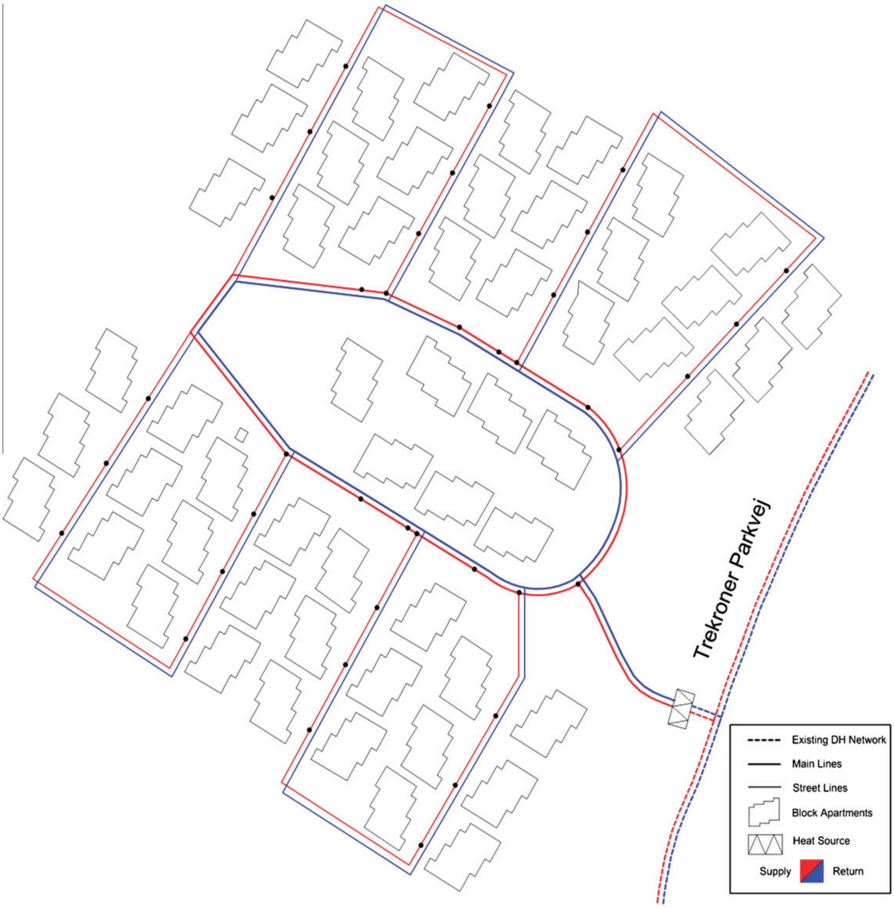


Fig. 5. Looped network layout considered for use in the Trekroner area.

namic simulations. Accordingly, the supply temperature arriving at the heat-demanding consumers below a certain base temperature level of 50 °C were investigated by use of degree–minutes formulation. In this way, in comparing the two different layouts described in the Section 2.2, the dissatisfaction of consumers regarding the supply temperature can be followed comprehensively during periods studied by means of dynamic analyses.

3. Results

In the present paper, two aspects of the utilization of a low-energy DH system in the area in question were examined: (1) the effects of differing substation types and of additional booster pumps on pipe diameters, and (2) the effects of the network layout on the energy efficiency of heat distribution during the summer months.

3.1. Effects of substation types and of booster pumps

Fig. 6 shows heat load values, calculated for separate pipe segments dependent on the cumulative numbers of consumers. These were used in calculating the simultaneity factor applying to the Trekroner low-energy DH network. The various pipe segments differed in the rate of reduction in heat load obtained with use of Substation Type 2 as compared with that obtained with use of Substation Type 1. For example, for Substation Type 2 the rate of reduction in heat load was found to be 30% for the main pipe segment designated as "1", whereas the rate reached 70% for the end branch (the last pipe segment) in each route. Each end branch pipe segment was defined as supplying heat to six consumers.

The branched network consisted of 38 pipe segments in the configuration consisting of separate routes, each composed of sequences of pipe segments in reverse–hierarchical order, as shown in Table 1. The same pipe-segment order applies to the other tables (Tables 2–4) as well with the same branched network layout.

Optimal pipe diameters, as found for a low-energy DH network connected to consumers by way of Substation Type 1 are shown, together with final pressure-drop values, in Table 2. The order of presentation there is the same as in Table 1.

Optimal pipe diameters found for a low-energy DH network connected to consumers by way of Substation Type 2 are shown, together with final pressure-drop values, in Table 3, the order of presentation there too being the same as in Table 1.

Booster pumps with a head lift capacity of 3.8 bar were installed at the start of the series of pipe segments located at the street level (start of the series of pipe segments at the third level in the reverse-hierarchy of pipe segment, in accordance with the order given in Table 4). Pipe segments 3 and 21, which belonged to

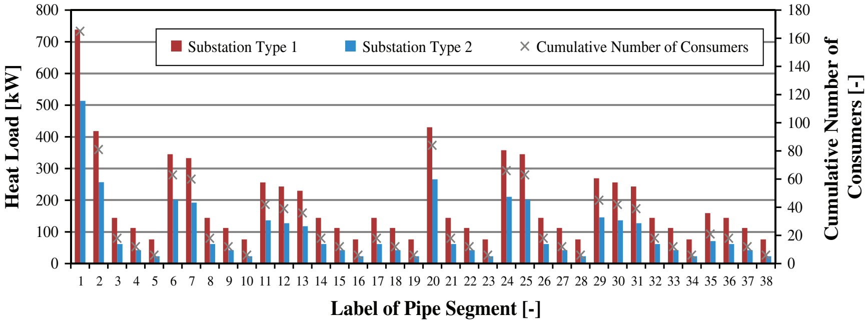


Fig. 6. Effects of substation types on heat load values determined for each pipe segment on the basis of the simultaneity factor, shown as a function of cumulative numbers of consumers.

Table 1
Configuration of routes as sequences of pipe segments, the lengths of the different pipe segments being indicated.

		1[a]	2	3	4	5	6	7	8	9	10	11
Route 1	Pipe segment (–)	5	4	3	2	1	–	–	–	–	–	–
	Length (m)	24.4	21.6	41	19	66	–	–	–	–	–	–
Route 2	Pipe segment (–)	10	9	8	7	6	2	1	–	–	–	–
	Length (m)	22.8	23	23.4	37.4	35.7	19	66	–	–	–	–
Route 3	Pipe segment (–)	16	15	14	13	12	11	7	6	2	1	–
	Length (m)	23.4	23.8	18.5	31.1	26.2	31	37.4	35.7	19	66	–
Route 4	Pipe segment (–)	19	18	17	13	12	11	7	6	2	1	–
	Length (m)	22.5	23	81.8	31.1	26.2	31	37.4	35.7	19	66	–
Route 5	Pipe segment (–)	23	22	21	20	1	–	–	–	–	–	–
	Length (m)	23.5	22	32.3	28.5	66	–	–	–	–	–	–
Route 6	Pipe segment (–)	28	27	26	25	24	20	1	–	–	–	–
	Length (m)	24	23.9	22.7	36	35	28.5	66	–	–	–	–
Route 7	Pipe segment (–)	34	33	32	31	30	29	25	24	20	1	–
	Length (m)	22.8	23	20.9	29.9	24.9	34.2	36	35	28.5	66	–
Route 8	Pipe segment (–)	38	37	36	35	31	30	29	25	24	20	1
	Length (m)	23.8	22	68.9	33.6	29.9	24.9	34.2	36	35	28.5	66

[a] On the top line, 1 denotes the end branch (last pipe segment) for each route and the numbers to the right of it the successive pipe segments from the last one to the root node (or heat source).

Table 2
Optimal pipe diameters and the pressure drop values observed, shown for Substation Type 1.

		1	2	3	4	5	6	7	8	9	10	11
Route 1	Pipe diameter (mm)	10	15	20	37.2	70.3	–	–	–	–	–	–
	Pressure drop (bar)	3.4	1.3	1.2	0.5	0.2	–	–	–	–	–	–
Route 2	Pipe diameter (mm)	10	15	20	37.2	37.2	37.2	70.3	–	–	–	–
	Pressure drop (bar)	3.2	1.3	0.7	0.6	0.6	0.5	0.2	–	–	–	–
Route 3	Pipe Diameter (mm)	10	15	20	37.2	37.2	37.2	37.2	37.2	37.2	70.3	–
	Pressure drop (bar)	3.3	1.4	0.5	0.2	0.2	0.2	0.6	0.6	0.5	0.2	–
Route 4	Pipe diameter (mm)	15	20	20	37.2	37.2	37.2	37.2	37.2	37.2	70.3	–
	Pressure drop (bar)	0.4	0.3	2.3	0.2	0.2	0.2	0.6	0.6	0.5	0.2	–
Route 5	Pipe diameter (mm)	10	15	20	37.2	70.3	–	–	–	–	–	–
	Pressure drop (bar)	3.3	1.3	0.9	0.8	0.2	–	–	–	–	–	–
Route 6	Pipe diameter (mm)	10	15	20	37.2	37.2	37.2	70.3	–	–	–	–
	Pressure drop (bar)	3.4	1.4	0.6	0.6	0.6	0.8	0.2	–	–	–	–
Route 7	Pipe diameter (mm)	11.6	15	20	37.2	37.2	37.2	37.2	37.2	37.2	70.3	–
	Pressure drop (bar)	1.5	1.3	0.6	0.2	0.2	0.3	0.6	0.6	0.8	0.2	–
Route 8	Pipe diameter (mm)	10	15	37.2	37.2	37.2	37.2	37.2	37.2	37.2	37.2	70.3
	Pressure drop (bar)	3.3	1.3	0.1	0.1	0.2	0.2	0.3	0.6	0.6	0.8	0.2

Routes 1 and 5, respectively, were not equipped with booster pumps, since otherwise the maximum static pressure there would have exceeded the system's maximum allowable static pressure, which was defined as design limit of 10 bara.

The heat loss observed in the DH network connected to Substation Type 2 resulted in an 8% increase as compared with Substation Type 1 equipped at substation of each consumer, while 6% increase observed when booster pumps were installed at the DH network.

Table 3
Optimal pipe diameters and pressure drop values as observed for Substation Type 2.

		1	2	3	4	5	6	7	8	9	10	11
Route 1	Pipe diameter (mm)	15	26	26	70.3	70.3	–	–	–	–	–	–
	Pressure drop (bar)	4.2	0.5	1.5	0.0	0.5	–	–	–	–	–	–
Route 2	Pipe diameter (mm)	15	37.2	37.2	37.2	37.2	70.3	70.3	–	–	–	–
	Pressure drop (bar)	4.0	0.1	0.2	1.6	1.7	0.0	0.5	–	–	–	–
Route 3	Pipe diameter (mm)	26	37.2	37.2	37.2	37.2	37.2	37.2	37.2	70.3	70.3	–
	Pressure drop (bar)	0.3	0.1	0.2	0.6	0.6	0.8	1.6	1.7	0.0	0.5	–
Route 4	Pipe diameter (mm)	20	37.2	37.2	37.2	37.2	37.2	37.2	37.2	70.3	70.3	–
	Pressure drop (bar)	0.9	0.1	0.7	0.6	0.6	0.8	1.6	1.7	0.0	0.5	–
Route 5	Pipe diameter (mm)	15	20	37.2	70.3	70.3	–	–	–	–	–	–
	Pressure drop (bar)	4.1	1.9	0.3	0.1	0.5	–	–	–	–	–	–
Route 6	Pipe diameter (mm)	20	20	37.2	37.2	37.2	70.3	70.3	–	–	–	–
	Pressure drop (bar)	1.0	2.0	0.2	1.7	1.7	0.1	0.5	–	–	–	–
Route 7	Pipe diameter (mm)	26	37.2	37.2	37.2	37.2	37.2	37.2	37.2	70.3	70.3	–
	Pressure drop (bar)	0.3	0.1	0.2	0.7	0.6	1.0	1.7	1.7	0.1	0.5	–
Route 8	Pipe diameter (mm)	37.2	37.2	37.2	37.2	37.2	37.2	37.2	37.2	37.2	70.3	70.3
	Pressure drop (bar)	0.1	0.1	0.6	0.3	0.7	0.6	1.0	1.7	1.7	0.1	0.5

Table 4
Optimal pipe diameters and the pressure drop values observed, for Substation Type 2, together with additional booster pumps, in the DH network.

		1	2	3	4	5	6	7	8	9	10	11
Route 1	Pipe diameter (mm)	15	20	37.2	54.5	70.3	–	–	–	–	–	–
	Pressure drop (bar)	4.2	1.9	0.3	0.1	0.5	–	–	–	–	–	–
Route 2	Pipe diameter (mm)	15	20	26	37.2	37.2	54.5	70.3	–	–	–	–
	Pressure drop (bar)	4.0	2.0	0.9	1.6	1.7	0.1	0.5	–	–	–	–
Route 3	Pipe diameter (mm)	20	20	20	37.2	37.2	37.2	37.2	37.2	54.5	70.3	–
	Pressure drop (bar)	1.0	2.0	2.5	0.6	0.6	0.8	1.6	1.7	0.1	0.5	–
Route 4	Pipe diameter (mm)	15	26	37.2	37.2	37.2	37.2	37.2	37.2	54.5	70.3	–
	Pressure drop (bar)	3.9	0.5	0.7	0.6	0.6	0.8	1.6	1.7	0.1	0.5	–
Route 5	Pipe diameter (mm)	15	20	37.2	54.5	70.3	–	–	–	–	–	–
	Pressure drop (bar)	4.1	1.9	0.3	0.3	0.5	–	–	–	–	–	–
Route 6	Pipe diameter (mm)	15	20	37.2	37.2	37.2	54.5	70.3	–	–	–	–
	Pressure drop (bar)	4.2	2.0	0.2	1.7	1.7	0.3	0.5	–	–	–	–
Route 7	Pipe diameter (mm)	15	37.2	37.2	37.2	37.2	37.2	37.2	37.2	54.5	70.3	–
	Pressure drop (bar)	4.0	0.1	0.2	0.7	0.6	1.0	1.7	1.7	0.3	0.5	–
Route 8	Pipe diameter (mm)	15	37.2	37.2	37.2	37.2	37.2	37.2	37.2	37.2	54.5	70.3
	Pressure drop (bar)	4.1	0.1	0.6	0.3	0.7	0.6	1.0	1.7	1.7	0.3	0.5

Table 5
Ratio of bypass flow to total flow, as observed for different scenarios.

	25_1	25_2	25_3	25_4	25_5	50_1	50_2	50_3	50_4	50_5	75_1	75_2	75_3	75_4	75_5
Mean	14.0	14.1	11.1	16.2	11.3	3.7	4.6	4.2	3.5	4.2	1.6	1.5	1.4	1.4	1.3
Standard Deviation	2.4	2.7	2.8	2.6	2.7	1.3	2.4	2.6	1.2	1.0	1.4	0.8	0.9	1.4	0.9

Table 6
Heat loss from the DH network and heat supplied to the DH network, as observed for a branched layout.

	25_1	25_2	25_3	25_4	25_5	50_1	50_2	50_3	50_4	50_5	75_1	75_2	75_3	75_4	75_5
Heat loss (kW h)	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44
Heat supplied (kW h)	556	556	556	560	558	969	970	977	973	972	1416	1440	1416	1414	1415

Table 7
Heat loss from the DH network and heat supplied to the DH network, as observed for a looped layout.

	25_1	25_2	25_3	25_4	25_5	50_1	50_2	50_3	50_4	50_5	75_1	75_2	75_3	75_4	75_5
Heat loss (kW h)	51	48	50	48	50	51	51	51	51	51	52	52	52	52	52
Heat supplied (kW h)	565	563	565	563	565	983	984	983	983	983	1424	1449	1424	1424	1424

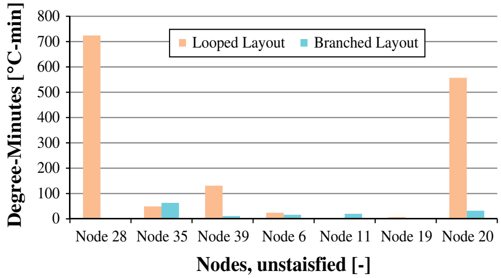


Fig. 7. Degree–minutes for the unsatisfied nodes alone, for scenario S25_3.

3.2. Dynamic analyses

In these analyses the low-energy DH network was considered as supplying heat to low-energy buildings, each equipped with a substation having a 120 l storage tank. Five different scenarios were generated per each occupancy ratio of 25%, 50%, and 75%, using a time step of 10 min within a time range of 8 h. Here the occupancy ratio refers to the consumers present in the DH network in vacation periods. The return temperature observed at the heat source varied appreciably with changes in consumer consumption profiles in the case of the branched network layout. For the looped layout, in contrast, the return temperature was found to be constant at about 25 °C, independent of the dynamic behavior of the consumers and of the occupancy ratio. In addition, the operation intensity of the bypasses could be followed on the basis of the ratio of bypass flow to total flow observed in the branched distribution network, as shown in Table 5.

The heat loss from the DH network and the heat supplied to it, as observed in simulations of the branched and the looped layouts, respectively, are given in Tables 6 and 7.

The degree–minutes found in analyses of scenario S25_3 regarding unsatisfied heat-demanding nodes there are shown in Fig. 7. Changes over time in the heat demand and in supply temperatures in the looped layout are shown in Fig. 8. The supply temperatures observed for the same heat demand scenario, but involving a branched layout, are shown in Fig. 9.

Fig. 10 shows three different flow configurations, and the variable pressure differences observed, in a simulation involving use of the input of scenario S25_3.

4. Discussion

The study provides analyses and comparisons of different low-energy DH systems, particularly as regards substation types, booster pumps, and the type of network and network layouts involved in the case study carried out concerned with Trekroner, a suburban area located in the Municipality of Roskilde in Denmark.

4.1. Substations types and booster pumps

Pipe segments of differing level were found to differ considerably in the degree of variation in the heat load values that were observed due to different heat demand values defined dependent on the substation type established at each consumer site. For example,

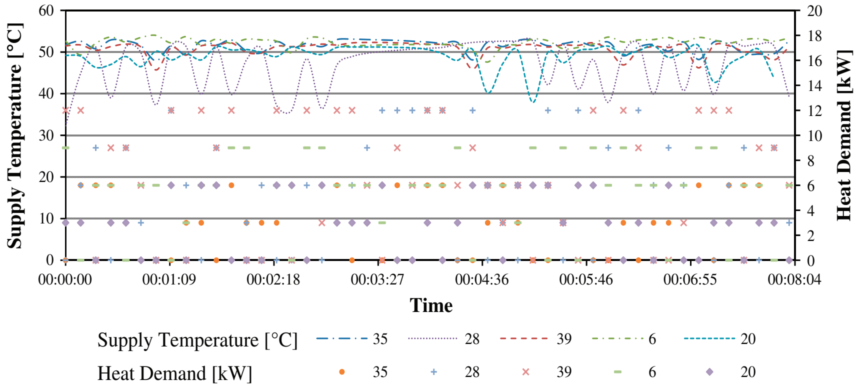


Fig. 8. Changes over time in the supply temperature and in the DHW heat demand, as shown for the unsatisfied heat-consuming nodes (35, 28, 39, 6, and 20), for the looped layout when using scenario S25_3.

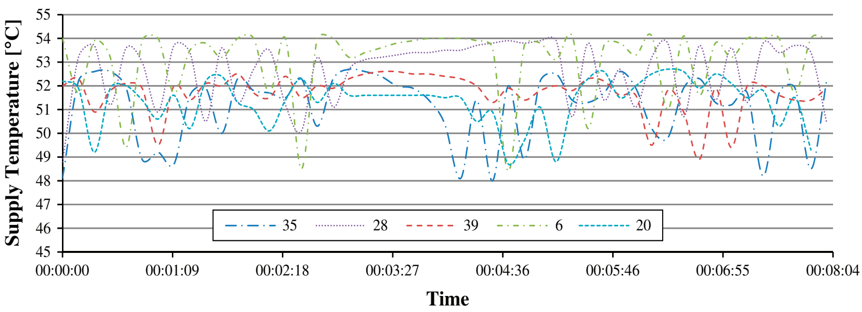


Fig. 9. Changes over time in the supply temperature of the unsatisfied heat-consuming nodes (35, 28, 39, 6, and 20), for the branched layout when using scenario S25_3.

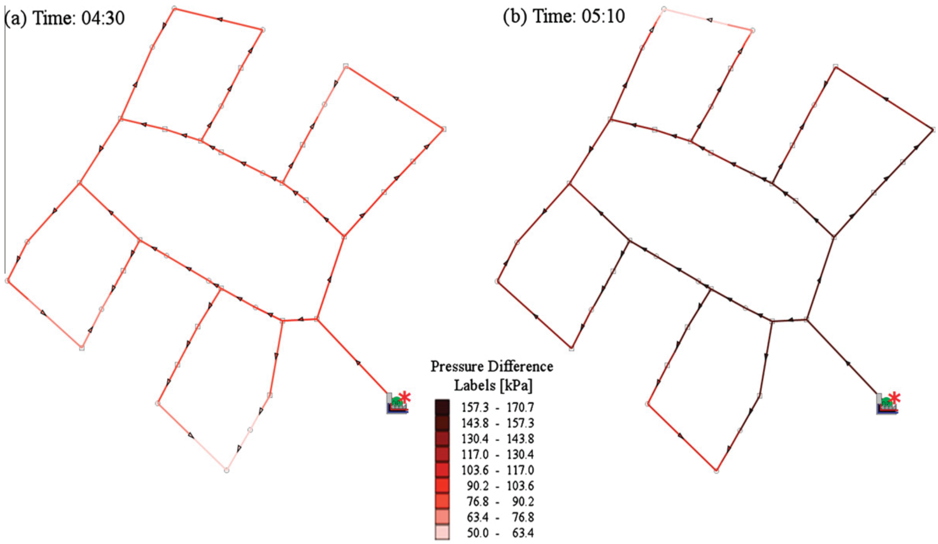


Fig. 10. Simulation results for pressure difference observed in the distribution network at times 04:30, and 05:10, respectively.

the heat load of the successor pipe segments of the root nodes varied by a ratio of 30%, whereas the heat load of the predecessor pipe segments of the leaf nodes varied by a ratio of 70%, comparing the Substation Types 1 and 2 established in each consumer site with the same branched network layout formed in the case area (Fig. 6). The differing variation ratios of the heat load values observed dependent on differing level of pipe segment are based on the simultaneity factor being dependent upon the cumulative number on consumers involved, since the simultaneity factor decreases as the number of consumers affected increases. In DH networks generally, the number of pipe segments in the end branches is much greater than the number of main transmission pipe segments that supply heat to the smaller branches that are closer to the leaf nodes. Thus, it is highly desirable that consumers in a DH network each be provided with a substation having a storage tank, in order to prevent heat loss occurring excessively at the pipe segments close to the end branches due to their being preponderance.

Although the optimization method described in studies [16,22] applied to networks for each substation type, the effects of heat load were found to be significant on optimal diameter obtained at each of the pipe segment, as can be seen in Tables 2 and 3, because of the substation each consumer was provided with being equipped with a storage tank (Substation Type 1) due to reduction obtained at the flow requirements of consumers further. The booster pumps located at the start of the pipe segments in each street had a similar function, their making possible a reduction in pipe diameters in networks supplying heat to substations without storage tanks, although in terms of the degree of heat loss from the DH network that took place they were not competitive with DH networks that supplied heat to substations provided with a storage tank.

4.2. Network layouts

In the study, excessive drops in the supply temperature were analyzed by means of dynamic simulations of periods in the summer months, branched network layouts being compared with looped ones. Different heat-load scenarios involving the partial absence of consumers, as well as differing degrees of simultaneity in heat consumption, resulted in differences in the manner of operation of the DH network, for example differing return temperatures at the heat source in various of the branched layouts, and differing supply temperatures for heat-demanding consumers in response to the level of heat demand, in various of the looped layouts. A lesser presence of consumers resulted in increased variance in operation of the DH system as dynamic response of differing scenarios of heat demand profiles. When only 25% of the consumers were present, for example, results for a branched and for a looped layout differed considerably, particularly in regard to return temperatures in the former case and to supply temperatures (in terms of degree–minutes) in the latter case. When 50% or 75% of the consumers were present, operation of the DH system was less dependent upon the heat demand profiles of consumers. This could be noted in changes in return temperatures and in degree–minute results for branched and for looped layouts, respectively, using different scenarios of consumers' heat demand profiles as input in dynamic analyses.

Regarding heat losses as determined in analyses, results in the branched networks for all of the scenarios were very similar. The bypasses at the leaf nodes circulated supply water when it reached a temperature of 50 °C, but did not allow the supply temperature to be cooled down any further. This resulted in a constant heat loss of 44 kW h from the DH network while higher presence of consumers resulted in increased necessity of heat supply from the heat source (Table 6). Slight differences between scenarios in the heat supplied were observed for each of the three consumer presence levels. For the looped layout, variance was more likely to be observed for the heat loss from the DH network, mainly at the low consumer presence level of 25% (as can be seen in Table 7), though not for the heat supply, such as had been observed in the branched layout. Heat loss was found to be more likely to occur from the return line when a branched layout was involved, due to mixing of the supply heat carrier medium with the return heat carrier medium occurring by means of circulation through the bypasses, and from the supply line when the layout was a looped one, due to long waiting times for the supply heat carrier medium then. However one should note that the overall heat loss from the supply line is considerably higher than the overall heat loss from the return line, regardless of the network layout.

The long waiting times for the supply heat carrier medium that the low heat demand of consumers during the summer period brought about led to an appreciably greater lowering of the supply temperature for the looped than for the branched layout. The long waiting times also resulted in the failure of consumers' supply temperature needs to be fully met. It was found also that the heat loss from the DH network was greater in a looped layout than in a branched layout under these circumstances, as can be seen in Tables 6 and 7.

It can be useful to assess on the basis of degree–minutes calculations the extent to which the needs of heat-demanding consumers are satisfied, as illustrated in Fig. 7. High values there were obtained under looped layout conditions for various heat-demanding customers, suggesting them to be confronted to no more than a slight extent or for only short durations with inadequate supply temperatures, whereas others were confronted with continuously inadequate supply temperatures, low in level and for extended periods of time. Figs. 8 and 9 illustrate a lack of satisfaction of the needs of heat-demanding customers under looped and under branched layout conditions, respectively, in dynamic simulations involving use of scenario S25_3. For the looped layout the supply temperature was observed to reach down to a level of about 40 °C, whereas for the branched layout it sometimes reached a level of about 50 °C.

One should take note of the fact that sometimes operational changes in the DH network occurred such that in certain parts of the network some of the high-demand profiles could result in differences in the flow direction occurring. As can be seen in Fig. 10, the direction of flow can change in a manner such that some pipe segments show a change in direction of flow within a given simulation, analyzed by use of the scenario S25_3. One should also note that neutral points can be formed when at a particular point in a local loop two separate flows are directed at each other. Neutral points could be observed in separate local loops at two different steps time wise, as can be observed in Fig. 10. Changing heat demand profiles led to the relocation of neutral points while the DH network was in operation.

5. Conclusions

The paper has considered various technical aspects of low-energy DH systems in detail; taking up in particular different substation types and network layouts, as well as various substation types. The aim here has not been to adjudge what the best possible solution is to any of the problems taken up, but rather to explore the effects of each of the parameters of interest that are considered here can have on a variety of different matters of interest here. One such matter is that of determining in an adequate way the heat load in different parts of a low-energy district heating system and at different points in time. Another is that of equipping the substations of individual consumers with a storage tank that can result in a significant reduction in the pipe dimensions needed in the network in question, especially at end branches of the network, which are in preponderance in most district heating systems. Employing a simultaneity factor at each level of a pipe segment is also shown to be useful, in particular for avoiding over-dimensioning, since the consumers in a district do not all consume heat at the same time. Use of booster pumps and their relevance to avoidance of over-dimensioning in cases in which the maximum static pressure allowable is very limited is also taken up, as are important characteristics of different network layouts, the special usefulness of looped network layouts in areas of dense population and the superiority of branched DH networks with bypasses at leaf-nodes in matters relating to heat loss and the satisfaction of consumer needs.

Specific methods proposed here are seen as being of potential interest in the planning of future energy structures for supplying heat to low-energy buildings. The study reported on, concerning a geographical case area and a reference house there of a particular type serves as a basis for considering the various topics of concern here in concrete terms. Use is made in various analyses of the software Be06. There are obvious limitations to the focus taken in the study, but it is seen as providing a sensible basis for further study. One could investigate, for example, low-energy DH systems designed for different house types. Also, the effects of booster pumps on pipe dimensioning should be investigated for large networks, due to their possible applicability to the allowed pressure difference between supply and return lines in large networks. One can also study complex network structures involving both the branched and the looped network together, can be appropriate.

Acknowledgement

The work presented in the paper was aided to a very significant extent by based on the data and the map provided by Roskilde Forsyning A/S.

References

[1] Veziroğlu TN, Şahin S. 21st Century's energy: hydrogen energy system. Energy Convers Manage 2008;49:1820–31.
[2] Arif H. A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs). Energy Convers Manage 2010;51:2041–61.
[3] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76.
[4] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90.
[5] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050. Energy 2009;34:524–31.
[6] Lund H. Renewable energy systems: the choice and modeling of 100% renewable solutions. Burlington, USA: Elsevier; 2010.
[7] Dincer I, Hepbasli A. District energy systems. In: Capehart BL, editor. Encyclopedia of Energy Engineering and Technology – 3 Volume Set (Print Version). FL, Boca Raton: CRC Press; 2007. p. 316–31.
[8] Christiansen CH, Worm J, Jørgensen H, Thorsen JE, Bennetsen J, Larsen CT, et al., Demonstration of low energy district heating system for low energy building in Ringgårdens Afd. 34 in Lystrup,. Copenhagen, Teknologisk Institute, Maj 2011, 104p. Report No: EUDP 2008-II. <http://www.ibe.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r250.pdf> [accessed 06.01.12, in Danish].
[9] Thorsen JE, Christiansen CH, Brand M, Olesen PK, Larsen CT. Experiences on low-temperature district heating in Lystrup – Denmark. In: International conference on district energy, Portorož, Slovenia, March 20–22, 2011.
[10] Christiansen CH, Paulsen O, Bøhm B, Thorsen JE, Ting Larsen C, Jepsen BK et al. Development and demonstration of low-energy district heating for low-energy buildings. Main report and appendices. Teknologisk Institut, March 2009, Report No.: EFP 2007. <http://www.teknologisk.dk/_root/media/34221_EFP%202007.pdf> [accessed 06.01.12, in Danish].
[11] SSE, SSE zero carbon home development. <http://www.ssezerocarbonhomes.com/> [accessed 10.01.12].
[12] Wiltshire R. Low temperature district energy systems. In: Urban energy conference, Debrecen, Hungary, October 13–14, 2011. p. 91–99.
[13] 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. In: The 11th international symposium on district heating and cooling, Reykjavik, Iceland, August 31–September 2, 2008.
[14] Paulsen O, Fan J, Furbo S, Thorsen JE. Consumer unit for low energy district heating net. In: The 11th international symposium on district heating and cooling, Reykjavik, Iceland, August 31–September 2, 2008.
[15] 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 Convers Manage 2011;52:1200–7.
[16] Tol Hİ, Svendsen S. Improving the Dimensioning of Piping Networks and Network Layouts in Low-Energy District Heating Systems Connected to Low-Energy Buildings: A case study in Roskilde. Denmark. Energy 2012;38:276–90.
[17] Yıldırım N, Toksoy M, Gökçen G. Piping network design of geothermal district heating systems: case study for a university campus. Energy 2010;35:3256–62.
[18] Şener AC, Gökçen G. Pipelines and piping network in geothermal district heating systems. In: IEEES – proceedings of the first international exergy, energy and environment symposium, İzmir, Turkey, July 13–17, 2003.

[19] Overgaard J, Knudsen S. District heating networks – choosing the right pipe dimensions, DBDH. 2006. <http://www.dbdh.dk/images/uploads/pdf-distribution/district-heating-networkschoosing-the-right.pdf> [accessed 10.01.11].
[20] Benonysson A, Bøhm B, Ravn HF. Operational optimization in a district heating system. Energy Convers Manage 1995;36:297–314.
[21] Sanks RL. Flow in conduits. In: Sanks RL, editor. Pumping station design. Boston, USA: Elsevier Gulf; 1998. p. 33–9.
[22] Tol Hİ, Svendsen S. Design of low-energy district heating system for a settlement with low-energy buildings. In: 3rd international symposium on environmental management, Zagreb, Croatia, October 26–28, 2011. p. 166–171.
[23] Tol Hİ, Svendsen S. Determination of optimum network layout for low-energy district heating systems with different substation types. In: The third international renewable energy congress, Hammamet, Tunisia, December 20–22, 2011. p. 179–184.
[24] Aggerholm S, Thomsen KE, Wittchen KB. Implementation of the EPBD in Denmark – status in November 2010. Aalborg: Denmark, Danish Building Research Institute; 2011. 13 p.
[25] Stevanovic VD, Zivkovic B, Prica S, Maslovaric B, Karamarkovic V, Trkulja V. Prediction of thermal transients in district heating systems. Energy Convers Manage 2009;50:2167–73.
[26] Gabrielaitiene I, Bøhm B, Sunden B. Modelling temperature dynamics of a district heating system in Naestved, Denmark—a case study. Energy Convers Manage 2007;48:78–86.
[27] Boysen H, Thorsen JE. Hydraulic balance in a district heating system, Danfoss, 2011, 8 p. <http://www.heating.danfoss.com/PCMPDF/VFLRC202_Hydraulic_balance.pdf> [accessed 10.01.12].
[28] Danfoss, 8 steps – control of heating system. <http://www.heating.danfoss.com/Content/61078BB5-1E17-4CA2-AC49-8A7CAC2BA687_MNU17424997_SIT54.html> [accessed 10.11.11].
[29] Brand M, Dalla Rosa A, Svendsen S. Performance of low temperature district heating systems for low energy houses. In: Annex 49 low exergy systems for high-performance building and communities, Munich, Germany, October 19–21, 2010. p. 174–183.
[30] Brand M, Thorsen JE, Svendsen S, Christiansen CH. A direct heat exchanger unit used for domestic hot water supply in a single-family house supplied by low energy district heating. In: The 12th international symposium on district heating and cooling, Talinn, Estonia, September 5–7, 2010. p. 60–68.
[31] Li H, Dalla Rosa A, Svendsen S. Design of low temperature district heating network with supply water recirculation. In: The 12th international symposium on district heating and cooling, Talinn, Estonia, September 5–7, 2010. p. 73–80.
[32] Dalla Rosa A, Li H, Svendsen S. Steady state heat losses in pre-insulated pipes for low-energy district heating. In: The 12th international symposium on district heating and cooling, Talinn, Estonia, September 5–7, 2010. p. 81–89.
[33] Dalla Rosa A, Li H, Svendsen S. Method for optimal design of pipes for low-energy district heating, with focus on heat losses. Energy 2011;36:2407–18.
[34] Bernot M, Caselles V, Morel J. Branched transportation networks. Berlin Heidelberg, New York: Springer; 2007.
[35] Lejano RP. Optimizing the layout and design of branched pipeline water distribution systems. Irrig Drain Syst 2006;20:125–37.
[36] González C, Macarulla B, Sallán D. Recursive design of pressurized branched irrigation networks. J Irrig Drain Eng 2010;137:375–82.
[37] Davidson JW. Learning program for the design of layout geometry of rectilinear looped water distribution networks. PhD thesis. Manitoba, Canada: University of Manitoba; 1998.
[38] Yazdani A, Otoo RA, Jeffrey P. Resilience enhancing expansion strategies for water distribution systems: a network theory approach. Environ Modell Software 2011;26:1574–82.
[39] Maunder C, editor. Termis help manual [disk]. Version 2.10. Denmark: Birkerød; 2010 [7-Technologies A/S].
[40] Zheng F, Simpson AR, Zecchin AC. A combined NLP-differential evolution algorithm approach for the optimization of looped water distribution systems, Water Resources Research. 47, W08531, doi: http://dx.doi.org/10.1029/2011WR010394.
[41] Xu B, Fu L, Di H. Field investigation on consumer behavior and hydraulic performance of a district heating system in Tianjin, China. Build Environ 2009;44:249–59.
[42] Larsen HV, Bøhm B, Wigbels M. A comparison of aggregated models for simulation and operational optimisation of district heating networks. Energy Convers Manage 2004;45:1119–39.
[43] Nystedt Å, Shemeikka J, Klobut K. Case analyses of heat trading between buildings connected by a district heating network. Energy Convers Manage 2006;47:3652–8.
[44] Durmayaz A. An application of the degree–hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul. Energy 2000;25:1245–56.

ISI ARTICLE III

Energy and Buildings 88 (2015) 324–334

Contents lists available at ScienceDirect

Energy and Buildings

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

Effects of boosting the supply temperature on pipe dimensions of low-energy district heating networks: A case study in Gladsaxe, Denmark

Hakan İbrahim Tol [*,1], Svend Svendsen

Department of Civil Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

A R T I C L E I N F O

Article history:
Received 19 June 2012
Received in revised form 15 August 2014
Accepted 29 October 2014
Available online 4 November 2014

Keywords:
Low-energy district heating
Low temperature
Control philosophy
Pipe dimensioning
Optimization
Boost temperature
Sensitivity analysis

A B S T R A C T

This paper presents a method for the dimensioning of the low-energy District Heating (DH) piping networks operating with a control philosophy of supplying heat in low-temperature such as 55 °C in supply and 25 °C in return regularly while the supply temperature levels are being boosted in cold winter periods. The performance of the existing radiators that were formerly sized with over-dimensions was analyzed, its results being used as input data for the performance evaluation of the piping network of the low-energy DH system operating with the control philosophy in question. The optimization method was performed under different mass flow limitations that were formed with various temperature configurations. The results showed that reduction in the mass flow rate requirement of a district is possible by increasing the supply temperature in cold periods with significant reduction in heat loss from the DH network. Sensitivity analysis was carried out in order to evaluate the area of applicability of the proposed method. Hence varied values of the original capacity and the current capacity of the existing radiators were evaluated with the design temperature values that were defined by two former radiator sizing standards.

1. Introduction

District Heating (DH) systems, distribution of heat supplied from centralized heat production facilities to urban districts, are environmentally friendly, highly efficient in heat production, and reliable from the perspective of long-term energy security due to availability in the use of a wide range of energy sources [1–5]. A recent project of IEA-District Heating and Cooling has aimed at developing the "4th Generation District Heating" with a focus directed to increase the energy efficiency of DH systems by the use of low temperature operation, reduced down to 55–25 °C in terms of supply temperature and return temperature, respectively [6,7]. Low-energy DH systems have some additional advantages such as increased efficiency in heat production, further exploitation of low-grade energy sources, reduced heat loss from the DH network, and ease attained in receding the use of natural gas [6,8–10]. Successful examples of employing low temperature operation in low-energy DH systems connected to low-energy buildings have been demonstrated in real-case projects in Lystrup, Denmark [11,12], and in the SSE Greenwatt Way development project in Chalvey, UK [6,13]. Also, some studies pointed out that low temperature operation can satisfy the heat demand of existing buildings at low supply temperature since the existing indoor heating systems were over-dimensioned in their design stage [14–18]. One successful example of a large-scale low temperature DH system has been in operation in Kırşehir, Türkiye with temperatures of 54 °C and 49 °C for supply and for return, respectively. This low temperature DH system that is based from a geothermal source available at a temperature of 57 °C has been supplying heat to 1800 dwellings without any complaints delated from consumers since 1994 (more information can be obtained from [19–21]).

The objective of this study, therefore, has been defined to develop a dimensioning method for low-energy DH networks connected to existing buildings. The dimensioning method was developed with consideration directed to several points such as exploiting the over-capacity of the existing in-house heating systems (radiators) determined in their design stage, utilizing the control philosophy with boosting the supply temperature in peak

* Corresponding author. Tel.: +45 45 25 50 27; fax: +45 45 88 32 82.
E-mail addresses: hatol@byg.dtu.dk, hakantol@gmail.com (H.İ. Tol), ss@byg.dtu.dk (S. Svendsen).

[1] Faculty of Engineering and Applied Science, UOIT, Oshawa, ON, Canada.

http://dx.doi.org/10.1016/j.enbuild.2014.10.067
0378-7788/

Nomenclature

Sets

$\mathbb{R}$ set of real numbers
TPD set of inner diameters of the commercially available pipes

Roman letters

CC cumulative number of consumers at the node [dimensionless]
D inner diameter [mm]
h_f specific enthalpy [kj/kg]
i the index for the node [dimensionless]
$i-1$ the index for the predecessor node [dimensionless]
k the index for the period [dimensionless]
l the index for the route [dimensionless]
L length [m]
$\dot{m}$ mass flow rate [kg/s]
N node entry in the set of nodes [dimensionless]
n overall amount of the entry type, indicated in the subscript [dimensionless]
n_1 empirically determined exponent in radiator equation [dimensionless]
P pressure [bar]
p pipe segment entry in the set of pipe segments [dimensionless]
Pr period [dimensionless]
PS sequences of linked pipe segments [dimensionless]
q heat load rate [kW]
$\dot{Q}$ heat rate [kW]
R route [dimensionless]
s the index for the scenario [dimensionless]
Sc label number of scenario [dimensionless]
SF simultaneity factor [dimensionless]
T temperature [°C]
t time [hours]
U heat loss coefficient [W/m]
x the index for the situation [dimensionless]

Greek letters

Δ difference
μ heat load factor [dimensionless]

Subscripts

0 original design condition
a indoor air temperature
Alu aluFlex twin pipe
DHW domestic hot water
DHWD unique heat demand of domestic hot water
DHWL heat load of domestic hot water
G ground
GMTD geometric mean temperature difference
HD unique heat demand
HL heat load
int initial estimate value for iteration
LMTD logarithmic mean temperature difference
Loss loss
Max maximum
Min minimum
R return
S supply
SH space heating
SHD unique heat demand of space heating
SHL heat load of space heating
STPc steel twin pipe – continuous
STPt steel twin pipe – traditional

Superscripts

* continuous (non commercially available) value

winter periods, and changing the heating requirement of the existing buildings, expected to be renovated due to Danish building regulations [16,17].

2. Methods

2.1. Description of the site

This case study has been carried out on a district located in the municipality of Gladsaxe in Denmark, in which an existing natural gas distribution network currently supplies natural gas there to 783 dwellings. Each of the existing dwellings was considered with the same reference single-family house, constructed in the period of 1961–1972. In this project the existing natural gas heating system in the case area (Gladsaxe Municipality) was considered to be replaced to a low-energy DH system (its illustration is given in Fig. 1), with the layout of a reference substation with adequate control proper to low temperature operation of 55 °C in terms of supply and 25 °C in terms of return. Reasonable values of unique heat demand in proper with the existing single family houses were derived for the Current Situation (CS) and for the Future Situation (FS) by use of the studies [11,22,23], due to lack of available real data for existing Danish buildings and of studies in this field. Hereby, regarding space heating requirement, the reference single family house was assumed to have values of unique peak heat demand as 9 kW, 5.1 kW, and 2.9 kW, defined for design value, CS, and FS, respectively (the heat demand values are based on the references [12–14,22,23]). The reference substation was considered to be equipped with a direct connection from DH network to the in-house space heating system. Moreover, the heat demand requirement for the production of domestic hot water was assumed to be 3 kW both in CS and in FS since the reference substation was considered to be equipped with an indirect connection involving of a buffer tank with a capacity of 120 L and a heat exchanger unit (the heat requirement is based on the references [11,12]).

The search-space of the optimization method was defined as finding the minimum pipe diameter within the commercially

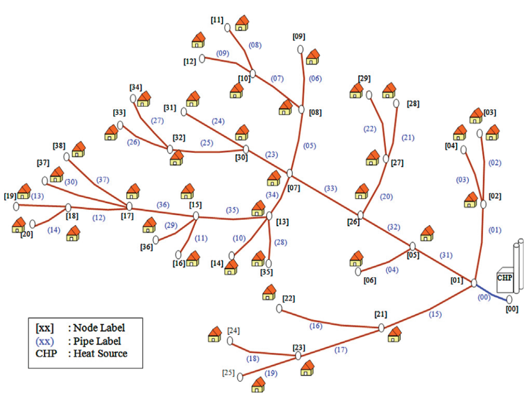


Fig. 1. Illustrative sketch of the DH network indicating both, the nodes and pipe segments.

available pipe types, consisting of AluFlex twin pipe, of steel twin pipe–continuous (STPc), and of steel twin pipe-traditional (STPt). The dimensions for twin pipes are shown as i.e. 14/14 which indicates two pipes having the same diameter, both exists in one accommodating outer casing. However, the optimization algorithm was developed with the inner diameter of each type of twin pipe (more information can be found in [24]). Hence, sets of inner diameter of the pipes were formed in the range of {10, 11.6, 15, 20, 26} as $\mathbf{TPD}_{Alu}$, of {37.2, 43.1, 54.5, 70.3, 82.5} as $\mathbf{TPD}_{STPc}$, and of {107.1, 132.5, 158.3, 210.1} as $\mathbf{TPD}_{STPt}$ [24], all of which constitutes the whole set of inner diameter space, **TPD**. Also, the maximum static design pressure was defined as 10 bara. With the holding pressure defined as 1.5 bar and the pressure loss through the substations being defined as 0.5 bar, the maximum allowable pressure loss through the routes of the DH network was defined as 8 bar, measured as sum of the pressure losses inclusive of both the supply and the return line. The piping network, formed as a branched layout, constituted a total length of 9.3 km that was embodied along 22 routes.

2.2. Determination of heat load

Heat load value has a major determinative effect on pipe dimensions during the design stage of DH networks. Hence several issues were considered while determining the heat load, such as consideration of simultaneity of heat consumption involved at each pipe segment, variation of overall heat load throughout a year, and the performance of the in-house heating systems to changing supply temperature [25]. Applying the control philosophy of boosting the supply temperature in the cold periods, led to the investigation of the performance of the existing radiator systems to changing supply temperatures.

2.2.1. Performance of existing radiators

The model given in the study [25] was used to obtain the performance of the existing radiator systems for differing levels of supply temperature with outputs in terms of return temperature and of mass flow. An implicit model based on the log mean temperature difference (LMTD) was used to find the return temperature as a function of the supply temperature, the equation for the iterative solution being given in the Eq. (1).

$$T_{\text{R-SH}} = T_a + (T_S - T_a)/\exp\left[\frac{\left(\dot{Q}_X/\dot{Q}_Q\right)^{(-1/n_1)}(T_S - T_{R-SH})}{T_{\text{LMTD}_0}}\right] \quad (1)$$

where, T_R refers to the return temperature [°C] being the output variable that is computed as a function of the input variable T_S that refers to the supply temperature [°C], of the input variable $\dot{Q}_x$ that refers to the heat requirement of the radiator in a condition X that can be substituted with CS or with FS, and of the input parameter T_a referring to the indoor air temperature which was defined as 20 °C. The dimensionless parameter n_1 indicate the empirically determined coefficients, defined as 1.3 [26], the value being used in the studies [25–28]. $T_{\text{LMTD\_0}}$ refers to LMTD value, defined in terms of the original design parameters, its equation being given in Eq. (2). The subscript SH refers to space heating.

$$T_{\text{LMTD}_0} = T_{S-SH_0} - T_{R0}/\ln\left[\left(T_{S-SH_0} - T_a\right)/T_{R-SH_0} - T_a\right] \quad (2)$$

here the subscript O indicates that the variables referring to the original design parameters.

The first approximation of the return temperature was obtained by use of an explicit model based on the geometric mean temperature difference (GMTD), given in Eq. (3), to be used as an initial estimate of the return temperature variable standing in the right-hand side of the iterative equation given in Eq. (1) [25].

$$T_{R-SH_{int}} = T_a + (T_S - T_a)^{-1}(T_{\text{GMTD}_0})^2\left(\dot{Q}_X/\dot{Q}_O\right)^{(2/n_1)} \quad (3)$$

Here subscript int refers to the initial estimate of the return temperature and T_{GMTD_0} refers to GMTD value, defined in terms of the original design parameters, its equation being given in Eq. (4).

$$T_{\text{GMTD}_0} = \left(T_a^2 \text{-} T_{S-SH_0}T_{R-SH_0} - T_aT_{S-SH_0} - T_aT_{R-SH_0}\right)^{1/2} \quad (4)$$

The study focused on different temperature levels in different winter periods therefore; the heating demand was converted to mass flow requirements since the heating demand of a consumer can be satisfied as soon the required mass flow is provided in the supply temperature needed with an adequate pressure difference potential maintained between the supply and the return lines of the DH network [14,15,29]. Hence the mass flow values were derived by the use of the expression being originated from the heat balance principle, given in Eq. (5), which can be applied to any temperature configuration.

$$\dot{m}_{\text{SHD}} = \dot{Q}_X/[h_f(T_{S-SH}) - h_f(T_{R-SH})] \quad (5)$$

where, $\dot{m}$ refers to the mass flow rate in kg/s and $h_f(T)$ is the specific enthalpy [kj/kg] of the heat carrier medium at temperature T [°C]. The subscript SHD indicates the unique demand in terms of space heating.

2.2.2. Performance of domestic hot water production unit

The domestic hot water production unit involves use of a storage tank and a heat exchanger unit that transfers the heat provided from the storage tank to the consumer site. The highest temperature stored in the storage tank is dependent to the supply temperature provided from the DH site while the lowest temperature contained in the storage tank is dependent to the return temperature coming from the in-house heat exchanger unit. The heat exchanger unit heats up the incoming cold water supply (from the city water mains) from its temperature 10 °C up to 45 °C in the heat production rate of 32 kW, by use of the stored heat in the storage tank equipped in the substation. The storage tank is charged from the DH network with a fixed mass flow rate $\dot{m}_{\text{DHWD}}$ of 0.0208 kg/s (more information regarding substation can be obtained from [8,11,12,16,17,30–32]). The regression expression for computing the return temperature of the domestic hot water unit in the DH site was derived based on the observations found by use of the commercial software SWEP [33], given in Eq. (6).

$$T_{R-DHW}(N_i) = 5.69E - 6T_S^4 - 1.90E - 3T_S^3 + 0.24T_S^2 - 13.55T_S + 302.97 \quad (6)$$

2.2.3. Simultaneity factor

Consumers in a DH network neither consume heat at the same time nor at the same level [6] therefore; the simultaneity factor was taken into account in each pipe segment in accordance with the consumer load to which the pipe segment is supplying heat, as described in the study [15]. The same expression of simultaneity factor regarding space heating, referred with SF_{SH}, which is given in [15,34,35] was also used in this study. However, in order to formulate a general expression to calculate the heat load on each pipe segment distinctively, the simultaneity factor regarding domestic hot water load was derived by use of Eq. (7).

$$\text{SF}_{\text{DHW}}(N_i) = \dot{Q}_{\text{DHWL}}(N_i)/\left[\text{CC}(N_i)\dot{Q}_{\text{DHWD}}\right] \quad (7)$$

where, SF_{DHW} refers to the simultaneity factor regarding the consumption of domestic hot water, $\dot{Q}_{\text{DHWL}}$ being the expression of the

Table 1
Heat Load factor with duration of occurrence over a year period.

		Pr_1	Pr_2	Pr_3	Pr_4	Pr_5	Pr_6	Pr_7	Pr_8
Heat load factor	CS	1.44	1.28	1.07	0.77	0.57	0.43	0.25	0.10
[dimensionless]	FS	1.00	0.89	0.74	0.53	0.40	0.30	0.17	0.07
Duration [h]		8	19	111	653	1724	1399	1565	3281

heat load calculation with the simultaneity factor involved, which was taken from the study [15], $CC(N_i)$ is the cumulative number of consumers at the node i, and $\dot{Q}_{DHWD}$ is the unique heat demand rate for the domestic hot water in respect to DH site [kW].

2.2.4. Heat load factor

Load duration curves show the variation of the occurrence rate of the heat load in a district, which make use of different heat load levels, in the order from highest to lowest, together with the duration of occurrence of each heat load level defined [36]. Heat load factor refers to the periods of the heat load levels, which, more specifically, is the ratio of any particular heat load taking place in a year period compared to the peak heat load. In this study the heat load factors were derived by use of the heat consumption data given in eight periods that was illustrated regarding the Lystrup low-energy DH system in the study [11], the data being shown in Table 1. In the table, the reference heat load value was chosen as peak heat load of FS that was used as the reference value to derive the heat load factors both for FS and CS.

2.2.5. Mass flow required

A general formulation was defined to calculate the overall mass flow required by including the simultaneity factor as a function of the cumulative number of consumers $CC(N_i)$ and the heat load factor μ_{HL}, as shown in Eq. (8).

$$\dot{m}_{HL}(N_{i,k}) = CC_{HL-SH}(N_{i,k})\dot{m}_{SHD}(Pr_k) + CC_{HL-DHW}(N_{i,k})\dot{m}_{DHWD}(Pr_k) \quad (8)$$

where, $\dot{m}_{HL}(N_{i,k})$ is the mass flow rate at the node i in the period k [kg/s] and $CC_{HL}(N_{i,k})$ is the cumulative number of consumers, involved with the heat load factor, that takes part at the node i in the period k, its equation being given for SH in Eq. (9) and for DHW in Eq. (11).

$$CC_{HL-SH}(N_{i,k}) = c_\mu(N_{i,k})SF_{SH}[CC_\mu(N_{i,k})] \quad (9)$$

where, $CC_\mu(N_{i,k})$ is the cumulative number of consumers involved with the heat load factor, as shown in Eq. (10).

$$CC_\mu(N_{i,k}) = CC\ \ (N_{i,k})\mu_{HL}(Pr_k) \quad (10)$$

where, $CC(N_i)$ is the cumulative number of consumers connected to the DH network and $\mu_{HL}(Pr_k)$ refers to the heat load factor in the period k.

$$CC_{HL-DHW}(N_{i,k}) = c_\mu(N_{i,k})SF_{DHW}[CC_\mu(N_{i,k})] \quad (11)$$

A function to compute the overall return temperature at the heat source was formed by means of conservation of energy principle, applied to the mixture of return temperatures originating from the consumer units regarding SH and DHW, shown in Eq. (12).

$$T_R(N_{i,k}) = T\left\{\left[\dot{m}_{HL-SH}(N_{i,k})h_f(T_{R-SH}(N_{i,k})) + \dot{m}_{HL-DHW}(N_{i,k})h_f(T_{R-DHW}(N_{i,k}))\right]/\dot{m}_{HL}(N_{i,k})\right\}^{1/2} \quad (12)$$

where, $T\{h_f\}$ is the function that returns the temperature of the specific enthalpy h_f. The equations that were formed to compute the overall mass flow rate for SH and for DHW are given, respectively, in Eqs. (13) and (14).

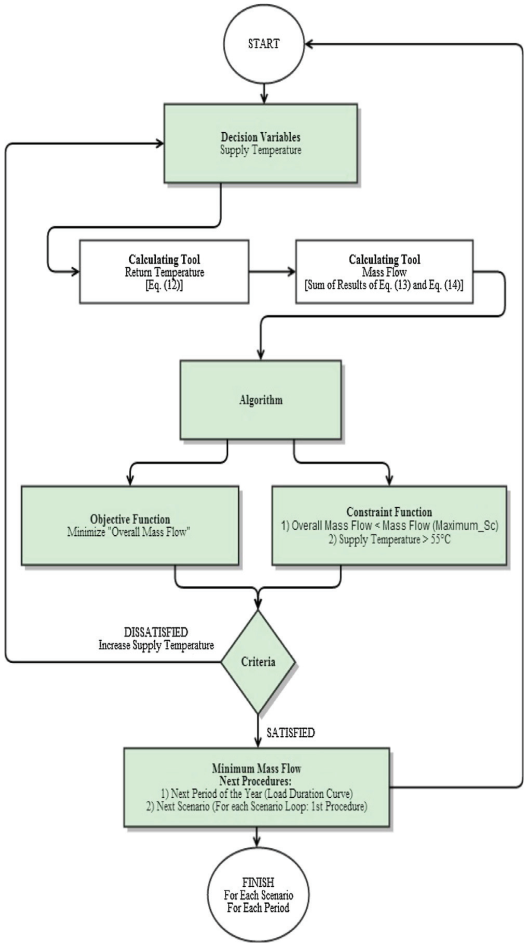


Fig. 2. Diagram of flow-chart for determination of the supply temperatures for periods of a year.

$$\dot{m}_{SHL}(N_{i,k}) = CC_{HL-SH}(N_{i,k})\dot{m}_{SHD}(Pr_k) \quad (13)$$

$$\dot{m}_{DHWL}(N_{i,k}) = CC_{HL-DHW}(N_{i,k})\dot{m}_{DHWD}(Pr_k) \quad (14)$$

Different mass flow limitations were adopted in different scenarios each of which consists of different temperature configurations that was being generated by means of adjusting the supply temperature level severally in each period, the algorithm used being given in the Eq. (15) (Fig. 2).Minimize $\dot{m}_{HL}(N_{i,k})$ with respect to

$$T_s \quad i = 0 \wedge \forall k = 1, \ldots, n_k \quad \forall S = 1, \ldots, n_s \wedge \forall x = \text{FS and CS} \quad (15)$$

Subjects to the criteria:

$i_{ff}[\dot{m}_{HL}(N_{i,k}) > \dot{m}_{max}(Sc_s)]$

Subjects to the constraints:

$\dot{m}_{HL}(N_{i,k}) \lesssim \dot{m}_{max}(Sc_s)$
$T_s > 55\,^{\circ}C$

2.3. Performance analysis of boosting the supply temperature

This study is based on the idea of boosting the supply temperature until a certain level during the peak winter periods. However, up to what extent boosting should be applied was the investigation question that formed the basis of this study, which led the study, at first, to carry out the performance analysis of the DH network to evaluate the changes in the annual heat loss energy from the DH network. This is done by applying differing levels of the supply and the return temperatures in the scenarios defined with different mass flow limits. Hence several temperature configurations were generated with different increments applied on the supply temperature in the cold winter periods, when necessary. The purpose here was to avoid the required mass flow rates (to satisfy the heat load of the district) exceeding a certain level. The range of changing the supply temperature subjected to two limitations, one being that supply temperature of 55 °C that must always be provided to the consumers as minimum, and second being that maximum continuous operating temperature of AluFlex twin pipe is defined as 95 °C.

In accordance with the limits concerned with the supply temperature, five different scenarios each of which consists of different profiles of supply temperature severally adjusted in each period were generated, each appointed with differing upper limit of overall mass flow required. The generated scenarios is available in Section 3.1.

2.4. Dimensioning the DH network

The dimensioning method was defined as the optimization method used in our previous study [15]. However the formulations with regard to objective function with the aim of minimizing the heat loss from the DH network, to constraint function dealing with pressure drop through the routes, and to optimization algorithm were modified in accordance with the control philosophy, boosting the supply temperature in cold winter periods, as described below.

2.4.1. Heat loss from the DH network

The statistical method, the multi-variable regression equation was used to predict the heat loss coefficient to be used in the optimization algorithm, since regression equation models can easily provide precise data as the original data [37]. Several independent variables such as supply, return, and ground temperatures as well as pipe diameter have determinative influence on the heat loss coefficient of a pipe segment. Hence, a regression equation, aimed at finding the dependent variable – the heat loss coefficient – was formed on the basis of the observations. The observations were extracted with combinations of the different parameters. These parameters consisted of the set of inner diameters **TPD** involved, of the supply temperature values chosen amongst 55 °C and 95 °C, of the return temperature values observed amongst 20 °C and 80 °C as thermal response of the DH network to the supply temperature values applied, and of the ground temperature values chosen amongst 2 °C and 13 °C. The generated samples were later used as input data to observe the heat loss coefficients by use of the commercial software Logstor Calculator with consideration given to different pipe types involved in this study [24,38] (detailed information can be obtained from [16]). The multi-variable regression equation was obtained from 408 samples, the equation being given in Eq. (16).

$$U_{loss} = -4.055 + 0.11T_s(Pr_k) + 0.10320T_R(Pr_k) - 0.21097T_G(Pr_k) + 0.05302D(p_{i-1,i}) \quad (16)$$

where, U_{loss} refers to the heat loss coefficient in W/m, $T_G(Pr_k)$ is the ground temperature [°C] in the period k and $D(P_{i-1,i})$ is the diameter of the pipe segment $P_{i-1,i}$ taking place between the nodes N_{i-1} and N_i [mm].

Hence the equation to calculate the annual heat loss from the DH network was formed as shown in Eq. (17), to be used by the optimization algorithm. The reason behind using annual heat loss energy as the objective function in the optimization in this study, instead of using peak heat loss power as used in the previous study [15], was to take into account the increment of heat loss due to raising temperatures in the DH network occurring because of the new control philosophy adopted.

$$Q_{loss} = \sum_{k=1}^{n_k}\sum_{i=1}^{n_i}\left\{U_{loss}\left[T_S(Pr_k),\quad T_R(Pr_k),\quad T_G(Pr_k),\quad D(P_{i-1,i})\right] L(P_{i-1,i})t(Pr_k)\right\} \quad (17)$$

where, $L(P_{i-1,i})$ is the length of the pipe segment $P_{i-1,i}$ and $t(Pr_k)$ is the duration of occurrence of the period k.

2.4.2. Pressure loss

Considerations regarding the pressure loss calculation, used in our previous studies [15,39,40], were also considered in this study by using of Darcy–Weisbach equation for finding the pressure drop through the pipe segments, of Clamond algorithm for solving the implicit Colebrook equation, and of the basis of exploiting the head lift provided from the main pump station as much as possible in each route [41,42]. Pre-analysis of this study, previously presented at [16], showed that the pressure drop values yielded in higher values in peak winter period in comparison to the pressure drops obtained in the rest periods out of peak period, despite the same pipe dimensions formed in the case DH network. Once a pump is established with a head lift capacity that can satisfy the pressure drops through all of the routes in the critical condition, then it can also meet the pressure drops occurring in conditions out of the critical one. Hence pressure drop calculations were carried out only for the peak winter period of the CS, in which mass flow rates are certain to be observed with high values due to higher heat load in comparison to the FS, being used as the limit defined in the constraint of the optimization method applied. The study [43] presented the comparison of heat loss effect and the effect of pump electricty consumption in low-energy DH systems. The exergetic value of heat loss is substantially more than the exergy consumption by the increased pumping power (exergy analysis is out of the scope of this paper however the exergy is the only way to compare two different energy forms). Hence the optimization in this study was not included with optimization between heat loss from the DH network and the pump power consumption.

2.4.3. Optimization algorithm

The optimization algorithm was formulated to reduce the pipe diameter of each pipe segment with the objective function aimed at minimizing the annual heat loss from the DH network with consideration directed to the change of supply, return, and ground temperatures and with the constraint function directed to keep the pressure loss occurring in each route to the same extent as the potential of head lift provided by the main pump station of the DH network (Fig. 3). The optimization algorithm, shown in Eq. (18),

Table 2
List of the pipe segments involving the data of the length of them and the cumulative number of consumers.

Pipe [dimensionless]	Successor node [dimensionless]	Predecessor node [dimensionless]	Length [m]	Cumulative number of consumers [dimensionless]
0	0	1	0	783
1	1	2	283	33
2	2	3	86	4
3	2	4	128	2
4	5	6	205	18
5	7	8	135	115
6	8	9	368	34
7	8	10	128	72
8	10	11	436	59
9	10	12	85	9
10	13	14	180	16
11	15	16	127	9
12	17	18	70	42
13	18	19	123	12
14	18	20	270	25
15	1	21	570	112
16	21	22	112	7
17	21	23	355	55
18	23	24	117	7
19	23	25	287	12
20	26	27	415	82
21	27	28	120	9
22	27	29	417	33
23	7	30	300	128
24	30	31	194	15
25	30	32	348	88
26	32	33	230	14
27	32	34	755	52
28	13	35	335	25
29	15	36	445	46
30	17	37	595	60
31	1	5	120	638
32	5	26	80	608
33	26	7	120	524
34	7	13	295	271
35	13	15	124	196
36	15	17	117	130
37	17	38	210	21

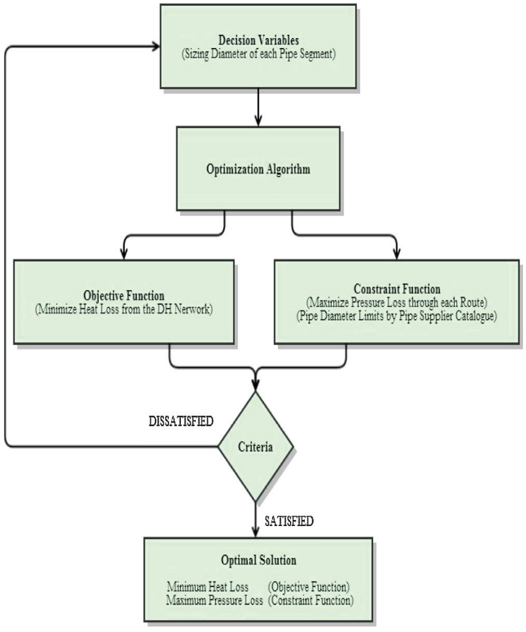


Fig. 3. Diagram of flow-chart for optimization algorithm.

was carried out for all scenarios each of which constitutes of particular mass flow rates computed severally for each pipe segment by use of Eq. (8).

$$\text{Minimize } Q_{\text{loss}} \text{ with respect to } D^*(p_{i-1,i}) \quad (18)$$

Subject to the constraints:

$$\Delta P[\text{PS}_l(Pr_k)] = \Delta P_{\max} \quad \forall l = 1, \ldots, n_l \wedge k = 1$$
$$D_i^* \in \mathbb{R}$$
$$D_{\min} \leq D_i^* \leq D_{\max}$$

where, D^* is a continuous pipe dimension being reduced by optimization algorithm in a search-space subjecting to the pipe diameter interval, its borders defined with $D_{\min}$ and $D_{\max}$ that are, respectively, the minimum and the maximum pipe diameters of the pipe catalogue set **TPD**. PS_l refers to one of the routes, existing in a total number of n_l, in the DH network that ends with the leaf node l.

The continuous pipe diameters obtained by the use of the optimization tool of Matlab were rounded upwards by means of Eq. (19) to the next diameter of the commercially available pipes.

$$D(P_{i-1,i}) = \lceil D^*(P_{i-1,i}) \rceil ; \quad D^*(P_{i-1,i}) \in \mathbb{R} \wedge D(P_{i-1,i}) \in \text{TPD} \quad (19)$$

2.5. Sensitivity analysis

The sensitivity analysis was carried out with the purpose to define the limitations of the new dimensioning method (together with the limitations of the control philosophy used there) for any possible design conditions i.e.:

Table 3
Different limits of the mass flow rate defined for each scenario [kg/s].

Sc_1	Sc_2	Sc_3	Sc_4	Sc_5
100.9	80.0	50.0	20.0	15.4

1. Building site: the heat demand of the existing building in CS may be different than what defined for the optimization conditions (i),
2. Radiator site: The existing radiators in the existing buildings may have different design capacity (ii) and may be dimensioned with different design standards (iii).

More specifically; the mass flow limits, its details being described in Section 2.3, were investigated to analyze if the limits can still be obtained with boosting applied in supply temperature among the cold winter periods in cases with different heat demand values at the dimensioning stage and at the existing situation (CS). Hence, after the optimal pipe dimensions were observed, a sensitivity analysis was applied with changing values of: (i) current heat demand (q_x), (ii) original radiator capacity (q_0), and (iii) old radiator dimensioning standards, one being 75 °C for supply and 65 °C for return, the other being 90 °C for supply and 70 °C for return, based on two former radiator standards, respectively, of BS EN 338 and of BS 3528 [44].

3. Results

The pipe-node list was defined as the DH model for the case area located in Gladsaxe Municipality together with the length of each pipe segment and the cumulative number of consumers that each pipe segment is obliged to supply heat, as given in Table 2 and as its illustration shown in Fig. 1.

3.1. Mass flow levels

Five different scenarios were generated; each having different mass flow limits obtained by use supply temperatures within the limits in between 55 °C and 95 °C. Table 3 shows the mass flow limitations defined for each scenario.

The level of supply temperature was adjusted severally in each period of load duration, for, both, CS and FS by use of Eq. (15). Table 4 shows the temperature configuration, involving the temperature values of supply and of return, obtained to limit the mass flow levels in the periods where the mass flow limitations, given in Table 3, exceeded if the supply temperature would be fixed in value of 55 °C for the whole year.

It should be noted that in the scenario Sc_5, the first period is defined with a supply temperature of 98.4 °C, which considered as a part of the investigation although it exceeded the limit of 95 °C stated as the maximum continues operating temperature of AluFlex twin pipes.

Table 5 shows the mass flow values severally observed in each period of the load duration, found due to the temperature configuration given in Table 4.

3.2. Optimal pipe dimensions

Table 6 shows the overall length of each pipe type obtained in the pipe segments of the DH network, as a result of optimization applied for each scenario.

The equation to calculate the heat loss coefficient was derived by the use of the multi-variable regression method from 408 samples. The regression formulation is shown in Eq. (16), which was considered to be reliable as a result of the observations consisting of 'adjusted regression square' found high enough with a value observed as 0.91, of 'significance *F*' found low enough with a value observed as 6.998e − 211, and *P*-values of independent variables found low enough with a value observed nearly as zero [16].

3.3. Sensitivity analysis

The sensitivity criterion was directed to evaluate the level until which the boosting of the supply temperature can be applied in order to keep the overall mass flow requirement below a certain limit. Tables 7–9 show the supply temperature levels observed in each combination of values of original radiator capacity between 6 kW and 25 kW with values of current heat demand between 2 kW and 8 kW, with consideration directed to both of the radiator dimensioning standards (BS 3528 and BS EN 338). The results of the sensitivity analysis can be interpreted as i.e. the supply temperature has to be 88.6 °C to keep the DH mass flow rate below 20 kg/s for an existing radiator originally dimensioned for a heat load of 20 kW which accommodates in an existing building of which heat load is currently 7 kW.

Although the supply temperature values above 95 °C cannot be operated in the low-energy district heating network,

Table 4
Temperature configurations adjusted for each scenario, on account of CS and of FS [°C].

Situation	Temperature	Scenario	Pr_1	Pr_2	Pr_3	Pr_4	Pr_5	Pr_6	Pr_7	Pr_8
Current situation	Supply	Sc_1	55	55	55	55	55	55	55	55
		Sc_2	56.3	55	55	55	55	55	55	55
		Sc_3	59.5	55.8	55	55	55	55	55	55
		Sc_4	79.9	73.9	65.9	55	55	55	55	55
		Sc_5	98.4	90.2	79.5	64	55	55	55	55
	Return	Sc_1	49.2	44.3	38.2	30.5	25.9	23.2	20.6	20
		Sc_2	48.1	44.3	38.2	30.5	25.9	23.2	20.6	20
		Sc_3	45.8	43.7	38.2	30.5	25.9	23.2	20.6	20
		Sc_4	35.7	34.6	33.1	30.5	25.9	23.2	20.6	20
		Sc_5	30.2	29.6	28.8	27.4	25.9	23.2	20.6	20
Future situation	Supply	Sc_1	55	55	55	55	55	55	55	55
		Sc_2	55	55	55	55	55	55	55	55
		Sc_3	55	55	55	55	55	55	55	55
		Sc_4	57.6	55	55	55	55	55	55	55
		Sc_5	68.3	63.3	56.7	55	55	55	55	55
	Return	Sc_1	32.5	30.1	27.2	23.6	21.7	20.7	20.1	20
		Sc_2	32.5	30.1	27.2	23.6	21.7	20.7	20.1	20
		Sc_3	32.5	30.1	27.2	23.6	21.7	20.7	20.1	20
		Sc_4	31.4	30.1	27.2	23.6	21.7	20.7	20.1	20
		Sc_5	27.8	27.3	26.7	23.6	21.7	20.7	20.1	20

Table 5
The mass flow rates observed in each period, both, in CS and in FS.

		Pr_1	Pr_2	Pr_3	Pr_4	Pr_5	Pr_6	Pr_7	Pr_8
Current situation	Sc_1	107.7	55.4	32.8	19.6	14.8	12.4	9.7	7.9
	Sc_2	78.5	55.4	32.8	19.6	14.8	12.4	9.7	7.9
	Sc_3	49.6	49.9	32.8	19.6	14.8	12.4	9.7	7.9
	Sc_4	20.1	20.1	20.1	19.6	14.8	12.4	9.7	7.9
	Sc_5	15.4	15.4	15.4	15.4	14.8	12.4	9.7	7.9
Future situation	Sc_1	22.2	19.2	16.0	12.7	10.9	9.8	8.5	7.5
	Sc_2	22.2	19.2	16.0	12.7	10.9	9.8	8.5	7.5
	Sc_3	22.2	19.2	16.0	12.7	10.9	9.8	8.5	7.5
	Sc_4	20.0	19.2	16.0	12.7	10.9	9.8	8.5	7.5
	Sc_5	15.4	15.4	15.4	12.7	10.9	9.8	8.5	7.5

Table 6
Overall length of optimal pipe diameters and annual heat loss from the DH network regarding CS and FS, as obtained for each of five scenarios.

		Sc_1	Sc_2	Sc_3	Sc_4	Sc_5
Pipe length [m]	AluFlex 14/14	–	–	–	128	128
	AluFlex 16/16	–	–	–	410	530
	AluFlex 20/20	–	128	411	939	1049
	AluFlex 26/26	214	410	487	727	1753
	AluFlex 32/32	684	1169	1306	2188	1368
	STPc 32/32	809	210	1256	436	2248
	STPc 40/40	1385	1543	932	3301	1053
	STPc 50/50	1300	1368	2684	417	541
	STPc 65/65	919	2248	1053	419	295
	STPc 80/80	2818	1470	541	–	120
	STPt 100/100	417	124	295	320	200
	STPt 125/125	419	295	–	–	–
	STPt 150/150	320	320	320	–	–
Annual heat loss from the DH network [MWh]	CS	44.7	30.8	17.1	5.5	3.9
	FS	43.8	30.1	16.6	5.3	3.8

Table 7
The level of supply temperature required [°C] in the peak period, adjusted to keep the mass flow rate below 15.3 kg/s.

q_0	Radiator standards													
	BS 3528 (90 °C—70 °C)							BS EN 338 (75 °C–65 °C)						
	$q_x=2$	$q_x=3$	$q_x=4$	$q_x=5$	$q_x=6$	$q_x=7$	$q_x=8$	$q_x=2$	$q_x=3$	$q_x=4$	$q_x=5$	$q_x=6$	$q_x=7$	$q_x=8$
25	55.0	62.0	75.6	89.1	~~102.5~~	~~115.8~~	~~128.7~~	55.0	61.3	74.8	88.2	~~101.6~~	~~114.9~~	~~127.8~~
22	55.0	62.6	76.3	89.8	~~103.3~~	~~116.6~~	~~129.5~~	55.0	61.7	75.2	88.7	~~102.1~~	~~115.4~~	~~128.3~~
20	55.0	63.2	76.9	90.5	~~104.0~~	~~117.4~~	~~130.3~~	55.0	62.0	75.6	89.1	~~102.5~~	~~115.8~~	~~128.7~~
18	55.0	63.9	77.7	91.4	~~105.0~~	~~118.4~~	~~131.3~~	55.0	62.5	76.1	89.6	~~103.1~~	~~116.4~~	~~129.3~~
16	55.0	64.8	78.7	92.6	~~106.3~~	~~119.8~~	~~132.7~~	55.0	63.1	76.8	90.4	~~104.0~~	~~117.3~~	~~130.2~~
14	55.0	66.0	80.2	94.2	~~108.1~~	~~121.7~~	–	55.0	64.0	77.9	91.6	~~105.2~~	~~118.6~~	~~131.5~~
12	55.0	67.7	82.2	~~96.5~~	~~110.7~~	–	–	55.0	65.3	79.4	93.3	~~107.0~~	~~120.6~~	–
10	55.0	70.1	85.1	~~99.9~~	–	–	–	55.0	67.1	81.6	~~95.8~~	~~109.8~~	–	–
8	57.4	73.7	89.6	–	–	–	–	55.0	70.0	85.0	–	–	–	–
6	61.9	79.7	–	–	–	–	–	58.3	74.9	–	–	–	–	–

due to the AluFlex twin pipes formed there, the values exceeding the maximum operating limit of 95 °C was shown in the tables. The reason behind including these observations was to show the tendency of the change of the supply temperature observed, not to indicate that the temperature configurations are applicable in each. The observations that are not suitable to be applied were shown with effect strikethrough on them.

Table 8
The level of supply temperature required [°C] in the peak period, adjusted to keep the mass flow rate below 20 kg/s.

q_0	Radiator standards													
	BS 3528 (90 °C–70 °C)							BS EN 338 (75 °C–65 °C)						
	$q_x=2$	$q_x=3$	$q_x=4$	$q_x=5$	$q_x=6$	$q_x=7$	$q_x=8$	$q_x=2$	$q_x=3$	$q_x=4$	$q_x=5$	$q_x=6$	$q_x=7$	$q_x=8$
25	55.0	55.0	58.8	67.9	76.9	85.9	94.8	55.0	55.0	57.4	66.3	75.1	83.9	92.7
22	55.0	55.0	59.9	69.1	78.3	87.4	~~96.4~~	55.0	55.0	58.1	67.1	76.0	84.9	93.8
20	55.0	55.0	60.8	70.2	79.4	88.6	~~97.7~~	55.0	55.0	58.8	67.9	76.9	85.8	94.7
18	55.0	55.0	61.9	71.4	80.9	90.2	~~99.5~~	55.0	55.0	59.6	68.9	78.0	87.0	~~96.0~~
16	55.0	55.0	63.3	73.1	82.7	92.2	~~101.7~~	55.0	55.0	60.7	70.1	79.4	88.6	~~97.7~~
14	55.0	55.0	65.1	75.2	85.1	94.9	–	55.0	55.0	62.2	71.8	81.2	90.6	~~99.9~~
12	55.0	56.8	67.5	78.0	88.3	–	–	55.0	55.0	64.1	74.0	83.7	93.4	–
10	55.0	59.5	70.9	82.0	–	–	–	55.0	56.2	66.8	77.1	87.3	–	–
8	55.0	63.6	75.9	–	–	–	–	55.0	59.5	70.8	81.9	–	–	–
6	55.5	70.0	–	–	–	–	–	55.0	64.8	–	–	–	–	–

Table 9
The level of supply temperature required [°C] in the peak period, adjusted to keep the mass flow rate below 50 kg/s.

q_0	Radiator standards													
	BS 3528 (90 °C–70 °C)							BS EN 338 (75 °C–65 °C)						
	$q_x = 2$	$q_x = 3$	$q_x = 4$	$q_x = 5$	$q_x = 6$	$q_x = 7$	$q_x = 8$	$q_x = 2$	$q_x = 3$	$q_x = 4$	$q_x = 5$	$q_x = 6$	$q_x = 7$	$q_x = 8$
25	55.0	55.0	55.0	55.0	55.0	55.0	57.4	55	55	55	55	55	55	55
22	55.0	55.0	55.0	55.0	55.0	55.5	59.8	55	55	55	55	55	55	55.7
20	55.0	55.0	55.0	55.0	55.0	57.3	61.8	55	55	55	55	55	55	57.4
18	55.0	55.0	55.0	55.0	55.0	59.4	64.1	55	55	55	55	55	55.1	59.3
16	55.0	55.0	55.0	55.0	57.0	62.1	67.0	55	55	55	55	55	57.2	61.7
14	55.0	55.0	55.0	55.0	59.9	65.3	–	55	55	55	55	55.1	60	64.7
12	55.0	55.0	55.0	57.6	63.7	–	–	55	55	55	55	58.3	63.5	–
10	55.0	55.0	55.1	62.1	–	–	–	55	55	55	56.7	62.6	–	–
8	55.0	55.0	60.6	–	–	–	–	55	55	55.1	62	–	–	–
6	55.0	59.1	–	–	–	–	–	55	55	–	–	–	–	–

3.4. Effect of boosting supply temperature

Fig. 4 shows the comparison of the DH networks (i) one of which was dimensioned with the operational planning of boosting of supply temperature and [labelled as “with boosting applied” in Fig. 4] (ii) other of which was dimensioned without consideration of the operational planning, which is supply of $T_S = 55\,°C$ for all periods in a year [labelled as “without boosting applied” in Fig. 4]. Two operation situation of both DH networks is presented, one for CS with high heat demand from the existing buildings [Fig. 4a] and the other for FS with lowered heat demand from the renovated of the same existing buildings [Fig. 4b].

4. Discussion

This study provides a dimensioning method of the piping networks of low-energy DH systems – operating in low temperature generally and in increased temperature in cold periods occurring in short durations – that supply heat to existing settlements with existing buildings located there, to which heat is provided with an existing heating system, concerned with a case study for a district located in the Municipality of Gladsaxe in Denmark. The dimensioning method was based on the achievements reached via the analysis of the performance of in-house heating elements such as radiators and domestic hot water production units.

Matter-of-fact, heat demand level is the major element that affects the pipe dimensions in their design stage in DH networks. However the rate of mass flow required, which is a function of the heat demand depending on the supply and the return temperature values, was defined as the key parameter for investigating the optimal solution, instead of using heat demand when operational control philosophy of boosting supply temperature is considered in design stage of DH networks. The reason for this was due to the decreasing mass flow rates observed with increasing supply temperature, in case the in-house heating systems were originally over-dimensioned, as can be seen together in Tables 3 and 4. When the temperature configuration was provided with a fixed supply temperature of 55 °C through the whole year, for example, the mass flow required yielded in high amount of rates such as 107.7 kg/s in the first peak period of Sc_1 for CS. However, for the same first peak period, increasing the supply temperature to 98 °C resulted in an excessive decrease in the mass flow rate required i.e. the rate of mass flow required for Sc_5 was found to be 14% of the rate required for Sc_1. It should be noted that boosting of the supply temperature was observed more extensively in cold-periods with decreasing mass flow limits assigned. For instance, the supply temperature was observed to be boosted only in the first cold period for the scenario Sc_2, while in the first four period for the scenario Sc_5.

The Darcy–Weisbach equation which is used to calculate the pressure loss along a circular pipe is directly proportional to the mass flow of the medium circulated through the pipe while inversely proportional to the diameter of the pipe. This brought out the phenomena that the pipe diameter could be reduced with decreasing mass flow required since the optimization algorithm was modeled with a fixed value of maximum allowable pressure drop through the routes. The resulting pipe diameters, shown in Table 6, were found with respectively smaller pipe diameters in each scenario compared to previous scenarios with higher mass flow limits assigned. Although the supply temperature and also the return temperature, which resulted due to the thermal response of in-house units, were increased in cold periods, the heat loss from the DH network did not yield with an increasing level but with a sharp reduction, as seen with 90% cut observed in Sc_5 in comparison to Sc_1 (Table 6). The increment of heat loss from the DH network may have expected to be increasing due to the increased temperature levels but however the reduction achieved in the pipe dimensions showed a greater influence on reducing the annual heat loss energy more than the effect of increasing temperature levels. This can also be seen with slight difference obtained in the values of the heat loss from the DH network that is between CS and FS. It should be noticed that each of the scenarios was formed with the same pipe diameters while the only changing parameter between CS and FS was being the temperature configurations assigned. (Detailed discussion about the optimality of the pipe dimensions can be found in the reference [15] which has the focus on the method of “optimization of DH networks” applied to the DH in the Gladsaxe case area in this study.)

Another discussion point should be directed to the shortness of the cold periods, which can also be counted as the reason why the heat loss from the DH network yielded in low values despite the increment of temperature levels applied. As can be seen in Table 4, the supply temperature was observed with a high level of 98 °C in order to achieve the lowest mass flow rate of 15.4 kg/s, but for a short term as low as 8 h. Also, it should be noticed that peak period should not necessarily be counted as lasting successively in a year period but in short durations. This intermittent occurring of peak period in extremely short durations such as in intervals of 1 h can also be passed over aside by means of the heat accumulated in the properties inside the house such as the furniture and of the available heat existing in the heat carrier medium of the radiators.

There are two approaches that can be mentioned for the results of the sensitivity analysis, one being the limitations of the applicability of the method developed in this study and the other being the availability of using different mass flow limits as the solution. The first approach can be addressed to the unavailable observations found with high temperatures that are highlighted with strike through in Tables 7 and 8 while the latter can be addressed to

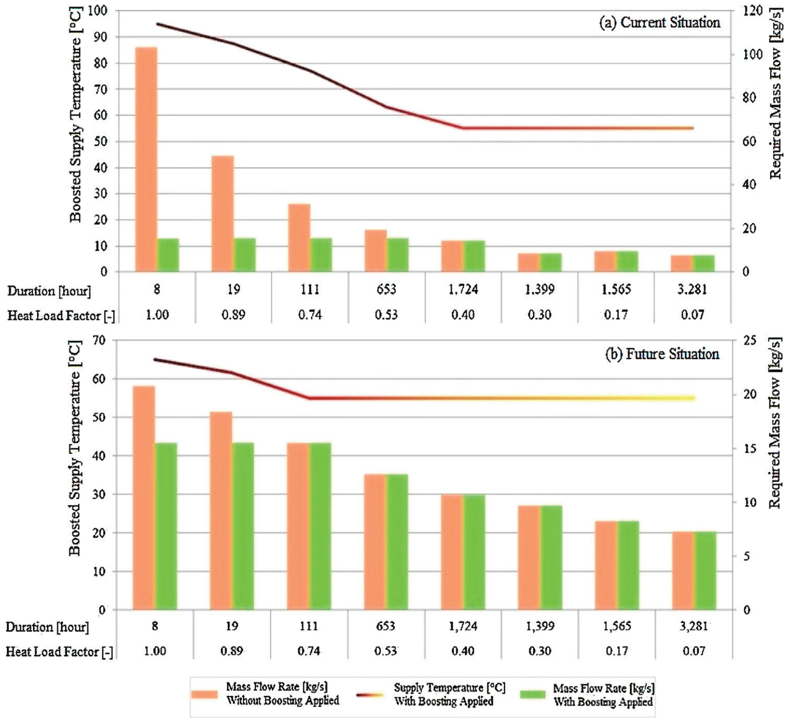


Fig. 4. Required overall mass flow rates with boosting (of supply temperature) applied, in comparison to the case of operation without boosting for the Gladsaxe DH network, both for (a) CS and (b) FS.

the increasing applicability of the method with decreasing mass flow limits assigned sequentially in Tables 7, 8 and 9. It can be seen in Table 9 that the mass flow limit of 50 kg/s could easily be obtained in almost all configurations of original design and current heat requirement, there the unavailable application of boosting the supply temperature was observed only due to current heat requirement value's being higher (or very close) than (to) the original design value. In all of the tables it was found that the radiator standard BS EN 338 resulted with boosted supply temperatures that are slightly lower than the temperatures observed for the radiator standard BS 3528. The reason behind this can be directed to lower temperature difference used in BS EN 338 than in BS 3528, which caused respectively higher radiator sizes established in the design stage.

Another discussion point was directed to the comparison of two DH networks both of which were dimensioned with the optimization method that is described in Section 2.4, one considered with boosting of supply temperature and the other without boosting. The excessive reduction of the overall mass flow requirement for the whole DH network in each period can be observed in Fig. 4 with the operational planning of boosting the supply temperature. Increment of supply temperature in different intensities for a duration of 791 h in one year (as operational planning), leads to excessively reduction of the overall mass flow for each period and as a consequence the pipe dimensions in the design stage. The CS can be interpreted as a transmission period for an existing settlement which is with existing buildings accommodating of originally over-dimensioned raditors and is planned to be converted to low-energy district heating system from an existing high-temperature district heating system or a natural gas heating system. It has to be considered that the transmission period (CS) will take lesser years than the long-lasting FS. The boosting of supply temperature to a great degree was observed to last for around 138 h with supply of 98–75 °C for CS (Fig. 4a). After renovation of existing buildings there (meaning of FS), the boost of supply temperature was then reduced to the level of 65–62 °C for a period of 27 h (Fig. 4b). The excessively high levels of mass flow requirements without boosting supply temperature is unnecessary when considering FS in which the heat demand from the existing buildings is planned to be reduced. One concern of the DH operating companies is if unexpected conditions occur such as i.e. (i) peak weather conditions colder than the design weather conditions and/or (ii) unsatisfaction of the heat demand of the existing buildings that may cause from unsatisfactory existing in-house raditors due to low temperature supply. The operational philosophy of boosting the supply temperature can still be the solution for such unexpected solutions by further increment of the supply temperature in such conditions.

5. Conclusion

General conclusions can draw attention to promote the use of low-energy DH systems operating in low temperature to be used in existing settlements in which the heat source of the district allows high temperature. The results presented in this paper are not the best possible solution to any other districts, but the method developed can be followed to design a new district heating network considered with control philosophy of boosting the supply temperature in peak winter periods. One important conclusion is that great savings can be provided for pipe dimensions by only increasing the supply temperature in peak periods, which occur in short durations compared to the whole year period; otherwise, through the rest of the peak periods and through the low-demand future, expected to be achieved with Danish Building Regulations, the DH network would oblige to an unnecessary over-dimensions that can be caused due to peak periods. Another conclusion is that the method developed is possible to be used in any district, but with different mass flow adjustment that can be provided with different boosting level applied on supply temperature in accordance with the temperature potential available by the heat source close-by and with the original radiator dimensions established. One should note that significant energy savings can be achieved by limiting the mass flow rate as low as possible despite high levels of boosting applied in winter periods.

The proposed dimensioning method should be considered mostly for existing heating infrastructures such as traditional district heating networks and natural gas grid which are close to the end of their life-cycle or which are in the need of an essential maintenance. There are some important limitations that need to be addressed regarding this study, which should be considered as the basis for the future studies. One could investigate the heat demand of existing buildings with focus directed to variation of heat demand rate on an annual basis in CS and FS. Also, one could investigate variations of load duration for different districts that needs to be considered with different types of building structures and with various consumer types located.

Acknowledgments

The work presented in the paper was aided to a very significant extent based on the data and the map provided by Gladsaxe Fjernvarme.

References

[1] H. Lund, Renewable Energy Systems: The Choice and Modeling of 100% Renewable Solutions, Elsevier Science & Technology, MA, USA, 2012.
[2] H. Lund, B. Möller, B.V. Mathiesen, A. Dyrelund, The role of district heating in future renewable energy systems, Energy 35 (2010) 1381–1390.
[3] I. Dincer, A. Hepbasli, District energy systems, in: B.L. Capehart (Ed.), Encyclopedia of Energy Engineering and Technology, 3, CRC Press, Boca Raton, FL, USA, 2007, pp. 316–331.
[4] L. Ozgener, A. Hepbasli, I. Dincer, Performance investigation of two geothermal district heating systems for building applications: energy analysis, Energy and Buildings 38 (2006) 286–292.
[5] C. Coskun, Z. Oktay, I. Dincer, New energy and exergy parameters for geothermal district heating systems, Applied Thermal Engineering 29 (2009) 2235–2242.
[6] R. Wiltshire, Low temperature district energy systems, in: Proceedings of the Urban Energy Conference, October 13–14, 2011, pp. 91–99.
[7] U. Persson, S. Werner, Heat distribution and the future competitiveness of district heating, Applied Energy 88 (2011) 568–576.
[8] P.K. Olsen, H. Lambertsen, R. Hummelshøj, B. Bøhm, C.H. Christiansen, S. Svendsen, et al., A new low-temperature district heating system for low-energy buildings, in: Proceedings of the 11th International Symposium on District Heating and Cooling, August 31–September 2, 2008, 2008.
[9] U. Persson, S. Werner, District heating in sequential energy supply, Applied Energy 95 (2012) 123–131.
[10] C. Reidhav, S. Werner, Profitability of sparse district heating, Applied Energy 85 (2008) 867–877.
[11] C.H. Christiansen, J. Worm, H. Jørgensen, J.E. Thorsen, J. Bennetsen, C.T. Larsen, et al., Demonstration af Lavenergifjernvarme Til Lavenergibyggeri I Boligforeningen Ringgårdens Afd34 I Lystrup, Teknologisk Institut, Taastrup, Denmark, 2011 (104p., Danish, Report No: EFP 2008-II).
[12] C.H. Christiansen, O. Paulsen, B. Bøhm, J.E. Thorsen, C. Ting Larsen, B.K. Jepsen, et al., Udvikling og Demonstration Af Lavenergi-Fjernvarme Til Lavenergibyggeri. Hovedrapport Og Bilag, Teknologisk Institut, Taastrup, Denmark, 2009 (173p., Danish, Report No: EFP 2007).
[13] Energy Saving Trust, Greenwatt Way—A Zero Carbon Homes Newbuild Case Study, 2011, 16 p., (Report No.).
[14] A. Hasan, J. Kurnitski, K. Jokiranta, A combined low temperature water heating system consisting of radiators and floor heating, Energy and Buildings 41 (2009) 470–479.
[15] H.İ. Tol, S. Svendsen, Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: a case study in Roskilde, Denmark, Energy 38 (2012) 276–290.
[16] H.İ. Tol, I. Dinçer, S. Svendsen, Regional energy planning tool for renewable integrated low-energy district heating systems: environmental assessment, in: I. Dinçer, K. Wada, A. Hiraki (Eds.), Causes, Impacts and Solutions to Global Warming, Springer, New York, USA, 2013, pp. 859–878.
[17] H.İ. Tol, I. Dinçer, S. Svendsen, Operational Planning of low-energy district heating systems connected to existing buildings, in: Proceedings of International Conference on Renewable Energy: Generation and Applications, ICREGA-12, Al-Ain, UAE, March 4–7, 2012.
[18] O. Mertoğlu, I. Dokuz, A. Canlan, N. Bakır, Alternatif enerji kaynakları ve düşük sıcaklıklı jeotermal bölgesel ısıtma, Tesisat Mühendisliği 55 (2000) 62–64.
[19] O. Mertoğlu, N. Bakır, T. Kaya, Geothermal applications in Turkey, Geothermics 32 (2003) 419–428.
[20] B. Erdoğmus, M. Toksoy, B. Özerdem, N. Aksoy, Economic assessment of geothermal district heating systems: a case study of Balcova–Narlidere, Turkey, Energy and Buildings 38 (2006) 1053–1059.
[21] Z. Oktay, A. Aslan, Geothermal district heating in Turkey: the Gonen case study, Geothermics 36 (2007) 167–182.
[22] B. Möller, H. Lund, Conversion of individual natural gas to district heating: geographical studies of supply costs and consequences for the Danish energy system, Applied Energy 87 (2010) 1846–1857.
[23] L. Pedersen, J. Stang, R. Ulseth, Load prediction method for heat and electricity demand in buildings for the purpose of planning for mixed energy distribution systems, Energy and Buildings 40 (2008) 1124–1134.
[24] LOGSTOR, Logstor Calculator [online], version 2.1, October 26, 2011.
[25] G. Phetteplace, Operational Planning of low-energy district heating systems connected to existing buildings, in: Optimal Design of Piping Systems for District Heating, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA, 1995 (August), pp. 103 (Report No: CRREL Report 95–17).
[26] B. Bøhm, Energy-Economy of Danish District Heating Systems: A Technical and Economic Analysis, Labaratory of Heating and Air Conditioning, Technical University of Denmark, Kongens Lyngby, 1988, pp. 229.
[27] R.D. Crommelin, P.J. Ham, The influence of modifications in a central heating system of a dwelling on the energy consumption, calculated with a dynamic model, Energy and Buildings 10 (1987) 1–17.
[28] K. Serhan, The thermal effects of some control logics used in GDHS, Applied Thermal Engineering 27 (2007) 1495–1500.
[29] T. Karlsson, A. Ragnarsson, Use of very low temperature geothermal water in radiator heating systems, in: Proceedings of the World Geothermal Congress, vol. 1, Firenze, Italy, May 1995, 1995, pp. 2193–2198.
[30] O. Paulsen, J. Fan, S. Furbo, J.E. Thorsen, Consumer unit for low energy district heating net, in: Proceedings of the 11th International Symposium on District Heating and Cooling, Reykjavik, Iceland, August 31–September 2, 2008.
[31] J.E. Thorsen, H. Kristjansson, Cost Considerations On Storage Tank Versus Heat Exchanger For Hot Water Preparation, Danfoss A/S, Nordborg, Denmark, 2002 (11p., Report No: VF.KQ.A1.02).
[32] J.E. Thorsen, C.H. Christiansen, M. Brand, P.K. Olesen, C.T. Larsen, Experiences on low-temperature district heating in Lystrup—Denmark, in: Proceedings of the International Conference on District Heating and Cooling, Portorož, Slovenia, March 20–22, 2011.
[33] SWEP, SSP G7 [disk], Version 7.0.3.4, 2003.
[34] W. Winter, T. Haslauer, I. Obernberger, Untersuchungen zur gleich-zeitigkeit in nahwärmenetzen: ergebnisse und projekterfahrungen, Euroheat & Power 30 (2001) 42–47 (German).
[35] J.B. Vestergaard, The distribution network (August), Lecture Note Presented at Summer School District Energy, Århus, Denmark, 2010.
[36] C.L. Wadhwa, Generation, Distribution and Utilization of Electrical Energy, New Age International (P) Ltd., Daryaganj, New Delhi, India, 1989.
[37] R.Z. Freire, G.H.C. Oliveira, N. Mendes, Development of regression equations for predicting energy and hygrothermal performance of buildings, Energy and Buildings 40 (2008) 810–820.
[38] A.C. Cameron, P. Mildenstein, EXCEL: Multiple Regression [Internet], Department of Economics, University of California, Berkeley, California, 2007, ⟨http://cameron.econ.ucdavis.edu/excel/ex61multipleregression.html.⟩ (cited 10.04.12.).
[39] H.İ. Tol, S. Svendsen, A comparative study on substation types and network layouts in connection with low-energy district heating systems, Energy Conversion and Management 64 (2012) 551–561.
[40] H.İ. Tol, S. Svendsen, Determination of optimum network layout for low-energy district heating systems with different substation types, in: Proceedings of the Third International Renewable Energy Congress, IREC, Hammamet, Tunisia, December 20–22, 2011, 2011, pp. 179–184.
[41] R.L. Sanks, Flow in conduits, in: R.L. Sanks, G. Tchobanoglous, B.E. Bosserman, G.M. Jones (Eds.), Pumping Station Design, Butterworth-Heinemann, Boston, USA, 1998, pp. 33–39.
[42] D. Clamond, Efficient resolution of the Colebrook equation, Industrial & Engineering Chemistry Research 48 (2009) 3665–3671.
[43] H.İ. Tol, S. Svendsen, The exergetic, environmental and economic effect of the hydrostatic design static pressure level on the pipe dimensions of low-energy district heating networks, Challanges 4 (2013) 1–16.
[44] B. Skagestad, P. Mildenstein, District Heating and Cooling Connection Handbook, IEA, Paris, France, 2002.

NON-ISI ARTICLE

Challenges **2013**, *4*, 1-16; doi:10.3390/challe4010001

OPEN ACCESS

challenges

ISSN 2078-1547

www.mdpi.com/journal/challenges

Article

The Exergetic, Environmental and Economic Effect of the Hydrostatic Design Static Pressure Level on the Pipe Dimensions of Low-Energy District Heating Networks

Hakan İbrahim Tol * and Svend Svendsen

Department of Civil Engineering, Technical University of Denmark (DTU), Kongens Lyngby DK-2800, Denmark; E-Mail: ss@byg.dtu.dk

* Author to whom correspondence should be addressed; E-Mail: hatol@byg.dtu.dk; Tel.: +45-4525-5099; Fax: +45-4588-3282.

Received: 10 September 2012; in revised form: 28 November 2012; / Accepted: 10 January 2013 / Published: 23 January 2013

Abstract: Low-Energy District Heating (DH) systems, providing great energy savings by means of very low operating temperatures of 55 °C and 25 °C for supply and return respectively, were considered to be the 4th generation of the DH systems for a low-energy future. Low-temperature operation is considered to be used in a low-energy DH network to carry the heat produced by renewable and/or low grade energy sources to low-energy Danish buildings. In this study, a comparison of various design considerations with different levels of maximum design static pressures was performed, and their results evaluated in terms of energetic, exergetic, economic, and environmental perspectives.

Keywords: low-energy; low-temperature; district heating; substation; pressure loss; maximum static pressure; optimization; environmental impact

1. Introduction

Low-Energy District Heating (DH) systems have been defined as the 4th generation DH systems which operate at very low temperatures such as 55 °C in terms of supply and 25 °C in terms of return. Here "low energy" is highlighted as the merit for such DH systems instead of using "low temperature", because of the great energy savings achieved due to low temperature operation, which shows a greater benefit than the low temperature operation itself [1,2]. Low-energy DH systems could become the key energy solution to mediate between the future's low-energy buildings and renewable energy sources. In addition to the proven benefits of employing DH systems [3–7], several advantages can be gained with the low-temperature operation, such as increased efficiency in the production of heat at the source, reduced overall heat loss from the DH system, exploitation of the low grade heat sources, for example low temperature renewable sources and the surplus heat from industry, and lowered thermal stress in the system equipment [8–10].

Some studies in this field have presented the conceptual and detailed analysis of utilizing low-energy DH systems. Olsen *et al.* and Paulsen *et al.* [9,10] found that the low-energy DH systems compete well with alternative heating systems in the socio-economic point of view, in which low temperature operation was obtained by means of using substations with an adequate control philosophy adopted in each building. Two pilot projects in operation with low-energy DH systems have been demonstrated in Lystrup, Denmark and in the SSE Greenwatt Way development in Chalvey, UK, their details being given, respectively, in [1,2,9–11] and in [8,12]. Another example can be directed to the geothermal based low-energy DH system which has been in operation at Kırşehir, Turkey, supplying heat to residents with an overall heated area of 180,000 m^2 since 1994. Kırşehir low-energy district heating system has the limitation for the supply temperature which is supplied at 54 °C due to a local source of low grade geothermal field available at a temperature of 57 °C [13,14]. More information regarding low-energy DH systems can be found in [15–23].

In the studies of Tol *et al.* [24–26], a pipe dimensioning method was presented for low-energy DH networks with an optimization method formulated to reduce the pipe dimensions of the network as much as possible with the aim of minimizing the heat loss from the DH network. The nonlinear constraint formulated in the optimization algorithm was provided with reducing the diameters of the piping network until the pressure loss in each route of the DH network reaches to the level of the head lift provided from the main pump station. The case study presented in [24] resulted in a particular optimal solution under a certain level of maximum static pressure being appointed during the design stage of the low-energy DH network. However, one should note that the level of the maximum design static pressure can affect the DH network dimension considerably. Hence the research question of this study was formed with consideration directed to investigating the effect of the maximum design static pressure on the energetic, exergetic, economic, and environmental performance of the low-energy DH network. The parameters such as optimal dimensions of the network, heat loss from the DH network, and pressure loss were considered to show variations each of which was expected to have a different weight. The reason for different expectations for the variation of each parameter is due to the limitations and properties of the pipe types involved, such as the maximum design static pressure limit, the heat insulation class, and the available range of the pipe diameter, each of which may change in accordance with the pipe catalogue considered in the design stage. Hence this study was formulated optimizing the piping network with various levels of maximum static pressure, in order to evaluate the variation of each parameter in question from different perspectives of performance evaluation. The method was carried out for a case area that was given in [24].

2. Background

The traditional pipe dimensioning methods used so far in the design of DH networks relied on the rule-of-thumb methods which were, most commonly, based on reducing the pipe dimension of each pipe segment of the DH network until reaching the defined criteria limit, whether it is defined as maximum pressure gradient, as maximum velocity of the heat carrier medium, or as simultaneous consideration of both [27–29]. However, in [24] it was found that lower pipe dimensions could be achieved by means of the optimization method in question compared to the pipe dimensions observed with the traditional rule-of-thumb methods, based on using the maximum pressure gradient as the maximum limit. Although another dimensioning method was formed on the basis of the rule-of-thumb—but in this case distinctive maximum pressure gradient limits were defined, each specific to one of the routes—the over-dimensioning of the piping network could not be avoided [24].

The heat requirement of a consumer can be met as soon as the substation equipped in the consumer site is provided with adequate levels of supply temperature and of pressure difference between the supply and the return line, their values being defined in accordance with the configuration of the substation of each consumer. The heat carrier medium circulates in the DH network, which is basically a closed loop both in the formation of layouts as branched (tree-like) or as looped [18,27,30]. This study deals with a branched type DH network formed in the case district.

3. Description of the Case Area

The Trekroner area located in Roskilde, Denmark, was studied in order to evaluate the effect of the pressure levels appointed in the design stage of the DH network on the resultant optimal pipe dimensions. The overall length of the DH piping network was found to be 1.2 km, supplying heat to 165 single family houses. The heat demand of each house was defined as 2.9 kW for space heating and 3 kW for domestic hot water requirement with a storage tank of 120 litres equipped in the substation of the house. More details regarding the substation can be found in [1,2,9–11,15,24,31–34].

The duration curve of heat load given for the low-energy DH system located in Lystrup, Denmark [11] was used to derive the annual hours of operation together with the partial load of the requiring overall flow defined on the basis of heat load factors given in Table 1.

Table 1. The heat load factors with duration of occurrence for Lystrup, Denmark [11].

Parameters	Units	Annual Periods							
Heat Load Factor	-	1.00	0.89	0.74	0.53	0.40	0.30	0.17	0.07
Duration	h	8	19	111	653	1724	1399	1565	3281

In the calculations regarding the yearly operation of the low-energy DH network, heat load factors were used to account for defining the mass flow rates required in the periods that are lower in heat demand than the peak period. It should be noted that supply temperature through the whole network has to be maintained at 55 °C. However the return temperature does not show a significant variation for different values of heat load factors *i.e.*, the return temperature showed a variation at 25.4 ± 0.29 in case of a heat load factor of 0.75 and at 28.6 ± 0.92 in case of a heat load factor of 0.25; data taken from [18,24]. Hence the supply and return temperatures were defined as constant at 55 °C and 25 °C, respectively, throughout the whole year period.

4. Methods

The methods in this section describe the calculations and evaluations considered in the case study given in this paper. It should be noted that each district has to be dimensioned and investigated individually by following the methods given but in accordance with the design conditions of the district and with the commercially available catalogues.

4.1. Optimization

The mass flow demand of each house was used as input value to the optimization method instead of using heat demand values due to the fixed temperature operation at 55 °C for supply and at 25 °C for return. The required mass flow rate on each pipe segment was considered with a simultaneity factor, its value based on the cumulative number of consumers to which the pipe segment supplies heat. Once determined, the mass flow rate on each pipe segment was kept constant for each level of the maximum static pressure. The dimensioning of the DH network was carried out with the optimization method that was presented in [24], its modified form to be used in this study being shown in Equation (1).

$$Minimize\ \dot{Q}_{Loss}(Di^{*})$$

Subject to the constraints:

$$\Delta P(PS_l) = \Delta P_{Max,k}\ \forall l=1,...,n_l \quad (1)$$

$$Di^{*} \in \mathbb{R}$$

$$D_{Min} \leq Di^{*} \leq D_{Max}$$

The static pressure of a DH network has to be provided with a certain level above atmospheric pressure. Hence in this way it can be guaranteed that each pipe segment is full with the heat carrier medium and that the heat carrier medium does not boil in locally-lower-pressure (than atmospheric pressure) sites through the DH network, avoiding any possible cavitation. The reason for the latter is due to the boiling temperature of water varying according to the pressure level. The static pressure for the whole DH network can be managed by means of a pressure vessel that keeps the DH network pressurized with a certain amount of holding pressure [35]. The holding pressure was defined as 1.5 bara (the unit bara refers to the absolute pressure) for this case area. Maximum allowable pressure loss value was therefore defined by use of Equation (2) for each maximum static pressure values defined. The pressure loss through the house connection branch and the substation was defined as 0.5 bara at maximum [10,15,26].

$$\Delta P_{Max,k} = SP_{Max,k} - P_h - P_S \quad (2)$$

where $\Delta P_{Max,k}$ is the maximum pressure loss for the routes of the DH network (bar), $SP_{Max,k}$ refers to the maximum static pressure [bara] for the scenario k (Table 2), P_h is holding pressure (bara), and P_s is pressure loss occurring through the substation and house connection branch (bar).

Table 2. Maximum Static Pressure Values Appointed in the Design Stage (bara).

$SP_{Max,1}$	$SP_{Max,2}$	$SP_{Max,3}$	$SP_{Max,4}$	$SP_{Max,5}$	$SP_{Max,6}$
4	6	8	10	15	25

The maximum static pressure is a major limitation while employing the instruments such as valves, gages, and meters; and the pipes at the DH network, *i.e.*, AluFlex twin pipes have a design pressure limit of 10 bara. However, AluFlex twin pipes were privileged in the optimization algorithm due to their heat saving potential. Therefore the optimization algorithm was carried out with only steel twin pipes when the maximum static pressure values exceeded the 10 bara limit (Table 3).

Table 3. The range of the nominal diameter in the unit (mm) applicable under the constraint of the design maximum static pressure limit for the pipe types involved.

Pipe Types	Maximum Static Pressure Levels (bara)	
	≤10	>10
AluFlex Twin Pipe	10–26	-
Steel Twin Pipe	37.2–82.5	21.9–82.5

The overall heat loss from the DH network was calculated by using Equation (3) in which the heat loss coefficient values are being derived by means of the multi-regression applied on the data retrieved from the commercial software LOGSTOR calculator [36], as shown in Equation (4).

$$\dot{Q}_{OHL} = \sum_{i=1}^{n_i} \left[L(p_{i-1,i}) \times u_L(p_{i-1,i}) \right] \tag{3}$$

where $\dot{Q}_{OHL}$ refers to the overall heat loss from the DH network (W), calculated with the multiplication of the length L [m] and of the heat loss coefficient u_L (W/m) for a pipe segment $p_{i-1,i}$.

The heat loss coefficient data can be found by using Equation (4), which was derived by means of the multi-regression method carried out in the basis of parameters such as: (i) the pipe diameter range given in Table 3; (ii) the insulation class chosen as Series 2 for the twin-pipes; and (iii) the application limit that the twin pipes have direct contact with the surrounding soil [36].

$$u_L = -4.1 + 0.11 \times T_S + 0.10 \times T_R - 0.21 \times T_G + 0.05 \times d \tag{4}$$

where T is the temperature (°C) with the subscripts S, R, and G indicating the temperatures of supply, return, and ground, respectively; and d is the inner diameter of the pipe segment (mm).

4.2. Evaluation Methods

The optimal pipe dimensions found by use of the optimization algorithm in question was later assessed from different perspectives, such as: (i) the energy; and (ii) the exergy loss evaluation considered with the annual heat loss from the district heating network and the annual pump electricity consumption; (iii) the economic impact of the investment costs involving of constructing the pipe network and employing pipe and the operating costs regarding the heat loss from the network and pump consumption; and (iv) the environmental impact of varying losses in two energy forms.

4.2.1. Exergy Measures

The exergy is a measure of the quality of an energy form [37–39]. In this study the evaluation was carried out with the exergetic values of both losses, one being the overall heat loss from the DH network and the second being the pump electricity consumption observed as a result of the optimizations that were carried out with differing maximum static pressure. These two different energy forms can be compared on equal terms by their exergy values that can be found by means of exergetic factors, given as 0.17 and as 1 (both in the unit of (MJ_{ex}/MJ_{en})) for heat energy form, and for electricity, respectively, by [39]. For example, heat loss energy of 100 MJ_{en} corresponds to an exergy value of 17 MJ_{ex} by employing the aforementioned exergetic factor for the energy form of heat, while in the case of electricity energy 100 MJ_{en} corresponds to 100 MJ_{ex}. The reason behind this is because electrical energy is a pure form of energy. The exergy value of each annual energy losses—one with respect to the heat loss from the DH network and the other to pump electricity consumption—was obtained to provide the basis for having an equal quality term to be used in the assessment of the exergy measures.

4.2.2. Economic Investigation

The economic cost calculations involved the investment costs of the pump and piping network and with the operating costs of heat loss from the DH network and the pumping power consumption, all of which vary with the changing values of maximum static pressure appointed in the design stage of the low-energy DH network.

The operating costs were calculated from two aspects: (i) the heat loss from the DH network and (ii) the pumping power consumption. The specific cost data was considered with the projections of the heat price for natural gas and of the electricity price that was reported for a period of 20 years by ENS (the report can be found in [40]). The future costs related to losses (excluding the common cost such as the production of the heat due to it being same for each analysis) were brought to their present value by means of the Net Present Value (NPV) equation considering an interest rate value of 1.29% that was taken for Denmark from [41]. The investment costs were calculated considering the DH piping network and the pump, their specific cost data being taken from, respectively [9,42].

A sensitivity analysis was performed with respect to the specific prices of heat and electricity regarding the future operating costs, and of pipe and pump regarding the investment costs, in order to evaluate the impact of all specific cost data on the overall cost of the low-energy DH network [43]. The sensitivity analysis was performed with various values appointed for each specific cost data. The appointed values defined for each specific cost data were determined by means of scaling factors ranging between −0.75 and +0.75 with an interval value of 0.25.

4.2.3. Environmental Impact

The environmental impact was also investigated for various values of the maximum static pressure appointed in the design stage of the low-energy DH network. The specific emission data based on the analysis reported for 2010 by CTR, Københanvs E, and VEKS was used in the calculations in [44], shown in Table 4.

Table 4. Specific emission data for the productions of DH and of electricity in the case of Copenhagen, Denmark (mg/kWh (except CO_2)) [44].

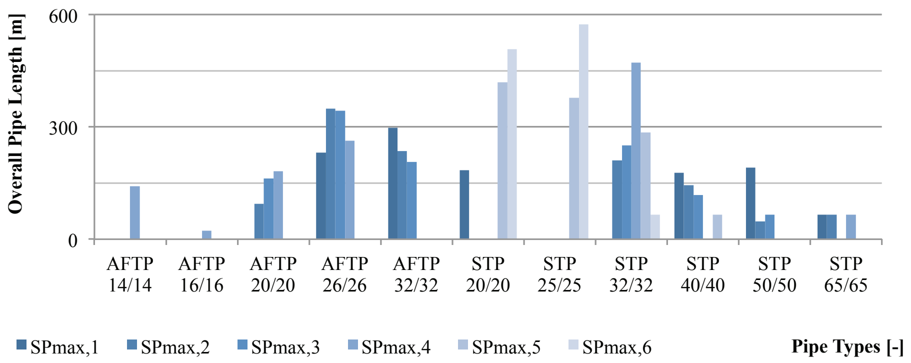
	DH	Electricity
CO_2	133 *	502 *
CH_4	13	272
N_2O	3	7
SO_2	18	93
NO_x	135	401
CO	80	188
Unburned Hydrocarbon	6	56
Particle	7	12

* CO_2 is in the unit of g/kWh.

5. Results

In this paper, the DH piping network was dimensioned by means of the optimization method (details described in Section 4.1) with different values of the maximum static pressure defined in the design stage. The resultant pipe dimensions were examined in terms of the exergetic values of the losses due to overall heat loss from the DH network and pump power consumption. The overall length of the resulting pipe diameters is shown in Figure 1 (In Figure 1; AFTP refers to AluFlex Twin Pipe and STP to Steel Twin Pipe while the numbering in the label shows the nominal diameters of the inner pipes carrying the heat carrier medium, *i.e.*, 14/14 has two inner pipes each of which has a nominal diameter of 14 mm).

Figure 1. Pipe diameters as obtained for differing values of maximum design static pressure values.



The annual pump electricity consumption and the overall heat loss of the DH network were obtained in terms of energy as shown in Table 5, the annual operation of DH system being based on the load duration data given in Table 1.

Table 5. The annual pump power consumption and the overall heat loss, as obtained for differing maximum design static pressure.

Parameters	Unit	Maximum Static Pressure Levels Defined					
Max. Static Pressure	bara	$SP_{max,1}$	$SP_{max,2}$	$SP_{max,3}$	$SP_{max,4}$	$SP_{max,5}$	$SP_{max,6}$
Annual Pump Electricity Consumption	MWh	3.4	5.8	8.0	10.1	16.6	35.6
Annual Overall Heat Loss	MWh	51,964	48,950	47,788	44,564	46,249	44,379

The comparison of the annual pump electricity consumption and the overall heat loss from the DH network was performed with respect to their exergy values, as shown in Figure 2. The environmental impact of differing maximum design static pressure is shown in Figure 3.

Figure 2. Exergy values as obtained for the annual pump electricity consumption and for the overall heat loss from the DH network.

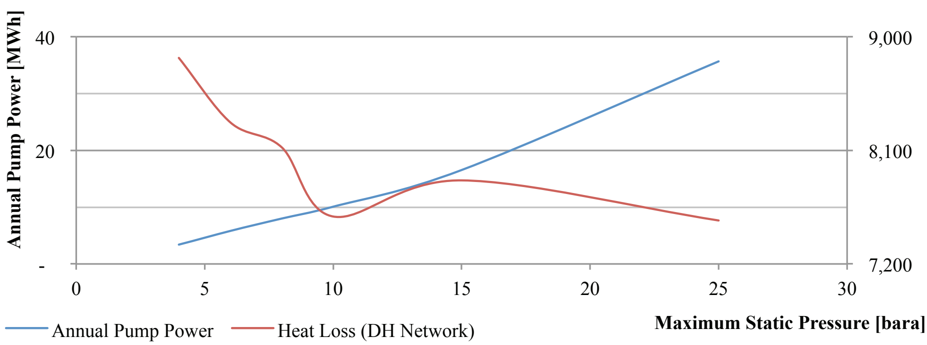
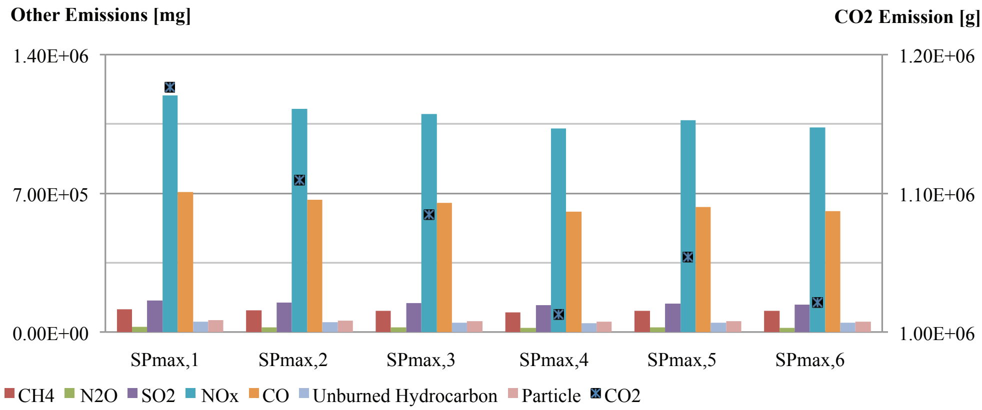
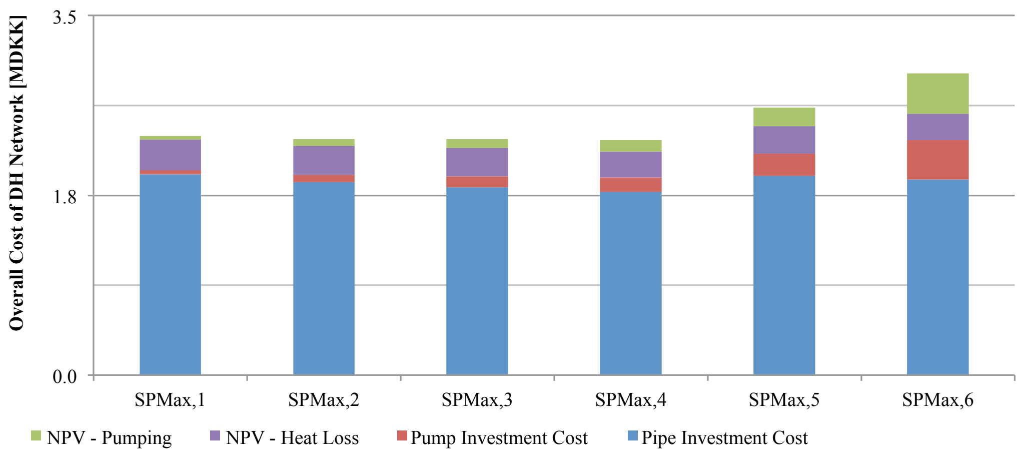


Figure 3. The environmental impact of DH system in differing maximum static pressure values.



The economic comparison involving the investment costs for the piping network, the pump equipment and the operating costs related to the heat loss from the DH network, and the pumping electricity consumption is shown in Figure 4. It should be noted that the cost of the heat requirement that is equivalent to the heat demand of all houses in the district is the same for each analysis considered with different static pressure values, which was found to be 0.241 MDKK (Million Danish Kroner) in case the heat is produced by means of natural gas (excluding the efficiency of the heat production plant). The heat supply needed to satisfy the heat demand of all houses in the district has to considered with the heat loss from the DH network, *i.e.*, the heat supply is equal to the overall heat requirement plus the heat loss from the DH network.

Figure 4. The comparison of the overall costs of the DH system with differing maximum static pressure values (the labels refer to the increment ratio compared to the reference case $SP_{Max,4}$).



The sensitivity analysis was presented for three scenarios of $SP_{Max,1}$, $SP_{Max,4}$ and $SP_{Max,6}$, as shown in Figure 5.

Figure 5. The sensitivity analysis with respect to specific cost data observed for various maximum static pressures obtained for: (**a**) SPMax,1, (**b**) SPMax,4 and (**c**) SPMax,6.

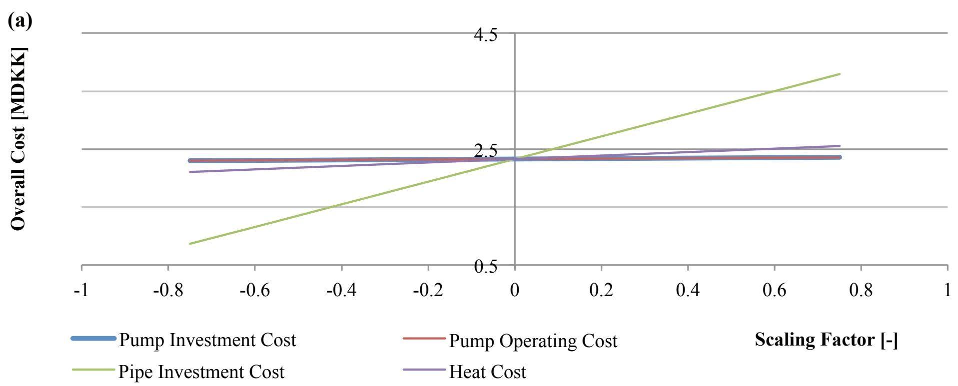
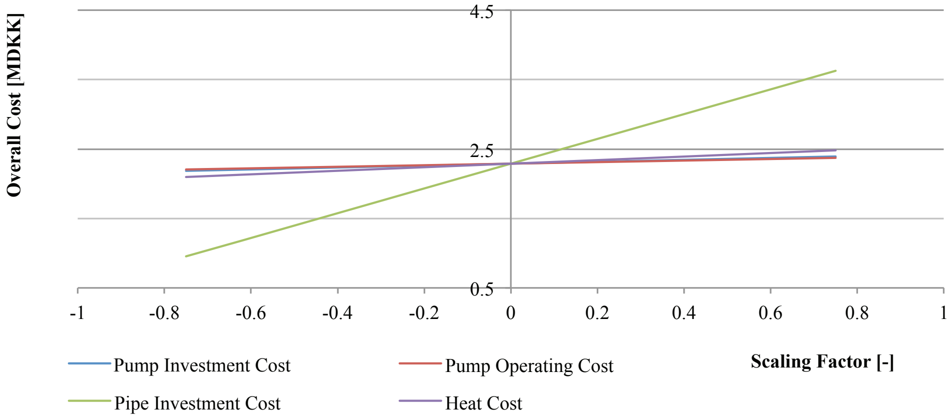
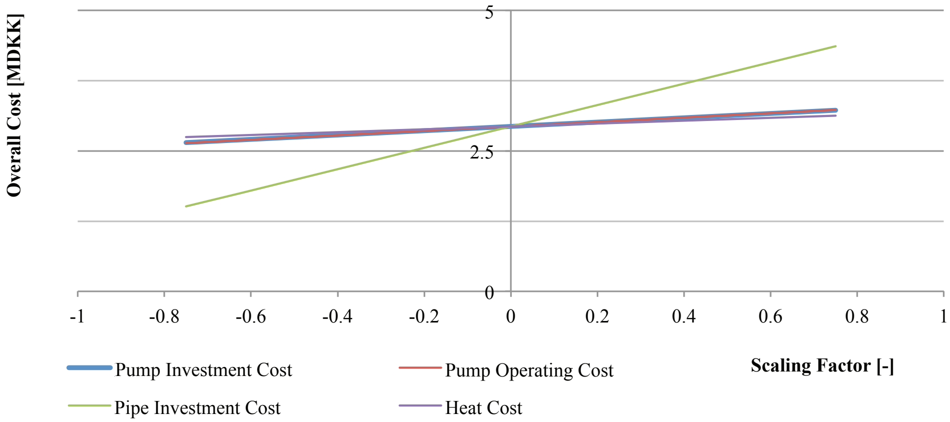


Figure 5. *Cont.*

(b)



(c)



It was observed that the main pipe segments (the first-order pipe segment supplied by the heat source and the second-order pipe segments in the following sequential pipe) were observed with high velocity levels up to 3.8 m/s for the first-order pipe segments and up to 3.37 m/s for the second-order pipe segments for the coldest peak winter period in scenario $SP_{Max,6}$.

6. Discussion

This study analyses the effect of different pressure levels on the pipe dimensioning of a low-energy DH network, with regard to Trekroner, a suburban area located in the Municipality of Roskilde in Denmark.

The same layout of low-energy DH network defined with a similar input of mass flow rate requirements was dimensioned using the same optimization method. The differing values of maximum static pressure appointed in the design stage of the DH network resulted in different optimal solutions, each of which obtained with varying overall lengths of the pipe types involved (Figure 1). Two reasons were found when addressing this issue: (i) the limitation of employing AluFlex twin pipes above the maximum static pressure defined as 10 bara, since their insulation properties are better than steel twin pipes; and (ii) the allowance of reducing the pipe diameters further through an optimization algorithm with increasing amounts of allowable pressure loss is appointed as maximum in the design stage. The latter reason is valid except when the former reason occurs. The idea behind (ii) is due to the existence of an inverse proportion between the pipe dimension and the pressure loss, since in this study the mass flow was defined as constant and the optimization method was modelled to decrease the pipe dimension until the pressure loss reached the defined maximum allowable pressure drop value.

The energetic and exergetic evaluation of the annual pump electricity consumption and the overall heat loss from the DH network (Table 5 and Figure 2) substantiated observations given for the Lystrup project that the annual pump electricity consumption is significantly lower than the overall heat loss from the DH network in all maximum static pressure values employed. The increase in the pump power requirement was observed to be significantly lower than the overall heat loss value with the increasing maximum static pressure below the maximum static pressure level of 10 bara. However, in high levels of the maximum static pressure values appointed, the allowable pressure loss through the routes of the DH network was defined to be as high as 23 bar, yielding significant reduction in pipe dimensions down to steel twin pipe 25/25 and steel twin pipe 32/32 as the longest in the overall length obtained. Such a high reduction being observed in the pipe dimensions resulted with an overall heat loss value almost as low as the maximum static pressure of 10 bara and resulted with pipe dimensions down to AluFlex twin pipe 10/10 (the high performance of heat saving in AluFlex twin pipes should be noted). The reason for having comparatively higher heat loss in the maximum static pressure of 10 bara rather than appointing 25 bara was due to the optimal solution found with a high variation in pipe dimensions observed, *i.e.*, the main pipe segment that was defined as the successor to the heat production plant, resulted in steel twin pipe 65/65 while the pipe segments close to the end-users (the nodes without successor pipe segments) were optimized to small pipe dimensions such as AluFlex 10/10.

The economic results showed that the investment cost for the piping network was found to be relatively higher compared to the other costs involved, which was valid for all of the maximum static pressure levels. The operating costs involving the heat loss from the DH network and the pumping power consumption constitute only a small percentage of the overall cost. However, the increasing static pressure resulted in a slight increase in the cost of heat loss, while a comparatively higher increase was observed in the pumping power consumption costs. The pipe investment cost was observed to have a considerable impact on the overall cost of the low-energy DH network. The degree of the sensitivity observed for the pipe investment cost was found to decrease in the high levels of maximum static pressure, *i.e.*, in case the specific pipe cost was reduced to −75% of its original value, the relative change of the overall cost (to the reference optimal point) was obtained with a reduction of −62.9% for the $SP_{Max,1}$ and with a reduction of −48.6% for the $SP_{Max,6}$.

In the simulation with the maximum static pressure level of 25 bara employed, the velocity of the heat carrier medium was observed to be in comparatively higher levels on the main pipe segments than the other pipe segments of the DH network for the coldest peak period, due to the excessive reductions achieved on the dimensions of these pipes by means of the optimization algorithm. The dimensions of these pipe segments can be increased to an upper diameter available in the pipe catalogue, which will lead to an increase in the heat loss from the DH network.

Based on the current specific data given for the environmental impact in Table 4, the emissions observed with the simultaneous consideration of the heat loss and the pumping power consumption showed a minimum of 10 bara as well as the results of the other evaluation methods from the energetic, exergetic and economic points of view.

7. Conclusion

The aim of this study was not to adjudge the best possible solution to any of the problems investigated, but rather to explore the effects of the parameter "the maximum static pressure" appointed in the design stage of a low-energy district heating network from the energy, exergy, economic and environmental points of view. One should note that district heating systems should always be designed in accordance with what works best within the district itself. It is rewarding to point out, however, some general conclusions found regarding the study and its results. The main conclusion refers to the maximum static pressure level of 10 bara resulting in a minimum impact on all these above-mentioned perspectives. However generally speaking, it is highly important to determine the level of the maximum static pressure and hence the maximum allowable pressure drop, while dimensioning the DH network according to local geographical conditions together with the heat demand properties of the heat consumers located in the area. Another particular observation is the increment in the maximum static pressure level yielding a reduction in the heat loss of which the exergetic value outweighed by far the increase of exergy use due to increased pumping power below 10 bara. The great energy saving potential due to the high insulation properties of the AluFlex pipe type can certainly be stressed for areas where the low levels of the maximum static pressure are applicable. However the increment in the maximum static pressure while being higher above 10 bara not only causes high pump power requirements, but also may cause an increase in the heat loss from the DH network. In addition, the lowered durability of piping and equipment in the DH network should be noted, which can be caused by the long-term effects of the high maximum static pressure levels. One should also note that a high level of velocity should be one of the main concerns while designing the piping networks due to the risk of noise and flow corrosion. However the coldest peak winter period lasted for 8 hours but only intermittently throughout the case study period presented in this paper.

Prevailing use of low-energy district heating systems can be rewarding for the future energy supply schemes since any type of heat source can be utilized to produce low temperature heat and supplied to low-energy houses by means of low-energy district heating networks. The research method presented in this paper can greatly help in pressure considerations regarding low-energy district heating systems. The obtained results together with their evaluations of various aspects, will provide reasons to overcome barriers that may be directed to the optimization algorithm in question due to its unique aim of utilizing the head lift provided from the pump station excessively by reducing the dimensions of the piping network until pressure loss of each route reaches the level of the head lift considered. One can see that employing AluFlex twin pipes provides superior measures from most evaluation aspects considered in this study. These two concluding points will advance the design of low-energy district heating systems being considered in future energy supply schemes.

Some shortcomings of this study should be specified in order to form the scope of further studies in this field: The design of a DH network must consider the elevation variations of the district, which was not considered in this study. The scope of the investigation would be further widened by including various types of pipes that are commercially available and by carrying out pressure investigations for different network layouts, such as looped and mixed layouts involving branched and looped forms together.

Acknowledgments

This research work has been financed partly by Roskilde and Gladsaxe Fjernvarmeforsyning A/S. Also the external study being currently carried out in collaboration with UOIT, Oshawa, ON, Canada has been supported financially, partly by the COWIfonden, the Oticon Fonden, and the Marie & M.B. Richter's Fond. We are thankful for their technical and financial supports.

References

1. Christiansen, C.H.; Worm, J.; Jørgensen, H.; Thorsen, J.E.; Bennetsen, J.; Larsen, C.T.; Juhl, Ole; Lang, S.; Rosenberg, F.; Olsen, P.K.; *et al. Demonstration Af Lavenergifjernvarme Til Lavenergibyggeri i Boligforeningen Ringgårdens Afd. 34 i Lystrup* (In Danish); Technical Report for Project CO_2-Reductions in Low Energy Buildings and Communities by Implementation of Low Temperature District Heating Systems. Demonstration cases in EnergyFlexHouse and Boligforeningen Ringgården: Århus, Denmark, May 2011.
2. Christiansen, C.H.; Paulsen, O.; Bøhm, B.; Thorse, J.E.; Larsen, C.T.; Jepsen, B.K.; Olsen, P.K.; Lambertsen, H.; Hummelshøj, R.; Svendsen, S.; *et al. Udvikling og Demonstration af Lavenergi-Fjernvarme til Lavenergibyggeri. Hovedrapport og Bilag* (In Danish); Technical Report for Project Development and Demonstration of Low-Energy District Heating for Low Energy Buildings: Copenhagen, Denmark, March 2009.
3. Rosen, M.A.; Le, M.N.; Dincer, I. Efficiency Analysis of a Cogeneration and District Energy System. *Appl. Therm. Eng.* **2005**, *25*, 147–159.
4. Dincer, I.; Hepbasli, A. District Energy Systems. In *Encyclopedia of Energy Engineering and Technology*; Capehart, B.L., Ed. CRC Press: Gainesville, FL, USA, 2007; Volume 3, pp. 316–331.
5. Persson, U.; Werner, S. Heat Distribution and the Future Competitiveness of District Heating. *Appl. Energy* **2011**, *88*, 568–576.
6. Lund, H.; Möller, B.; Mathiesen, B.V.; Dyrelund, A. The Role of District Heating in Future Renewable Energy Systems. *Energy* **2010**, *35*, 1381–1390.
7. Skagestad, B.; Mildenstein, P. *District Heating and Cooling Connection Handbook*; IEA: Paris, France, 2002; pp. 1–86.
8. Wiltshire, R. Low Temperature District Energy Systems. In *Proceedings of the Urban Energy Conference*, Debrecen, Hungary, October 2011; pp. 1–13.

9. Olsen, P.K.; Lambertsen, H.; Hummelshøj, R.; Bøhm, B.; Christiansen, C.H.; Svendsen, S.; Larsen, C.T.; Worm, J. A New Low-Temperature District Heating System for Low-Energy Buildings. In *Proceedings of the 11th International Symposium on District Heating and Cooling*, Reykjavik, Iceland, August 31–September 2, 2008; pp. 1–8.
10. Paulsen, O.; Fan, J.; Furbo, S.; Thorsen, J.E. Consumer Unit for Low Energy District Heating Net. In *Proceedings of the 11th International Symposium on District Heating and Cooling*, Reykjavik, Iceland, August 31–September 2, 2008; pp. 1–8.
11. Thorsen, J.E.; Christiansen, C.H.; Brand, M.; Olesen, P.K.; Larsen, C.T. Experiences on Low-Temperature District Heating in Lystrup-Denmark. In *Proceedings of the International Conference on District Energy*, Portorož, Slovenia, March 2011; pp. 1–10.
12. SSE Zero Carbon Homepage. Available on line: http://www.ssezerocarbonhomes.com (accessed on 1 October 2012).
13. Mertoğlu, O.; Dokuz, İ.; Canlan, A.; Bakır, N. Alternatif Enerji Kaynakları ve Düşük Sıcaklıklı Jeotermal Bölgesel Isıtma (In Turkish). *Tesisat Muhendisligi* **2000**, *55*, 52–62.
14. Mertoglu, O.; Bakir, N.; Kaya, T. Geothermal Applications in Turkey. *Geothermics* **2003**, *32*, 419–428.
15. Brand, M.; Thorsen, J.E.; Svendsen, S. Numerical Modelling and Experimental Measurements for a Low-Temperature District Heating Substation for Instantaneous Preparation of DHW with Respect to Service Pipes. *Energy* **2012**, *41*, 392–400.
16. Dalla Rosa, A.; Li, H.; Svendsen, S. Steady State Heat Losses in Pre-Insulated Pipes for Low-Energy District Heating. In *Proceedings of the 12th International Symposium on District Heating and Cooling*, Talinn, Estonia, September 2010; pp. 81–89.
17. Hasan, A.; Kurnitski, J.; Jokiranta, K. A Combined Low Temperature Water Heating System Consisting of Radiators and Floor Heating. *Energy Build.* **2009**, *41*, 470–479.
18. Tol, H.İ.; Svendsen, S. A Comparative Study on Substation Types and Network Layouts in Connection with Low-Energy District Heating Systems. *Energy Convers. Manag.* **2012**, *64*, 551–561.
19. Tol, H.İ.; Svendsen, S. Effects of Boosting the Supply Temperature on Pipe Dimensions of Low-Energy District Heating Networks: A Case Study in Gladsaxe, Denmark. *Energy Build.* Submitted for publication, 2012.
20. Li, H.; Dalla Rosa, A.; Svendsen, S. Design of Low Temperature District Heating Network with Supply Water Recirculation. In *Proceedings of the 12th International Symposium on District Heating and Cooling*, Talinn, Estonia, September, 2010; pp. 73–80.
21. Schmidt, D. New Ways for Energy Systems in Sustainable Buildings—Increased Energy Efficiency and Indoor Comfort through the Utilisation of Low Exergy Systems for the Heating and Cooling of Buildings. In *Proceedings of the 21st Conference on Passive and Low Energy Architecture*, Eindhoven, The Netherlands, September 2004; pp. 1–6.
22. Schmidt, D.; Ala-Juusela, M. Low Exergy Systems for Heating and Cooling of Buildings. In *Proceedings of the 21st Conference on Passive and Low Energy Architecture*, Eindhoven, The Netherlands, September 2004; pp. 1–6.
23. Torío, H.; Schmidt, D. Development of System Concepts for Improving the Performance of a Waste Heat District Heating Network with Exergy Analysis. *Energy Build.* **2010**, *42*, 1601–1609.

24. Tol, H.İ.; Svendsen, S. Improving the Dimensioning of Piping Networks and Network Layouts in Low-Energy District Heating Systems Connected to Low-Energy Buildings: A Case Study in Roskilde, Denmark. *Energy* **2012**, *38*, 276–290.
25. Tol, H.İ.; Svendsen, S. Design of Low-Energy District Heating System for a Settlement with Low-Energy Buildings. In *Proceedings of the 3rd International Symposium on Environmental Management*, Zagreb, Croatia, October 2011; pp. 166–171.
26. Tol, H.İ.; Svendsen, S. Determination of Optimum Network Layout for Low-Energy District Heating Systems with Different Substation Types. In *Proceedings of the 3rd International Renewable Energy Congress*, Hammamet, Tunisia, December 2008; pp. 179–184.
27. Phetteplace, G. *Optimal Design of Piping Systems for District Heating*. U.S. Army Corps of Engineers: Hanover, NH, USA, August 1995.
28. Overgaard, J.; Knudsen, S. District Heating Networks—Choosing the Right Pipe Dimensions. *DBDH* **2006**, *1*, 1–2.
29. General Piping Design. In *Liquid Process Piping*; Genetti, A.J., Ed.; U.S. Army Corps of Engineers: Hanover, NH, USA, 1999; pp. 3-1–3-32.
30. Hodge, B.K.; Taylor, R.P. Piping-System Solutions using Mathcad. *Comput. Appl. Eng. Educ.* **2002**, *10*, 59–78.
31. Brand, M.; Dalla Rosa, A.; Svendsen, S. Performance of Low Temperature District Heating Systems for Low Energy Houses. In *Proceedings of the Annex 49 Low Exergy Systems for High-Performance Building and Communities*, Munich, Germany, October 2010; pp. 174–183.
32. Brand, M.; Thorsen, J.E.; Svendsen, S.; Christiansen, C.H. A Direct Heat Exchanger Unit used for Domestic Hot Water Supply in a Single-Family House Supplied by Low Energy District Heating. In *Proceedings of the 12th International Symposium on District Heating and Cooling*, Talinn, Estonia, September 2010; pp. 60–68.
33. Tol, H.İ.; Svendsen, S. Optimal Dimensioning of Low-Energy District Heating Networks with Operational Planning—Case Study for Existing Buildings. In *Proceedings of the 11th International Conference on Sustainable Energy Technologies*, Vancouver, Canada, September 2012; pp 113–122.
34. Olsen, P.K. Low-Temperature District Heating. Presented at the Heat Network on Study Trip to Denmark and Sweden, Helsingør, Denmark, 14 September, 2011. The WARMTENETWERK Web site. Available online: http://www.koudeenwarmte.nl/files/1317483122Low-temp%20DH%20-%20Dutch%20delegation%2014-09-2011.pdf (accessed on 5 December 2011).
35. Danfoss, 8 Steps-Control of Heating System. Available online: http://www.heating.danfoss.com/Content/61078BB5-1E17-4CA2-AC498A7CAC2BA687_MNU17424997_SIT54.html (accessed on 10 November 2011).
36. Logstor Calculator, version 2.1. Available online: http://calc.logstor.com/ (accessed on 15 April 2012).
37. Dincer, I.; Rosen, M.A. *EXERGY: Energy, Environment and Sustainable Development*, 1st ed.; Elsevier: Burlington, VT, USA, 2007.
38. Nieuwlaar, E.; Dijk, D. Exergy Evaluation of Space-Heating Options. *Energy* **1993**, *18*, 779–790.
39. Elmegaard, B. Exergy Analysis. Presented at the Master Course of "Energy Systems—Analysis, Design, and Optimization", Lyngby, Denmark, May 2010; pp. 1–84.

40. Danmarks Energifremskrivning, 2012 (In Danish). Energi Styrelsen Web site. Available online: http://www.ens.dk/Documents/Netboghandel%20-%20publikationer/2012/Danmarks_energifremskrivning_2012.pdf (accessed on 19 September 2012).
41. Long-Term Interest Rate Statistics for EU Member States, 2012. European Central Bank Web site. Available online: http://www.ecb.int/stats/money/long/html/index.en.html (accessed on 13 November 2012).
42. Nielsen, A.G. Grundfos Holding A/S, Bjerringbro, Denmark. Personal communication, 2011.
43. Chinneck, J.W. Sensitivity Analysis. In *Practical Optimization: A Gentle Introduction*; Chinneck, J.W., Ed.; Carleton University: Ottawa, Ontario, Canada, 2006; pp. 1–8.
44. *Miljødeklaration 2011 for Fjernvarme i Hovedstadsområdet* (In Danish); CTR, Københavns E, and VEKS: Copenhagen, Denmark, April 2012.

BOOK CHAPTER I

Determining the Optimal Capacities of Renewable-Energy-Based Energy Conversion Systems for Meeting the Demands of Low-Energy District Heating, Electricity and District Cooling - Case Studies in Copenhagen and Toronto

Hakan İbrahim Tol[a], İbrahim Dinçer[b] and Svend Svendsen[a]
[a] Department of Civil Engineering, Technical University of Denmark, Kongens Lyngby, 2800, Denmark
[b] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada

Abstract
The paper presents a method for determining the optimal capacity of a renewable-energy-based energy conversion systems for meeting the energy requirements of a given district as considered on a monthly basis, with use of a low-energy district heating system operating at a low temperatures, as low as 55°C for supply and 25°C for return and with additional considerations being directed to supply electricity and cooling. Several optimal solutions with various nominal capacities of the technologies involved were obtained in each of two case studies, one being for the Greater Copenhagen Area, and the other for the Greater Toronto Area. Various climate conditions of the case areas in question caused different observation of nominal capacities for the energy conversion systems considered with single-production and multi-production based on different renewable energy sources.

Keywords: renewable energy, low-energy, district heating, low-temperature, district cooling, energy conversion system, municipal decision tool, exergoeconomy, lifecycle cost, optimization.

1. Introduction

Most countries aim, in their long-term energy plans, to integrate their Renewable Energy (RE) with the energy conversion systems at their disposal. Denmark, for example, aims at becoming totally fossil-fuel-free by the 2050s [1,2]. Ontario in Canada plans to have clean, reliable and cost-effective electrical energy production systems based on renewable energy sources by the 2030s [2]. The aim of lowering the supply temperature in District Heating (DH) systems has been achieved in successive generations of DH technology. The first generation involved use of steam, the second generation of superheated (pressurized) water at around 120°C, and the third generation the use of hot water at around 90°C [3]. Foged [4] found there to be an 18.5% reduction in the heat loss of a Danish DH network when the supply temperature was reduced from 85°C down to 70°C. The fourth generation of DH technology involved use of very low temperatures, such as 55 °C, for supply and 25°C for return, allowing for the use of low-grade (low-quality) heat sources and enabling the efficiency of heat production at plant sites to be improved [3,5-7]. Low-energy DH systems have been shown to be successful in demonstration projects carried out, in Lystrup, Denmark [8-10], in the SSE Greenwatt Way development project in Slough, UK [3], in the Drake Landing Solar Community in Okotoks in Alberta, Canada [3,11], and in Kırşehir, Turkey [12], and in various research studies in this area [7,13-19]. Because of their very large energy-saving potential and the ease of integrating them with virtually any type of heat source, low-energy DH systems are regarded as being the heating infrastructure needed to meet the requirements of the national energy plans of most countries.

1.1. Aim and Objectives

The present study is aimed in particular at determining the optimal capacities for a mixture of energy conversion systems making use of RE sources, which are to supply heat to low-energy DH networks. Hence, the residential heat demands of both space heating and the domestic hot water consumption are considered to be supplied with low temperature supply of 55°C. In view of the improvements in efficiency that are possible with use of multigeneration systems such as cogeneration plants [20] consideration was also given to other forms of residential energy requirements that need to be satisfied for a given district, such as those of electricity and cooling. The objective of this study, therefore, focuses on developing a method based on use of reducing the overall lifecycle costs of a variety of energy conversion systems through determining the optimal capacity of each with an integrated approach of satisfying various forms of energy demand together. Since there is a month-to-month variation in the energy production of various energy conversion systems in the energy demand of various energy types that are dissimilar with respect to each other and to the energy production, the analysis given in this paper was carried out on a monthly basis for a period of a year. The method developed was later employed in two case studies, the one being for the Greater Copenhagen Area in Denmark and the other being for the Greater Toronto Area, ON in Canada.

The method provided in this paper is novel in comparison to the studies described in section 1.2. Its novelty is based on various factors such as (i) the optimization algorithm that determines the optimal capacities to meet three different energy requirements simultaneously while taking into consideration of the monthly variation of the energy generation and of the energy requirement in each energy type considered, (ii) detailed focus on lifecycle cost calculations and also the technical considerations, (iii) waste heat that was involved with the renewable energy sources, and (iv) comparison of the energy conversion systems in the point of exergoeconomic values and the evaluation of the environmental protection compared to the fossil-fuel based energy conversion systems involved in this study.

1.2. Background

Various studies in this area have concerned the integration of RE sources with DH systems and/or with energy-supply decision tools. Lund et al. [21] discussed possibilities of establishing a DH system based solely on use of RE sources, comparing these with (i) the use of existing natural gas supplies and (ii) such alternative individual heating options as micro-CHP systems and individual heat pumps. They emphasized the need of expanding DH networks in stages in the urban areas and use of heat pumps in the rural areas. Sperling and Möller [22] pointed out that expanding DH networks together with the energy savings at residential sites provides results in reduced fuel consumption at heat production sites. Østergaard and Lund [23] described the transformation of the energy infrastructure in the city of Frederikshavn as being based on use of %100 RE for such differing forms of energy requirements as those of electricity, of the heat and fuel demand of industry, and of transportation. Mathiesen [24] analyzed the effects of the use of DH systems on biomass consumption, its being found that the reduced demand for biomass in the heating sector led to an increase in the potential of biomass for other sectors. Weber and Shah [25] developed the tool DESDOP, which assesses the capacity of each energy conversion system to meet the energy requirements in terms of electricity and heating for a given district, such as a town. Niemi [26] discussed a method based on a multi-energy approach to meeting the energy requirements for electricity and heat, one providing a distributed energy solution for each energy form. Ozlu et al. [27] compared various RE-based energy conversion systems with thermodynamic assessment in terms of their ability to satisfy electricity and heat requirements. An extensive review of the literature in this field can be found in [28].

2. System Description

In addition to the matters just referred to, the study was concerned with developing an energy system planning tool being able to determine the optimal capacities of RE-based energy conversion systems (also called as "plant" in this chapter manuscript) based on different primary RE sources available locally, involving different types of production, such as of the single-generation and the multi-generation (poly-generation) type. (The terms involved here, and in connection with this in the remainder of the paper, are based on two reports [28,29]). Since the residential energy requirements and the energy production of each energy conversion system vary over the course of a year, the analyses were carried out for successive monthly periods. More specifically, the method involved consideration of the degree to which, month by month, the energy demands for electricity, for heating (both space heating and the production of hot water for domestic use), and for cooling were adequately met. A black-box representation of each RE source and of the energy conversion systems involved is shown in Figure 1 so as used in [28].

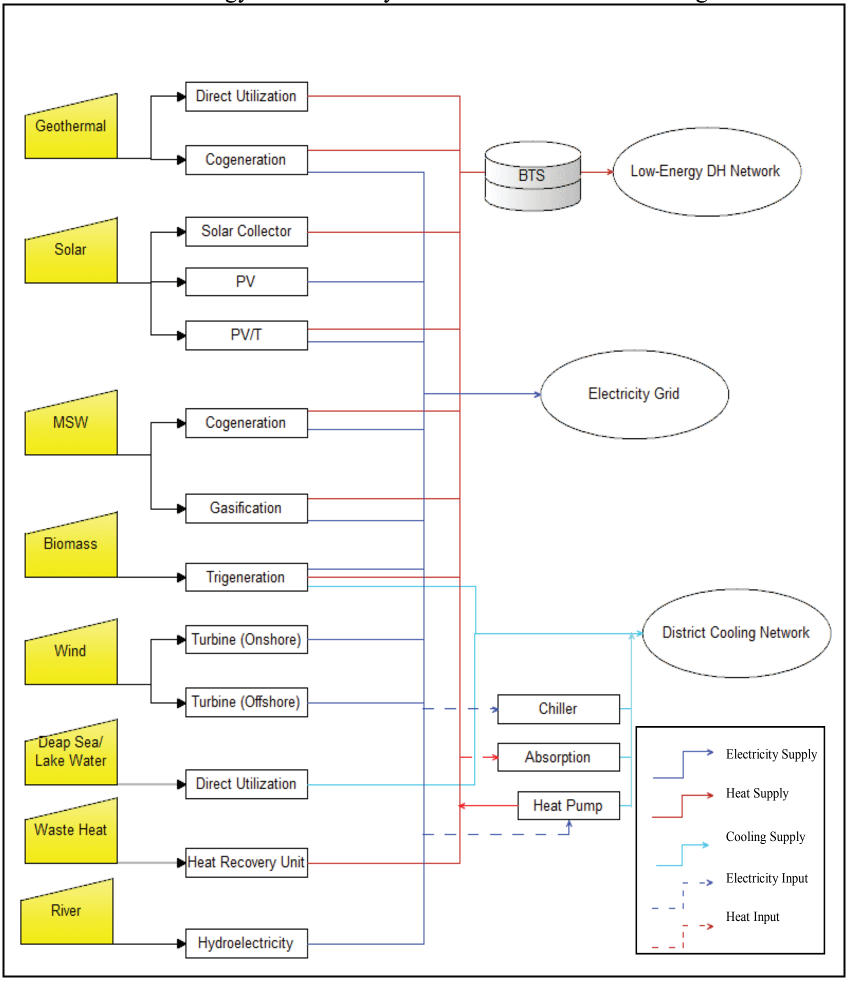


Figure 1. A black-box representation of the RE sources and the energy conversion systems involved.

2.1. Optimization Algorithm

An aim pursued here was to minimize the sum of the lifecycle costs of the various energy conversion systems involved, concerned with production of the various final forms of energy as whole that were needed for satisfaction of the residential energy requirements of different forms selected for study here, those of electricity, heating, and cooling. The decision variable used in the optimization algorithm employed here was defined as the nominal (installed) capacity of each energy conversion system, as shown in the Eq. (1), as being employed in [30].

$$Minimize \sum_{i=1}^{n_i} C_{LCC,i} \text{ with respect to } G_i \quad \text{(as the fitness function)} \tag{1}$$

Subject to the demand constraints

$$P_{e,m} \geq D_{e,m} \quad \forall e = 1, \ldots, n_e \wedge \forall m = 1, \ldots, n_m \quad \text{(as the constraint function)}$$

Subject to the resource availability constraints

$$G_i \leq G_{Max,i} \quad \forall i = 1, \ldots, n_i \quad \text{(as the upper-bound limits)}$$

where $C_{LCC,i}$ is the lifecycle cost and G is the nominal capacity of the energy conversion system I where P and D refer, respectively, to the overall production of the systems as a whole and to the total energy requirement of the district, the subscripts e and m referring to the energy type and to the month studied, respectively. The clarifications provided in paranthesis indicate the terms they refer to, as being used in the optimization solver, which involves use of the Genetic Algorithm (GA) with the commercial software Matlab [31].

2.2. Economic Calculations

The economic calculations performed were based on a lifecycle cost analysis carried out, concerned with investment costs; the Net Present Value (NPV) of future annual costs, such as operating and maintenance (O&M) costs, and of fuel costs; and with salvage costs, which represent the values of the plants at the end of their lifetime, its expression being shown in Eq. (2) [32,33], which excludes any investment grants, tax exemptions, or financial incentives provided.

$$C_{LCC,i} = C_I + \sum_{t=1}^{p} \frac{C_{O\&M} + C_F}{(1+r)^t} - \frac{C_{S,p}}{(1+r)^p} \tag{2}$$

where C is the general symbol indicating the costs, the subscripts I, O&M, F, and S,p referring, respectively, to the investment, to the operating and management, to the fuel, and to the salvage cost at the end of the period p, r referring to the discount rate used in the NPV calculations.

A base period was taken into account in the NPV calculations and in the salvage cost calculations so as to permit a comparison between different types of energy conversion systems to be made. The reason behind this was the considerable diversity found in the economic data pertaining to the different energy conversion systems. The smallest lifetime length was chosen as the base period amongst the range of various lifetimes of the energy conversion systems.

The energy conversion system for which the possible smallest size was regarded amongst the range of lifetimes varying in length was considered to be the base in defining the length of the base period involved. For any of the energy conversion systems that had longer lifetime than the base period as thus defined, the salvage value at the end of the base period was calculated by assuming a linear reduction in the expected value of the plant in question [34]. One should note that an energy conversion system that has a zero salvage value at the end of its lifetime cannot be assumed to have a linear reduction in its salvage value, since a salvaging of it during any period shorter than its lifetime still accounts for its having a zero salvage value.

The specific investment cost (unit cost per nominal capacity) of any energy conversion system becomes smaller as the nominal capacity increases. This is the basic idea behind the economy-of-scale [35,36], being included in determining the investment costs for all of the energy conversion systems. The specific investment costs for all of the plants were formulated in this manner, its expression being given in Eq. (3).

$$C_{I/P_i} = \mathrm{Re}\,g1 \times G^{\mathrm{Re}\,g2} \qquad (3)$$

where the subscript I/P refers to the specific investment costs and G to the nominal capacity of the plant as established, the units employed depending upon the energy conversion system employed, where, for example, the units are in [m^2] for solar systems and in [m^3] for borehole thermal storage. Reg1 and Reg2 are the regression parameters used to calculate the specific investment costs involved with use of an economy-of-scale.

Particular attention was directed at estimates of the costs of the hydroelectric plant, since a different model applies to it, one shown in Eq. (4) [37].

$$C_{\frac{I}{P_{hydro}}} = (1+\xi)\left[\beta_0 \Big/ \left(G_{hydro}{}^{\beta_1} dh^{\beta_2}\right)\right] \qquad (4)$$

where ξ is the factor representing the building facilities required for the hydro-electric plant, dh and G_{hydro} referring to the height of the dam in [m] and the nominal capacity of the hydroelectric plant in [kW].

An extensive literature review was performed for deciding upon the economic data to be used in the study. The cost data employed was obtained from earlier studies involving values from past years, i.e. earlier than the reference year of the study, for which the year 2012 was decided upon, the data being converted to prices which applied that year, use being made here of cost-index factors as given in [38].

2.3. Energy and Exergy Analyses

The energy output, appropriate for a particular energy conversion system was defined in terms of some performance measure, such as the energy conversion efficiency (in accordance with the first law of thermodynamics) and a capacity factor, these being obtained for all systems and electricity-to-heat ratios (commonly expressed as power-to-heat ratio) in a cogeneration plant [39]. Along with the energy output obtained in connection with the energy conversion efficiency of a system, the capacity factor represents the utilization rate of the nominal capacity, this being affected by the maintenance requirements of the energy conversion system, the temporary shortage of the primary source, and the over-dimensioning of the nominal capacity [35,40]. The capacity factors used in the present study were derived on the basis of only the first two factors referred to above, however. The latter of these two is valid for RE sources such as wind and solar energy, which thus differs in terms of the capacity factor rates involved, in accordance with the location of the energy conversion system which has been installed [40,41]. The annual production of an energy conversion system can be calculated by use of the general expression presented in Eq. (5). For cogeneration systems, the electricity-to-heat ratio was employed for determining the shares of each output from the Pe that was obtained, where a 1500 kW energy output together with an electricity-to-heat ratio of 1:2 refers to an electricity output of 500 kW and 1000 kW, as described in [39].

$$P_e = CF_i \times \eta_i \times G_i \times 8765 \qquad (5)$$

where η and CF refer to the energy efficiency and the capacity factor, respectively, of the energy conversion system i. Here, the number 8765 refers to the hours of operation over a period of a year.

An exergy analysis was performed in the study for evaluating the performance of the energy conversion systems, which consisted of various modes of energy production, such as single- and multi-output generation. This is because of the exergy measure providing the common quality level for comparing and uniting various forms of energy at different levels of quality [42]. The performance measures for the technologies involved in the study were compared by means of exergoeconomic analysis concerned with the costs of the exergy produced.

The general equations used in the exergy calculations are given below. Details, if called for, concerning calculations of the exergy values pertaining to each of the energy conversion systems involved are given under the heading of each (see section 2.4).Since electricity is a pure form of energy, the energy value of it was taken as its exergy value. However the exergy value of the heat energy involved was calculated by use of an exergetic temperature factor, as shown in Eq. (6) [7,43].

$$Ex_h = \tau_h \times Q_h \tag{6}$$

where Ex_h refers to the exergy value of the heat energy, which is represented by h. τ_h is the exergetic temperature factor, its expression in the case of heat energy being given in Eq. (7).

$$\tau_h \equiv 1 - T_O / T_h \tag{7}$$

where T refers to the temperature and the subscript O to the outdoor temperature, presented as a reference.

The expression for converting the cooling energy to its exergy value is presented in Eq. (8).

$$Ex_c = \tau_c \times Q_c \tag{8}$$

where Ex_c refers to the exergy value of the energy form cooling, denoted as c and τ_c is the exergetic temperature factor, its expression in the case of cooling being given in Eq. (9).

$$\tau_c \equiv \left|1 - (T_O / T_c)\right| \tag{9}$$

The exergetic efficiency can be calculated for any type of energy conversion system through dividing the overall exergy output by the exergy input, its general expression being shown in detail in Eq. (10). In the present study the exergetic efficiency was calculated on a monthly basis due to the varying outdoor temperature. The seasonal efficiency and/or the monthly variations in the capacity factor were involved in the energy conversion systems being based on the varying availability of the RE source, i.e. the solar system, wind turbines and hydroelectricity plants.

$$\Psi = Ex_{out/s} / Ex_{in/s} \tag{10}$$

where Ex refers to the exergetic value of the energy, the subscripts in, out, and /s representing the input, output, and the plurality of the energy forms, respectively.

The exergoeconomic calculations were based on the idea of the cost of exergy produced, the expression for it being given in Eq. (11) [44].

$$C_{Ex} = C_{LCC,i} / Ex_{out/s} \tag{11}$$

2.4. Environmental Assessment

Despite the well-known idea of RE-based technologies being totally clean, they nevertheless involve the risk of harming the environment if appropriate precautions are not taken. For example, manufacturing PV cells involves an environmental threat in the form of the fossil fuels and the hazardous materials required for their manufacture. Another concern has to do with the exploitation of the geothermal energy sources due to the possible release of underground gases in the drilling of wells and due to the metals, gases, and minerals contained within the geothermal medium if reinjection of the waste geothermal medium is not employed after its heat content has been transferred to the DH network or to the plants producing electricity [45]. The present study, however, is comparative in this respect, involving an investigation of the environmental impact of fossil-fuels and the greenhouse gas emissions they can release [46]. Cogeneration was considered as a possibility for the energy conversion systems based on fossil-fuel sources, their electricity-to-heat ratios being assumed to correspond to the electricity-to-heat profiles of the case areas of concern in the study, the monthly assessments of energy demands regarding production of electricity and heat, ranging from 0.15 to 2.55 (Table 1).

Table 1. The overall efficiencies and emission factors considered for the fossil-fuel based energy conversion systems

Energy Conversion Systems	Fuel Type	Overall Efficiency [-] (values taken from [47])	Emission Factors [kg/MJ] (values taken from [48])
Back-pressure steam turbine	Coal	88%	9.25E-02
Extraction-condensing steam turbine	Coal	70%	9.25E-02
Gas turbine	Natural Gas	80%	5.03E-02
Reciprocating engine	Propane	80%	5.97E-02

3. Energy Conversion Technologies

In this section, the large-scale energy conversion technologies involved in the study are described briefly and the exergetic calculations specific to each technology involved are presented. No comprehensive overview of the renewable energy sources available or of the relevant energy conversion technologies is undertaken, but an introduction to what is to be taken up in this respect is provided in order to specify clearly the energy conversion systems the study takes up. A review of energy conversion technologies of relevance here is to be found in [20,49].

3.1. Solar Energy

The utilization of solar energy today used by humankind already for many millenniums, evolved through its applications in passive heating, burning mirrors, and bathing, for example [50] and evolved to its use in recent technologies such as Photovoltaic (PV) cells, solar thermal collectors, and hybrid PV/T collectors [51,52]. Solar energy from the sun shows a variation in terms of obtainability and of supply rate, both on a diurnal and on a yearly basis. The specific energy outputs of PV cells, of solar thermal collectors, and of hybrid PV/T collectors can be determined by means of the commercial software “Polysun”, which is concerned with the differing of solar radiation in accordance with the specific location on the earth involved, its also taking account of the local weather conditions (e.g. the frequency of cloudy days and the amount of daylight), the inclination of solar light, and the thickness of the atmospheric layer [53].

The exergy input gained by solar energy Ex_{Sol} was defined using the Petela theorem, its expression being given in Eq. (12) [54].

$$Ex_{Sol} = A_{SC} \times I_{SR} \times \left[1 - \frac{4}{3}\frac{T_O + 273}{T_{Sol}} + \frac{1}{3}\left(\frac{T_O + 273}{T_{Sol}}\right)^4\right] \quad (12)$$

where A_{SC} refers to the area of the solar (thermal) collector or of the solar (PV) cell [m2] (according to the where the equation was employed), I_{SR} indicates the overall intensity of solar radiation for a given period (in this study evaluation was monthly) [Wh/m2], and Tsol is the temperature of the sun, defined as being 6000 K [49,52].

3.1.1. PV Cells

PV cells involve the technology of converting solar photons to electricity energy. Those absorbed photons not utilized by the PV cell cause an increment in the temperature of the PV cells and as a consequence a reduction in the energy conversion efficiency [55]. The expression for calculating the electrical output of the PV system is shown in Eq. (13) as a function of the PV cell area.

$$W_{PV} = A_{SC} \times \eta_{PV} \times I_{SR} \times CF_{PV} \quad (13)$$

where W_{PV} is the electrical energy produced by the PV cells [Wh], and η_{PV} is the electrical efficiency of the PV cells [-], their performance as a function of cell temperature T_{Cell} [°C] being given in Eq. (14) [56,57].

$$\eta_{PV} = \eta_0\left[1 - tdc \times \left(T_{Cell} - 25\right)\right] \quad (14)$$

where η_0 is the electrical efficiency of the PV cells under standard test conditions [-] and *tdc* is the temperature degression coefficient of the PV cells [1/°C] [58].

3.1.2. Solar Thermal Collector

The expression for calculating the thermal output of a solar thermal collector is given in Eq. (15) as a function of the solar collector area and the collector efficiency [59].

$$Q_{STC_h} = A_{SC} \times \eta_{STC} \times I_{SR} \times CF_{STC} \quad (15)$$

where Q_{STC} is the heat accumulated by means of the solar thermal collector [Wh] and η_{STC} is the collector efficiency [-], its expression being given in Eq. (16).

$$\eta_{STC} = \eta_O - c_1 \times x - c_2 \times {x^2}/{I_{SC}} \quad (16)$$

where η_O is the optical efficiency and x is the characteristic variable [m^2K/W], the definition of it being given in Eq. (17), c_1 and c_2, respectively, being the first- and second-order heat loss coefficients, defined as being 3.05 [W/m^2K] and 0.0051 [W/m^2K^2], respectively, for flat-plate solar collectors, as being used in studies [60,61].

$$x = {(T_R - T_0)}/{I_{SR}} \quad (17)$$

The exergetic efficiency of the solar thermal collector can then be calculated by means of Eq. (10).

3.1.3. PV/T

The output of a PV system is directly proportional to the solar radiation, although the efficiency decreases slightly with increasing temperature [36]. The defect caused by the effect of the increasing temperature of the cells on the efficiency of electricity output can be avoided by use of

hybrid PV/T cells in which the heat accumulated by the cells is swept away by the air or water circulating through the cells, this producing heat as a useful energy output [62-64].
The detailed application of the Eq. (10) is shown in Eq. (18), which serves as an example of how cogeneration systems of other forms function.

$$\psi_{\frac{PV}{T}} = \left(W_{\frac{PV}{T}} + \tau_h \times Q_{\frac{PV}{T_h}}\right) \Big/ Ex_{Sol} \tag{18}$$

3.2. Wind Energy

Earlier applications of harvesting the kinetic energy of wind involved use of windmills, which led then to the wind turbine technology of today in which large-scale use of wind farms produce electricity energy as a usable energy output [65]. Wind turbine technology is based on the principle of converting the kinetic energy of wind into rotation energy, which in turn is converted into electrical energy. In addition to the wind speed, which is the major factor affecting the efficiency of the system, there are numerous other factors that need to be taken into consideration, such as the direction of the wind, the permanence of the wind speed, how plane the site area is, and the air properties of the medium [66,67]. These factors need to be considered in defining the location and the properties of a wind farm at a given establishment site.

The theoretical conversion efficiency of any wind turbine cannot exceed the Betz Limit, which is a power coefficient with a magnitude of 0.593 [68]. The expression for calculating the electricity output of a wind turbine on this basis is given in Eq. (19).

$$W_{Wind} = {}^1\!/_2 \times \rho \times A_S \times v^3 \times C_p \tag{19}$$

where ρ is the air density, A_S is the area being swept, v is the wind speed, and C_p is the power coefficient.
Wind farms can be located either on land (on-shore) or out at sea or in fresh water (off-shore), both of these having various constraints that are of major concern for designers. Environmental defects can be encountered in onshore applications in the form of noise pollution or deaths of birds or bats during operation. Also, it is difficult to apply an economy-of-scale to on-shore wind turbine systems due to possibly differing costs of land because of there being a variety of landlords to deal with, the costs of land often representing a sizeable share of the overall costs. The frequent deficiencies of on-shore establishments can be avoided by use of off-shore installations, for which the capacity factors are often larger, the wind speed more stable and the disadvantages for humans less than for on-shore installations [69].

The exergy value of the wind energy serving as input to a wind turbine is equal to its kinetic energy prior to its passing through the turbine-swept area, the expression for it being given in Eq. (20). Further information regarding this can be found in the studies [44,70].

$$Ex_{Wind} = {}^1\!/_2 \times \rho \times A_S \times v^3 \tag{20}$$

3.3. Geothermal Energy

Geothermal energy, which is the domestic source of thermal energy in the form of hot water or steam found in the crust of the earth, is widely utilized, for two types of applications in particular: (1) production of electricity and (2) heat production. The temperature gradient of the geothermal energy source varies according to the location at which it is extracted, its ranging from 30 °C/km to 100 °C/km in size [71].

The quality of a geothermal resource, in the wellhead site, can best be described by use of the specific exergy index (SExI), defined in study [72].

3.3.1. Direct Utilization with use of DH systems

Low-quality SExI sources can be exploited by means of DH systems. Note here that the exergy level is always evaluated with respect to a reference environment (i.e. dead state). The exergetic efficiency varies with changes in the temperature of the reference (dead) state adopted for use in the calculations. Since in study [73], however, the exergetic efficiency was found to range from 45.5% to 47.5% when the temperature of the reference state ranged from 0 °C to 25 °C, hence the reference state temperature effect was not taken account of in the present study.

3.3.2. Indirect Utilization with Geothermal Power Plants

There are three types of plants commonly used in electricity production sourced by geothermal energy; the type employed depending upon the type of content of the brine present in the reservoir, as shown in Table 2.

Table 2. Detailed description of the geothermal power plant technologies employed [74-76]

Power Plant Technology	Geothermal Source Content	The base of the technology
Dry Steam	Vapor dominated	Direct utilization of the steam from the source
Flash	Two phase mixture of liquid and vapor	Deriving the steam by means of a steam separator
Binary	Liquid Dominated	Production of steam by means of a heat exchanger

(i) Dry steam plants are erected in fields that contain a reservoir, pure steam from it being used directly in a turbine [77]. The regression equation for the dependence of the exergetic efficiency on the brine inlet temperature is given in Eq. (21), which is based on results of study [78].

$$\psi_{DSP}(T_W) = -3.175 \times 10^{-6} \times T_b^{2} + 1.789 \times 10^{-3} \times T_b + 0.347 \quad (21)$$

(ii) Flash plants are used in cases in which the geothermal source is provided with a mixture of steam and hot water of high-enthalpy. In plants of this type the steam is extracted from the mixture during a flashing process. The maximum capacity of a plant of this type is one of up to 45 MWe [75]. The exergetic efficiencies of plants of this type with single flash ranges of between 20.5% and 43.35% were determined in studies [74,79]. The regression equation of the exergetic efficiency as dependent upon the reservoir temperature is given in Eq. (22) for plants operating on a single-flash basis, in Eq. (23) for plants operating on a double-flash, and in Eq. (24) for plants operating on a triple-flash basis, the equations being derived from the data obtained in the study [78].

$$\psi_{SF} = -1.050 \times 10^{-6} \times T_b^{2} + 1.305 \times 10^{-3} \times T_b + 5.335 \times 10^{-2} \quad (22)$$

$$\psi_{DF} = -2.945 \times 10^{-6} \times T_b^{2} + 2.337 \times 10^{-3} \times T_b - 1.053 \times 10^{-2} \quad (23)$$

$$\psi_{TF} = -3.956 \times 10^{-6} \times T_b^{2} + 3.016 \times 10^{-3} \times T_b - 7.664 \times 10^{-2} \quad (24)$$

(iii) Binary plants are used around the world for fields having liquid dominated brine in low- and medium-enthalpy, which can easily be reached in shallow depths. They operate with use of a binary working fluid with a low boiling point, such as R123a, R600a, and R152a [80]. The exergetic efficiency of binary plants was found to range in level between 16.3% and 29.6% according to the studies [49,81-83]. The exergetic efficiency was found to be improved to a level ranging between 20% and 40% with use of advanced improvements in the energy conversion cycle in studies [84,85]. In the present study a regression equation for the exergetic efficiency of a binary power plant dependent on the brine temperature was derived from the data given in study [86], as can be seen in Eq. (25).

$$\psi_B = -1.339 \times 10^{-6} \times T_b^{2} + 2.673 \times 10^{-3} \times T_b - 9.271 \times 10^{-3} \quad (25)$$

The exergetic efficiency of each plant type is shown in Figure 2, the data regarding the binary types being taken from [86] and regarding the flash and dry steam types from [78].

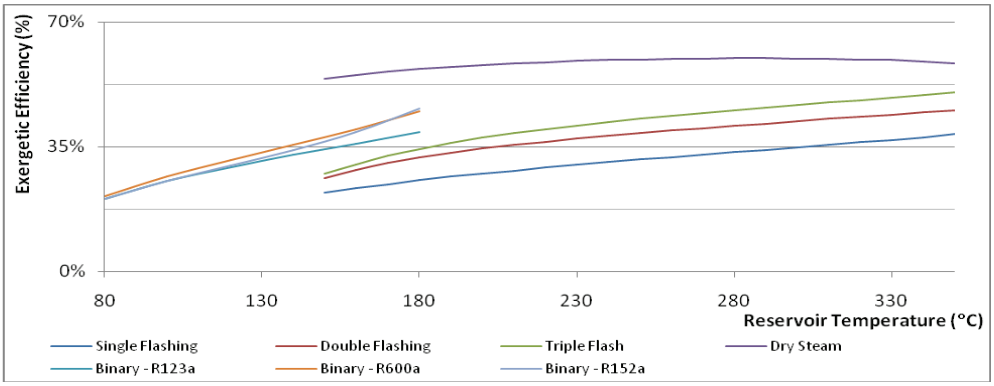


Figure 2. Illustration of the dependency of the exergetic efficiency on the reservoir temperature, given for each plant type (data taken from [78,86])

3.3.3. Indirect Utilization (Cogeneration Plants)

The efficiency of utilizing the source involved can be improved by means of multi-generation, which has been investigated thus far in cogeneration plants and been shown to be the case in recent studies carried out at tri-generation plants [80,87]. In a geothermal power plant, brine reinjection results in the major part of the overall exergy loss at a reasonable temperature that is suitable to be utilized in DH systems and can be further utilized in heating systems such as in greenhouse heating and drying processes [80,88]. Accordingly, in the present study a cogeneration plant based on use of geothermal sources was considered, one involving the extraction of heat from the brine just prior to its reinjection back into the ground [89].

The exergetic efficiency of a geothermal cogeneration plant producing electricity and heat for DH was found to be 44.1% for a binary power plant that was defined as producing 10 MW_e & 13.5 MW_{th} through use of a geothermal source at a temperature of 165 °C [90]. An increase in the exergetic efficiency of the cogeneration plant from 38% to 60% coupled with an increase in the inlet temperature of the brine from 140 °C to 170 °C was observed. Heberle and Brüggemann [77] studied the change in the overall exergetic efficiency of a geothermal cogeneration plant with a heat production unit coupled in series and in parallel to an Organic Rankin Cycle of the plant that utilized a geothermal source with a capacity of 4208 kW_{Ex}. The electricity-to-heat ratio in terms of the exergy connected with the geothermal cogeneration plant was given as 887.70 kW_e/968.92 kW_{Ex} in the case of parallel coupling and as 1219.99 kW_e/968.92 kW_{Ex} in the case of series coupling, the net electricity production being given as 1446.40 kW_e with use of the same configuration but this time in the geothermal power plant, the rate of exergy input from the geothermal source being the same in each case. They investigated the overall exergetic efficiency of the plant by changing the inlet temperature of the brine within the range of between 80 °C and

180 °C. The overall exergetic efficiency of the geothermal cogeneration plant with use of isopenthane as the working fluid was found to change between 50.7% and 42.1%; and between 55.5% and 52.1% in the case of the parallel and of the series circuit, respectively.

3.3.4. Borehole Thermal Energy Storage

The excessive production of heat during the summer months stemming from the solar thermal collector systems and from the waste heat captured from supermarket chiller systems results in the need of storing the excessive heat which is generated during the summer months and using this stored heat during the winter months to supply the low-energy DH network. Borehole thermal energy storage systems consist of aggregated circulation lines of boreholes underground in which the hot water produced during the summer (for example by use of a solar collector field) is supplied to the circuit of the boreholes to store the heat as radial thermal stratification in the ground stratums [91,92].

The exergetic efficiency of a borehole thermal energy storage system under set boundary conditions, quite apart from the heat production facility involved, was defined as shown in in Eq. (26) .

$$\psi_{BHTS} = {Ex_{DisCh}}/{Ex_{Ch}} \tag{26}$$

where the subscripts *Ch* and *DisCh* refer, respectively, to the charged heat in the borehole thermal storage system and the heat discharged from it during the winter period.

3.4. Biomass

Biomass, with its history in humankind dating back to the times when the fire was first discovered, still has its role through its properties of being renewable and easy to reach, and its ability to take the place of coal in current fossil-fuel-based technologies [93]. Along with its advantages, there are certain disadvantages of it connected with the increasing demand for biomass within the DH sector as a fuel source for heat production as well as in other sectors, such as the chemical sector and additional industrial sectors [24][24,94], loss of soil nutrients, and soil erosion occurring due to rainfall after the harvesting of biomass from the field [95]. Municipal solid waste (also called as MSW) can be regarded as a totally renewable after replacement of the fossil-fuel based plastics it contains by bio-based polymers [96]. Biomass energy conversion technologies were considered in the present study, together with three different technologies, those of cogeneration via the incineration and gasification of municipal solid wastes and the trigeneration sourced by the biomass. More regarding energy conversion systems in this area can be found in [97].

3.4.1. Municipal Solid Waste Incineration

Municipal solid waste, amounting to 3.5 million tonnes per annum (tpa) in Denmark, has a share there of 20% in the overall DH heat supply and of 4% in the overall electricity supply [98]. Despite their being capital-intensive, municipal solid waste incineration plants (also called as waste-to-heat plants) are an efficient and environment friendly way of managing this waste, as compared with the alternative waste management method of land-filling, when special attention is directed at removing from waste, prior to its incineration, such substances as heavy metals that can cause toxic air emissions [99].

In the present study, municipal solid waste incineration with the cogeneration production of electricity and heat with energy conversion efficiencies of 15% and 43%, respectively, was examined [100].

Computing the exergetic efficiency of the incineration was based on the use of Eq. (10), here as the ratio of the sum of the electricity production and of the exergetic value of the heat energy to the exergy rate of the fuel employed, the expression for this being given in Eq. (27) .

$$\psi_{MSW} = \left(W_{MSW} + \tau_h \times Q_{MSW_h}\right) \Big/ Ex_{fuel} \tag{27}$$

where Ex_{fuel} is calculated by multiplying the lower heating value of any biomass product by the exergy coefficient factor for it, as described in detail in [39,101].

3.4.2. Municipal Solid Waste Gasification

The gasification of municipal solid wastes into syngas (or some other form of gas) for use as an energy source in a combined-cycle gas turbine has the advantage of providing greater efficiency in the production of electricity than incineration, while having lesser efficiency in the production of heat[100,102]. In the present study the use of municipal solid waste gasification in the cogeneration production of electricity and heat was found to have energy conversion efficiencies of 27% and 24%, respectively [100]. The exergetic evaluation of an energy conversion system of this type can be carried out with use of the same equation as that for municipal solid waste incineration plants, namely Eq. (27).

3.4.3. Biomass Sourced Trigeneration

This energy conversion system was considered with trigeneration production type, involving the simultaneous production of three forms of energy, that of electricity, of heating, and of cooling. The trigeneration configuration based on utilizing an Organic Rankin Cycle for production of electricity during which the waste heat produced being recovered by use of a heat exchanger employed for heat production and/or being utilized by an absorption chiller for the production of cooling medium, as described in [103]. Maraver et al [104] studied trigeneration configurations having different layouts in energetic and exergetic terms. The expression for calculating the exergetic efficiency of a trigeneration based on the use of biomass is shown in Eq. (28).

$$\psi_{BT} = \left(W_{BT} + \tau_h \times Q_{BT_h} + \tau_c \times Q_{BT_c}\right) \Big/ Ex_{fuel} \tag{28}$$

3.5. Waste Heat

Industrial waste heat (also termed surplus heat) occurs in part due to the inefficiencies of the equipments employed, in part to the limitations of the thermodynamic cycle, heat of this type possessing strong potential for use either in increasing the efficiency of the industrial process or in producing usable energy forms that can be utilized in industrial plants, for example for capturing the heat from the exhaust gas of a boiler by means of a heat recovery exchanger unit in order to supply heat to the DH network. It is suggested, however that, re-utilizing the recovered high-quality waste heat in the same industrial cycle is suggested first before looking for heat recovery for producing usable energy forms for other applications [105-107]. The quality of the waste heat varies in terms in terms of the industrial process and the chiller equipment involved, its thus determining the type of the heat recovery equipment to be employed and the usable energy form produced [107,108].

3.5.1. Heat Recovery

Low-quality forms of waste heat can be connected to a local DH network, either directly or indirectly, and be boosted to a high level of quality there [109]. A successful example of utilizing waste heat from industry is that of a project in the refining industry in Sweden which has been in operation since the 1970s. The waste heat of 543.8 GWh_{th}/year recovered from two refineries with production capacities of 11 Mtons/year and 6 Mtons/year, respectively, was utilized in the

DH systems in Göteborg and in Lysekil, this providing savings in emissions corresponding to 152,400 tons of CO_2 [110]. Werner [99] described the Swedish heat recovery factors that can be used for determining the waste heat potential of different large-scale industrial sectors (see [111] for further details). In the present study attention in regard to industrial waste heat was directed at recovering the condensing heat of supermarket refrigeration, which is considered of being boosted with the aid of a heat pump, details of this and success stories regarding its use being given in [112-114]. Since waste heat recovery was considered to be beneficial due to the saving of the energy that would otherwise be lost, the cost of the waste heat that regards to the cost of the input energy consumed in the refrigeration cycle was not considered in the analysis carried out in the present study. The exergy value of the heat recovered can be calculated with use of the expression given in Eq. (29).

$$Ex_{Gain} = (\dot{Q}_{DH} \times \tau) / \eta_{HR} \tag{29}$$

where Ex_{Gain} refers to the exergy gain [kW] achieved by the implementation of the heat recovery unit, which has a recovery efficiency of η_{HR} [-], assumed to be 0.92 based on the studies of [106,115].

3.5.2. Hybrid Heat Pumps

Another energy conversion system, one involving use of large-scale hybrid heat pump technology and able to produce heating and cooling simultaneously was considered, its successful application can be seen in detail in the studies [91,116]. The exergetic efficiency of such systems can be given in terms of either of two different modes of operation, the one being production of heating alone (single-production), as shown in Eq. (30), and the other being the co-generation of heating and cooling, as shown in Eq. (31). In the present study the co-generation operation was considered for the summer period and single-production for the winter period.

$$\psi_{HHP_s} = \left(\tau_h \times Q_{BT_h}\right) / W_{HHP_s} \tag{30}$$

$$\psi_{HHP_c} = \left(\tau_h \times Q_{BT_h} + \tau_c \times Q_{BT_c}\right) / W_{HHP_c} \tag{31}$$

3.6. Hydroelectric Plants

Use of hydroelectric plants is an efficient way of producing electricity, permitting rapid response to sudden variations in amounts of electricity required, through taking advantage of the potential energy of a water body gathered by storing of river water behind a dam [117]. A minimum rate of flow on the river in question may be required for aesthetic reasons because of the attractiveness of the region for tourists and/or due to the additional requirements for agricultural fields and/or for urban clean water supply [117,118]. The exergetic efficiency of a hydroelectric plant is given as 85% – 95%, which is the same as the energetic efficiency, as shown in studies [118,119]. The monthly capacity factor for a small-scale hydroelectricity plant also varies, as can be seen in Figure 3 [47] (valid for the northern hemisphere). In the present study, small-scale use of hydro-electric plants was considered, in view of the fact that their large-scale use is already working in a highly satisfactory way in the Niagara Falls [118] as well as in other powerful rivers around the world.

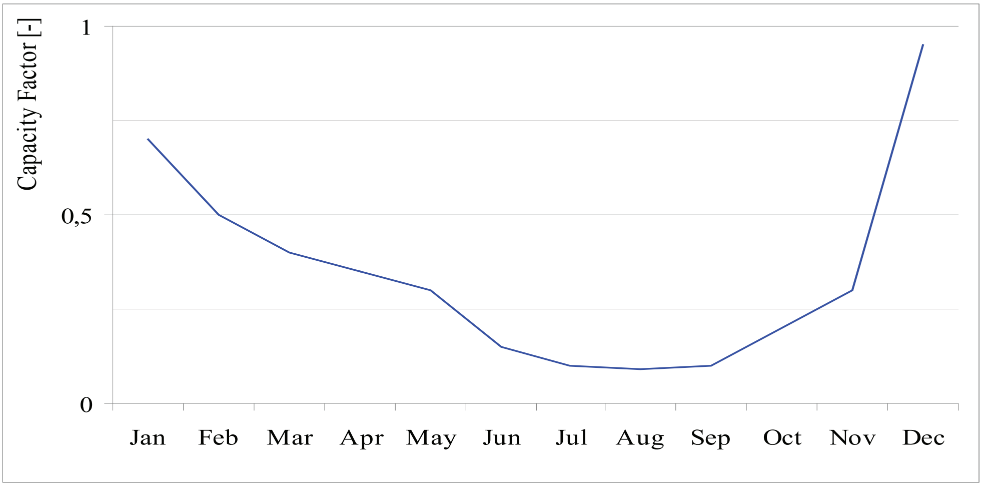


Figure 3. An illustration of the variation in capacity factor for the hydroelectricity production [37]

3.7. Cooling

Districts exposed both to very cold winter periods and to hot summer periods need to be considered, the district energy systems involved consisting both of district heating and of district cooling distribution lines, as can be seen in the case of Toronto, Canada [120]. Compared with that, regions having short summers and lesser requirements regarding district cooling can be considered of having district cooling network for the commercial buildings, as can be seen in Copenhagen, Denmark [121,122]. For both types of climatic conditions, the cooling energy requirements were considered to be supplied by use of a district cooling network, which operates according to the same principles as a district heating network, but involves chilled water instead of hot water being circulated through the network as the energy carrying medium [123]. The present study deals with three different energy conversion technologies: that for the generation of cooling energy alone, such as in the case of compressor-driven chillers, that of absorption chillers, and that involving free cooling, the exergetic evaluations of these being given in detail below.

3.7.1. Free Cooling

Free cooling is an economical way of producing chilled water, its involving exploiting of naturally-chilled reserves that can be found in the depth of such bodies of water as seas, lakes, and rivers [123,124]. Also, replacing conventional individual cooling systems with a district cooling system, its base load provided mainly by free cooling, provides a great saving in the peak electricity consumption [125].

For a free cooling system, as being similar in principle to the direct utilization of geothermal energy on the basis of its supplying of heat to a DH system, the expression of exergetic efficiency can be re-arranged to assume the simple form shown in Eq. (32).

$$\psi_{FC} = \tau_c \times Q_{FC} / W_{FC} \quad (32)$$

3.7.2. Compressor Chillers

The variation of water temperature in the case of utilizing free cooling or peak cooling requirements can be compensated by means of large-scale applications in order to improve the security of the supply in district cooling systems [125]. Large-sale compressor chillers are considered in the present study with having Coefficient of Performance (COP) ranging from 4 to 5 [123].

$$\psi_{CC} = \tau_c \times Q_{CC} / W_{CC} \qquad (33)$$

3.7.3. Absorption Chillers

Another type of equipment to be used for increasing the security of supply in district cooling systems can be referred to absorption chillers. They are driven by the heat source to produce the cooling energy needed (directly fired options of this sort are not considered in the present study). The heat source for absorption chillers can be the waste heat recovered from the industrial processes taking place or from the cogeneration facilities present that have low-cost surplus heat available. Although the COP of an absorption chiller is smaller than that of a compressor chiller, its consumption of electricity is significantly lower for absorption technology than for compressor chillers [123].

4. Economic Data

Indicative economic data was collected for the purpose of forming a rational basis for comparing different energy conversion technologies considered in the study, their values being given in Table 3 with reference to their being used to derive the formulation parameters employed and to define the economic data that is reasonable to use for comparison purposes to be used by the optimization algorithm. Some assumptions were included in defining the cost data which, together with the assumptions, in a base manner depends on the refences indicated in Table 3 to form functions for economic calculation in the optimization as a rational basis for comparing different energy conversion technologies. The values are given at Table 3 together with the other economic data used in the calculations, such as the maximum capacity permitted for use of Eq. (3) and the ratio of the value of O&M to the salvage value, both of them given as ratio to the investment costs.

Table 3. **The economic data used in the life cycle cost analysis, the values taken from references being given in the last column**

Energy Conversion Technologies	Reg1	Reg2	Output Unit	Maximum Capacity Limit*	Unit of Capacity	Ratio ($C_{O\&M}$ to C_I)	Ratio (C_S to C_I)	Lifetime	References
PV	8.635E+04	-2.951E-01	€/m^2	2.0E+08	m^2	0.6%	10%	20	[64,126-128]
PVT	1.243E+05	-2.951E-01	€/m^2	2.0E+08	m^2	1.9%	10%	30	[62,126,127]
SC	8.557E+03	-2.010E-01	€/m^2	2.0E+08	m^2	4.0%	7%	20	[126,129,130]
Wind (OnShore)	2.656E+03	-1.091E-01	€/kW†	7.8E+02	MW	8.3%	20%	20	[36,126,131-133]
Wind (OffShore)	2.257E+03	-5.053E-02	€/kW†	1.3E+03	MW	5.1%	20%	20	[36,126,131,132]
BTS	8.376E+03	-5.474E-01	€/m^3	2.8E+04	m^3	7.0%	0%	50	[36,134,135]
Geothermal - Direct	3.399E+03	-9.428E-01	€/kW†	5.0E+01	MW	2.5%	57%	25	[80,135-138]
MSW - Incineration	4.864E+04	-3.716E-01	€/tpa	6.0E+05	tpa	7.0%	10%	30	[36,100,126]
MSW - Gasification	3.847E+04	-3.716E-01	€/tpa	6.0E+05	tpa	11.5%	10%	25	[100,126]
Biomass	3.119E+04	-3.411E-01	€/tpa	6.6E+04	tpa	6.0%	25%	30	[103,139]
Hydroelectric	β_0=3300, β_1=-1.22E-01, and β_2=-1.07E-01‡		€/kW	2.0E+03	kW	5.0%	0%	20	[140-142]
Chiller	4.967E+02	-2.384E-02	€/kW	5.0E+04	kW	10.9%	5%	23	[143-145]
Absorbtion	5.549E+02	-2.384E-02	€/kW	5.0E+04	kW	16.8%	5%	23	[143-145]
Free Cooling	1.651E+03	-9.428E-01	€/kW†	2.0E+02	MW	3.6%	57%	25	[125,144,146]
Heat Pump	6.354E+02	-2.384E-02	€/kW	5.0E+04	kW	0.8%	10%	25	[36,116,147,148]
Heat Recovery	5.777E+02	-2.384E-02	€/kW	7.5E+02	kW	8.0%	10%	25	[112,149]

* The maximum capacity limits were defined on the basis of the maximum capacity available as found in the literature and/or of the application limits of the economy-of-scale expressions.
† Unit conversions must be included together with the multiplication of specific cost and an installed capacity i.e. [MW]x1000x[€/kW]
‡ The equations connected with these parameters are given in section 2.2.

Special focus was given to an expression for the investment cost of geothermal systems which was derived by means of cost breakdown method i.e. surface cost as a function of the nominal capacity and subsurface cost as a function of the depth of the geothermal pipeline that is dependent on the temperature gradient of the area in focus.

Evaluation of the costs connected with geothermal utilization can be undertaken, involving cost breakdowns into such as: (i) subsurface costs, including exploration and drilling (C_{subS}), and (ii) surface costs (C_{surf}), which vary in the case of different power plants and cogeneration plants, and direct utilization, all of them using the same Eq. (34) [80,150]. A regression equation for calculating the subsurface costs (well costs) was derived by use of data involved in cost index conversion, a factor of 1.8 being applied for the period from 2004 to 2012, the data being taken from the study [151] and the cost data being based on [38,152].

$$C_{Geo} = C_{surf} + C_{subS} \tag{34}$$

$$C_{subS} = 1.934 \times 10^{-7} \times d^2 + 1.664 \times 10^{-3} \times d + 0.380 \tag{35}$$

C_{subS} [M$'12] is the drilling costs as a function of the depth d in [m]. In the appendix here, $ refers to Canadian Dollars (CAD).

Surface costs are defined in accordance with the power plant technology adopted, which is defined in accordance with the properties of the brine found in the area in question. Regression equations as a function of the brine inlet temperature were derived for calculating the capital costs of geothermal power plants involving different technologies, with use of data provided in the studies [75,153-157].

$$C_{C-B} = 1.115 \times 10^{-1} \times {T_{bi}}^2 - 4.031 \times 10^{+1} \times T_{bi} + 5.104 \times 10^{+3} \tag{36}$$

where C_{C-B} refers to the specific capital costs of the binary geothermal power plant [$/kW$_e$] as a function of the brine inlet temperature T_{bi} [°C].

$$C_{C-SF} = -3.704 \times T_{bi} + 2.338 \times 10^{+3} \tag{37}$$

where C_{C-SF} refers to the specific capital costs of a single-flash geothermal power plant [$/kW$_e$].

$$C_{C-DF} = -3.974 \times T_{bi} + 2.336 \times 10^{+3} \tag{38}$$

where C_{C-DF} refers to the specific capital costs of a double-flash geothermal power plant [$/kW$_e$].

$$C_{C-DS} = -2.091 \times 10^{+1} \times T_{bi} + 7.788 \times 10^{+3} \tag{39}$$

where C_{C-DS} refers to the specific capital costs of a dry steam geothermal power plant [$/kW$_e$].

$$C_{C-DU} = 1.007 \times 10^5 \times \dot{Q}^{0.4225} \tag{40}$$

where C_{C-DU} refers to the specific capital costs of a heat production plant for the direct utilization of geothermal sources [$/MW$_{th}$], the regression being derived from data provided in[136] and $\dot{Q}$ is the nominal capacity in terms of the heat demand of the district.

5. Case Studies

The method described as defining the most economically optimal solution for supplying the mixture of renewable energy sources to satisfy the energy requirements of a particular district, as referred to in section 2.1 was carried out in two case areas of differing climatic conditions, the one being the Greater Copenhagen Area (GCA), and the other the Greater Toronto Area (GTA). The heating- and cooling-degree-days [158] for these two areas are shown in Table 4 and Table 5, respectively, to indicate the climatic conditions there.

Table 4. Heating-Degree-Days with respect to the base temperature of 15°C [158]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GTA	404	481	414	254	214	32	7	0	1	29	136	310
GCA	320	389	439	280	254	104	55	9	7	52	178	252

Table 5. Cooling-degree-days with respect to the base temperature of 20°C [158]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GTA	0	0	0	2	1	31	75	145	89	27	0	0
GCA	0	0	0	0	0	6	1	10	12	1	0	0

In the present study we took into consideration the avoiding of individual heating or cooling systems that run on a source of energy of some other form, such as an individual heat pump system (air conditioner) that produces cooling energy with use of electricity. The indicative data representing the energy requirements considered in the study, such as heating, electricity, and cooling are shown in Table 6 and in Table 7, for GCA, and GTA, respectively.

Table 6. The residential energy requirements for GCA [121,159-161]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat	1392	1308	1274	771	536	386	352	268	402	754	1107	1358
Electricity	850	767	787	661	680	636	630	685	689	726	751	786
Cooling*	0.77	0.72	0.80	0.99	0.99	1.27	1.65	1.65	1.10	0.69	0.69	0.69

*The residential cooling for GCA was found to be excessively small but the commercial requirement for cooling was considered here to benefit of the efficiency improvements with the cogeneration facilities considered.

Table 7. The residential energy requirements for GTA [2,162,163]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat	3652	3369	1872	1419	961	869	861	883	861	2158	3072	3502
Electricity	553	502	502	470	486	482	573	541	478	478	474	514
Cooling*	214	199	222	275	343	252	458	281	306	191	191	191

* The residential cooling requirements were calculated for the period of May – September alone. Additional consideration was given to the commercial cooling requirements, these being associated with the data of the case GCA for the periods of January – May and of September – December.

The parameters used in calculating the monthly energy production and exergy considerations are shown in Table 8 and in Table 9, for GCA, and for GTA, respectively. The long-term interest rates were found to be 2.73% for Denmark and 2.80% for Canada, the data being taken from [164].

Table 8. Parameters considered for the case of GCA [165-167]

Parameter	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outdoor Temperature	°C	0.5	1.1	2.4	6.6	11.1	14.3	16.8	17.6	13.6	9.3	5	1.7
Solar Irradiation	MW h	19.4	28.5	47.9	67.3	79.9	78.0	79.4	74.5	55.2	38.6	19.7	13.4
Rel. Humidity	%	86	84	82	76	72	72	73	75	78	83	84	85
Maximum Atmospheric Pressure	hPa	1047	1048	1044	1035	1041	1037	1031	1032	1039	1043	1048	1052
Wind Velocity	m/s	7.72	7.72	6.69	6.17	6.17	6.17	5.66	5.66	6.69	7.20	7.72	7.20

Table 9. Parameters considered for the case of GTA [166-168]

Parameter	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outdoor Temperature	°C	-5.2	-2.9	0.5	6.6	12.9	18.8	21.8	21.4	17.5	10.5	4.6	-0.7
Solar Irradiation	MWh	45.5	56.9	70.8	73.3	80.6	80.3	87.0	82.7	72.5	60.1	33.9	31.2
Rel. Humidity	%	72	68	62	55	55	55	54	57	59	62	67	72
Max. Atmospheric Pressure	hPa	980	980	980	980	980	980	980	980	980	980	980	980
Wind Velocity	m/s	9.26	8.75	8.75	8.75	7.20	6.69	6.17	5.66	6.17	6.69	8.23	8.23

Although the fuel costs were not determined for most of the energy conversion technologies involved in the study, the prices of biomass fuel does differ in line with the availability of the fuel locally (excluding the municipal solid waste). On this basis, the cost of biomass shows variations, such as of the market prices at seaports, excluding here the inland transportation costs, given as around 9.8 to 11.1 $/GJ for Europe and 3.7 $/GJ for the US in the report [169], presented here so as to show the differences. Thus, in this study the cost of biomass was assumed to be about 166 €/ton for district heating plants in Denmark, as taken from study [170], which was based on statistics of the Danish District Heating Association, and as 130 €/ton for wood pellets in Ontario, Canada, as derived from the report [171], taking account of a lower heating value of 18 MJ/kg there. Also, it should be noted that in Copenhagen hydrothermal resources does not exist [1]. Since, the geothermal temperature gradient was reported to be 30°C/km for both cases [172-174], only the direct utilization of geothermal energy (details regarding it are given in section 0) was taken account of in the study. However, for cases of high levels of the geothermal temperature gradient, the other geothermal based energy conversion technologies should be taken into consideration, details regarding them being given in section 3.3 and the cost considerations involved in 4. In the case of GTA, the dam of the hydroelectricity plant was considered as 50 m in height [118].

6. Results

The study provides a novel method of finding the minimal capacities of RE-based energy conversion systems, their production being considered on a monthly basis, satisfaction of the various types of energy requirements of relevance, such as for the heat involved in space heating and for producing hot water for domestic use, for electricity, and for cooling purposes. The energy requirements were considered to be provided through an integrated distribution infrastructure consisting of a low-energy district heating system, an electricity grid, and a district cooling system. The optimal solutions obtained for the case areas GCA and GTA, differing in the climatic conditions involved, were given in this section.

6.1. Case Study of GCA

Optimization that was carried out showed there to be various optimal solutions involving different combinations of the optimal capacities for the energy conversion systems, each satisfying the energy requirements decided upon for the study, the results being presented in Table 12 and the share on the overall lifecycle costs in Figure 4.

Table 10. Various optimal solutions obtained in the case of GCA for different installed capacities of the energy conversion systems, these involving different lifecycle costs and exergetic costs.

Energy Conversion Systems	Capacity Units	Optimal Solutions (OS)				
		OS 1	OS 2	OS 3	OS 4	OS 5
PV	m^2	6.00E+06	-	-	3.00E+05	2.16E+03
PVT	m^2	1.50E+04	-	4.00E+06	3.00E+05	2.16E+03
SC	m^2	1.00E+05	-	5.00E+06	5.00E+04	1.91E+03
Wind (OnShore)	MW	3.00E+03	-	1.00E+03	4.00E+03	3.90E+03
Wind (OffShore)	MW	4.02E+03	7.56E+03	1.00E+03	4.00E+03	4.34E+03
BTS	m^3	4.00E+05	-	4.90E+05	2.50E+05	3.00E+05
Geothermal - Direct	MW	2.00E+03	2.15E+03	6.00E+02	1.90E+03	1.80E+03
MSW - Incineration	tpa	1.50E+05	-	3.00E+06	6.00E+04	2.16E+03
MSW - Gasification	tpa	5.75E+03	-	3.00E+06	6.62E+03	2.15E+03
Trigeneration - Biomass	tpa	1.42E+04	-	5.50E+05	1.02E+04	2.18E+03
Chiller	kW	5.78E+03	-	1.00E+04	6.76E+03	1.88E+03
Absorption	kW	5.99E+03	-	4.00E+04	6.93E+03	1.94E+03
Free Cooling	MW	2.31E+02	2.51E+02	1.50E+02	2.32E+02	2.47E+02
Heat Pump (Hybrid)	kW	1.89E+04	-	1.00E+03	1.28E+04	2.04E+03
Heat Recovery (Chillers)	kW	1.00E+05	-	2.50E+04	1.10E+01	1.63E+04
Hydroelectric	MW	-	-	-	-	-
Overall Life-Cycle Cost		M€ 25,111	M€ 19,963	M€ 19,307	M€ 23,658	M€ 22,530
Overall Exergetic Cost		€/MWh 1,514	€/MWh 1,142	€/MWh 1,497	€/MWh 1,406	€/MWh 1,309

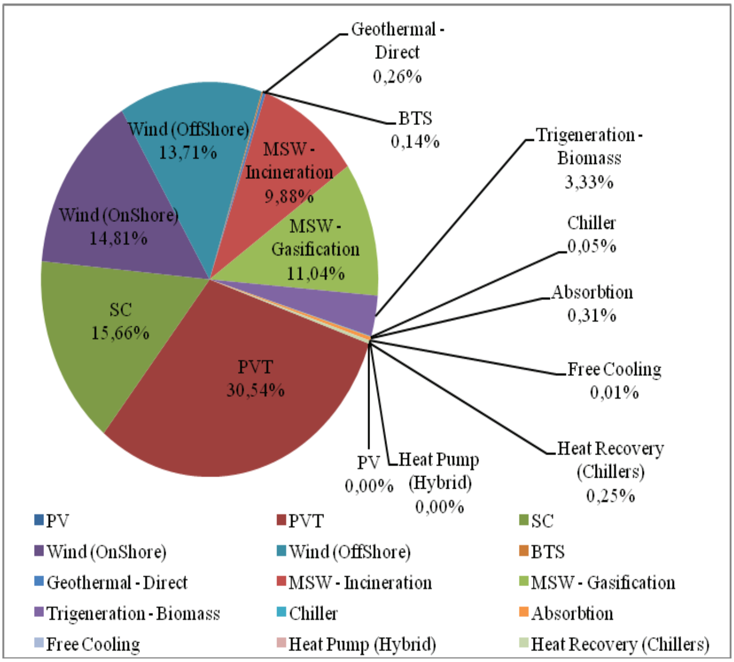


Figure 4. The share on the overall costs of the energy conversion systems in the case of GCA

The net overproduction observed (after taking account of the capacity factors in question) for the optimal solutions obtained are shown in Figure 5, Figure 6, and Figure 7, respectively, as regards heating, electricity, and cooling.

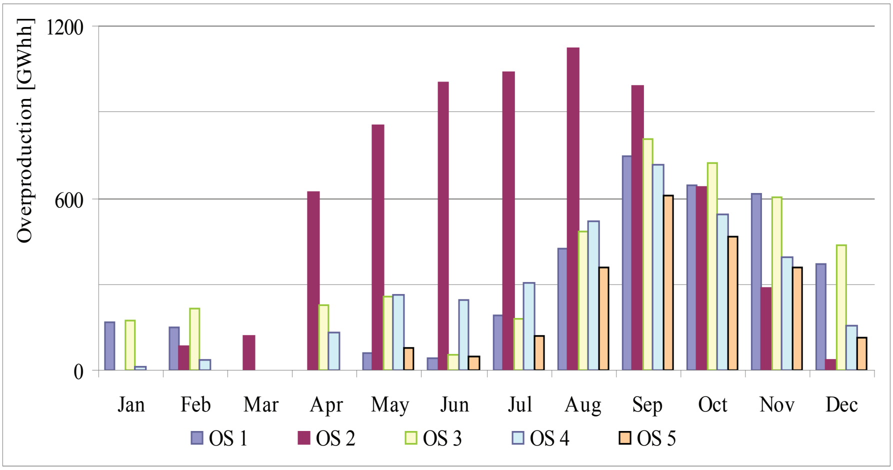


Figure 5. The monthly overproduction in terms of heating energy observed for the optimal solutions obtained in the case of GCA

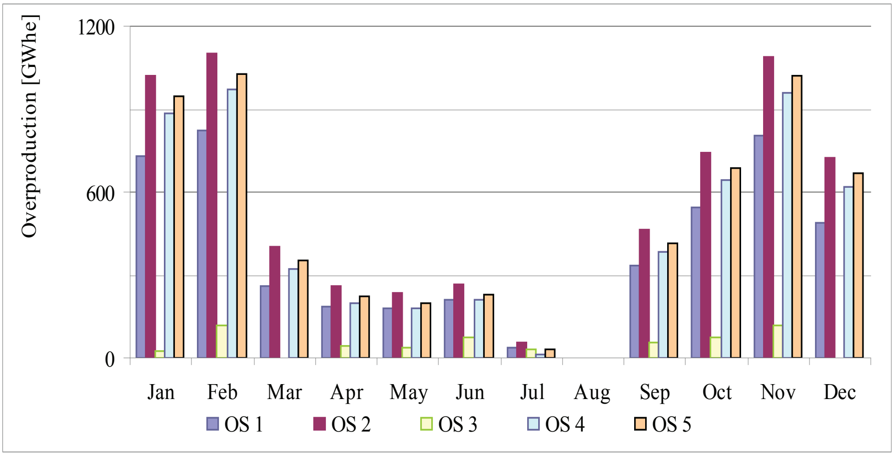


Figure 6. The monthly overproduction in terms of electricity energy observed for the optimal solutions obtained in the case of GCA

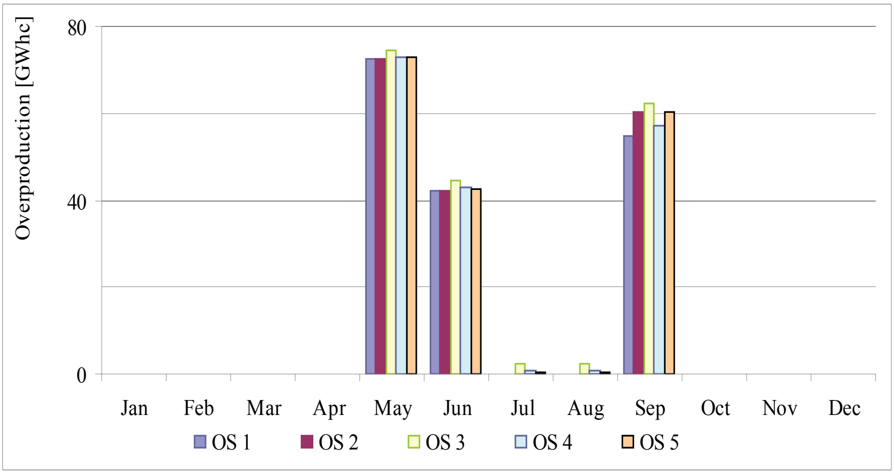


Figure 7. The monthly overproduction in terms of cooling energy observed for the optimal solutions obtained in the case of GCA

A detailed presentation of the energy outputs for an optimal solution is shown in Figure 8, Figure 9, and Figure 10 representing electricity, heat, and cooling, respectively.

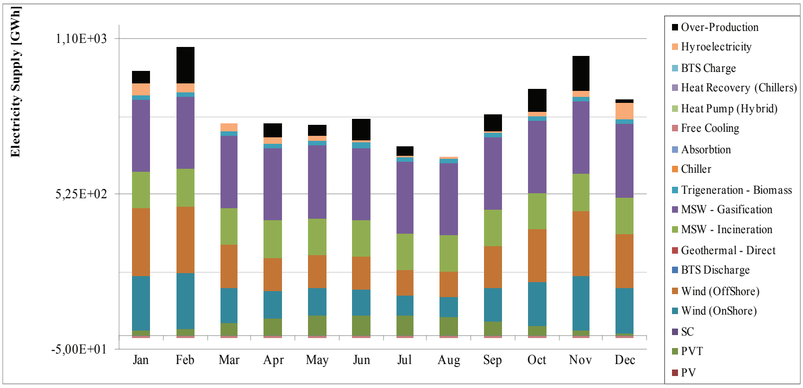


Figure 8. The electricity production for the period of a year as obtained for OS 3 in the case of GCA (the chiller, the free cooling system, and the heat pump being considered here with their consumptions of electricity) (Also published in [175] by the same authors)

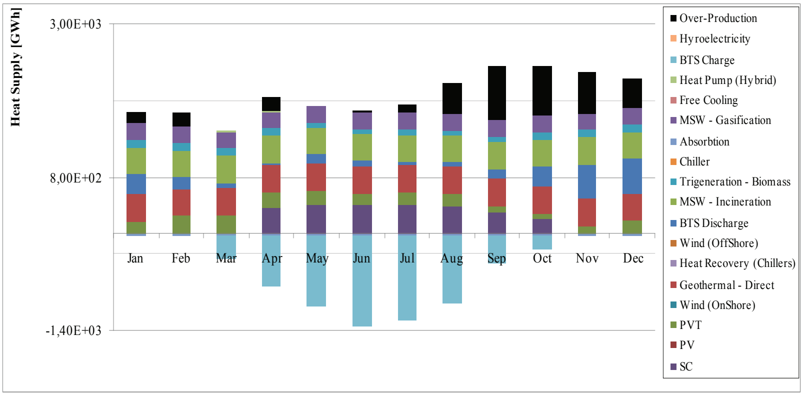


Figure 9. The heat production for the period of a year as obtained for OS 3 in the case of GCA (the absorption system with its consumption of heat being considered here) (Also published in [175] by the same authors)

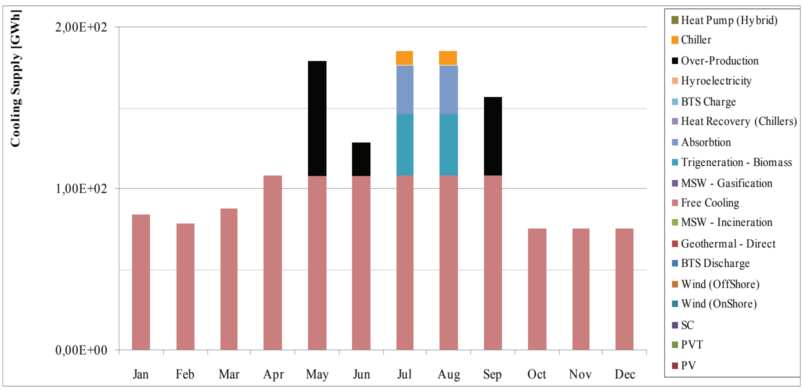


Figure 10. The cooling production for the period of a year as obtained for OS 3 in the case of GCA (Also published in [175] by the same authors)

A detailed presentation of the proportion of each energy conversion system involved in the annual production of energy is shown in the Figure 11, Figure 12, and Figure 13.

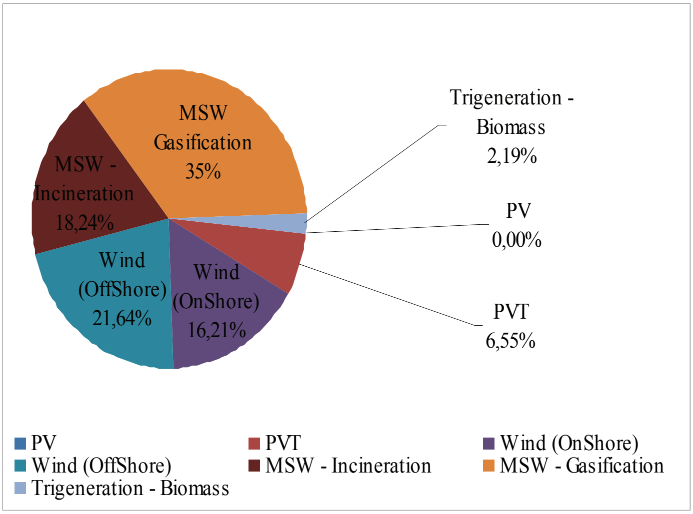


Figure 11. The proportion of the different energy conversion systems involved in the overall annual production of electricity in the case of GCA

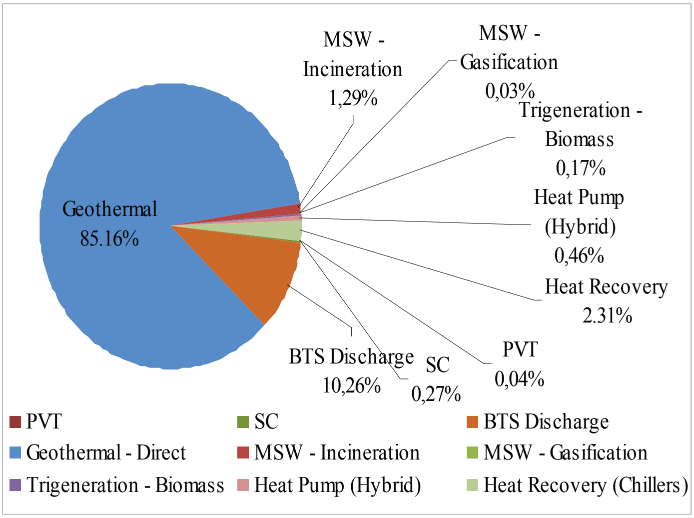


Figure 12. The proportion of the different energy conversion systems involved in the overall annual production of heat in the case of GCA

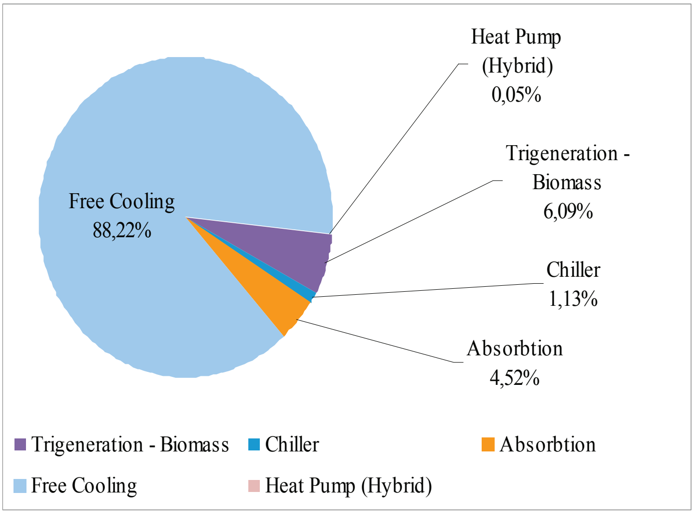


Figure 13. The proportion of the different energy conversion systems on the overall annual cooling production in the case of GCA

6.2. Case Study of GTA

The optimal solution obtained for the GTA with use of the nominal capacities for the energy conversion systems is shown in Table 11, their share of the overall costs being given in Figure 14. The monthly overproduction of energy in terms of electricity, heat, and cooling is given for the optimal solution in the case of GTA in Figure 15.

Table 11. The optimal solution being obtained for the case of GTA

Energy Conversion Systems	Capacity Units		OS
PV	m^2		2.05E+07
PVT	m^2		5.00E+04
SC	m^2		0.00E+00
Wind (OnShore)	MW		8.50E+02
Wind (OffShore)	MW		8.00E+02
BTS	m^3		1.10E+06
Geothermal - Direct	MW		4.30E+03
MSW - Incineration	tpa		5.32E+03
MSW - Gasification	tpa		1.00E+06
Trigeneration - Biomass	tpa		9.45E+05
Chiller	kW		0.00E+00
Absorption	kW		8.00E+04
Free Cooling	MW		5.40E+02
Heat Pump (Hybrid)	kW		1.00E+02
Heat Recovery (Chillers)	kW		8.00E+05
Hydroelectricity	kW		1.00E+05
Life-Cycle Cost		M€	23,751
Overall Exergetic Cost		€/MWh	1,576

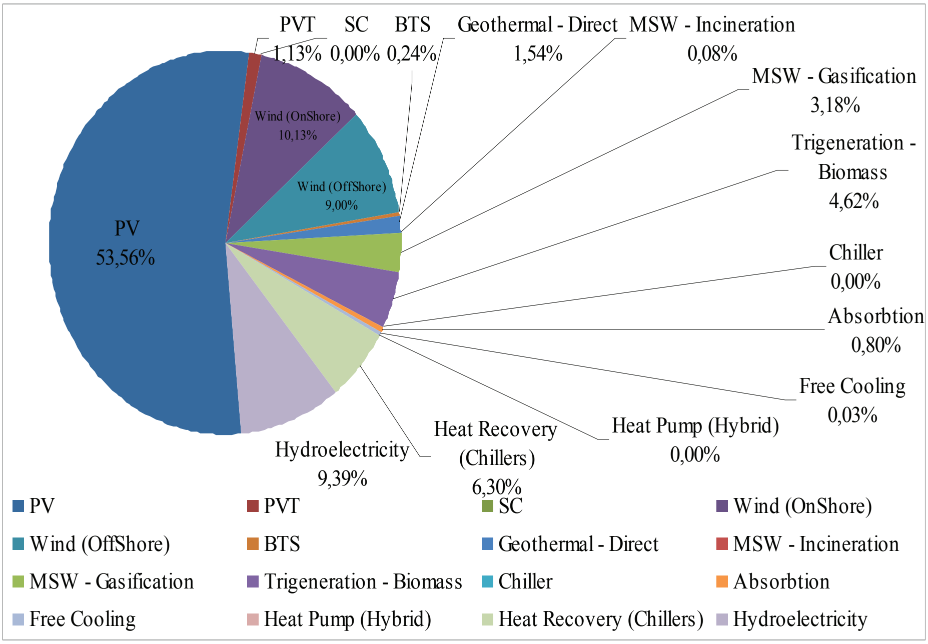


Figure 14. The share on the overall costs of the different energy conversion systems in the case of GTA

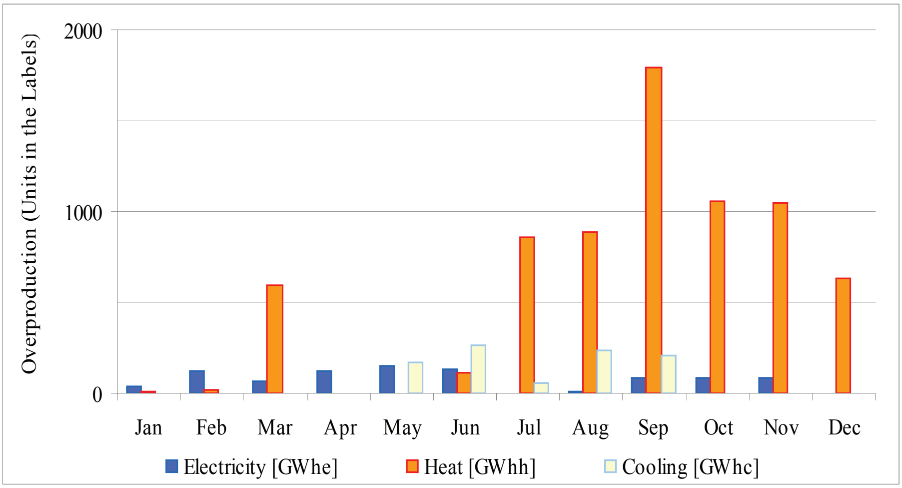


Figure 15. The monthly overproduction of energy in terms of electricity, heat, and cooling observed for the optimal solution in the case of GTA

A detailed presentation of the different energy outputs for the optimal solution is given in Figure 16, Figure 17, and Figure 18, representing electricity, heat, and cooling, respectively.

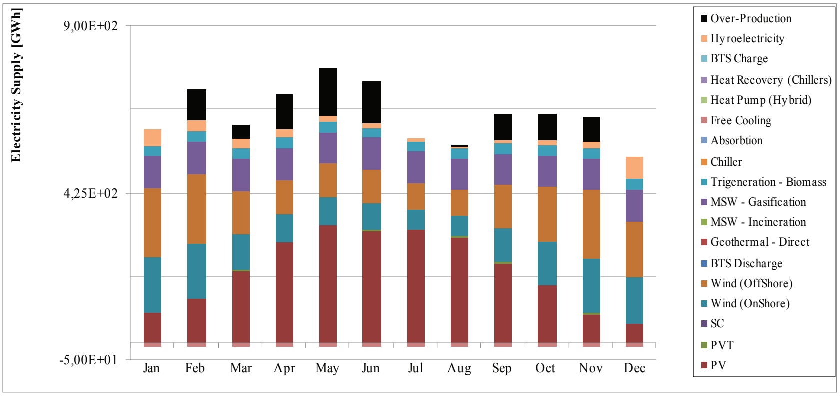


Figure 16. The electricity production for the period of a year as obtained for OS in the case of GTA (Also published in [175] by the same authors)

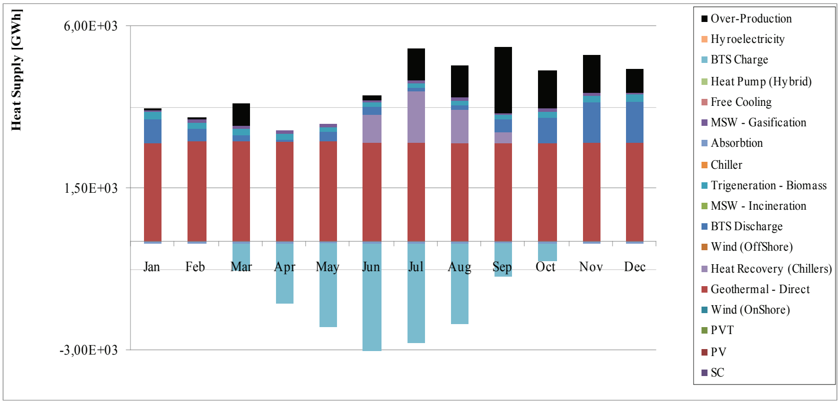


Figure 17. The heat production for the period of a year as obtained for OS in the case of GTA (Also published in [175] by the same authors)

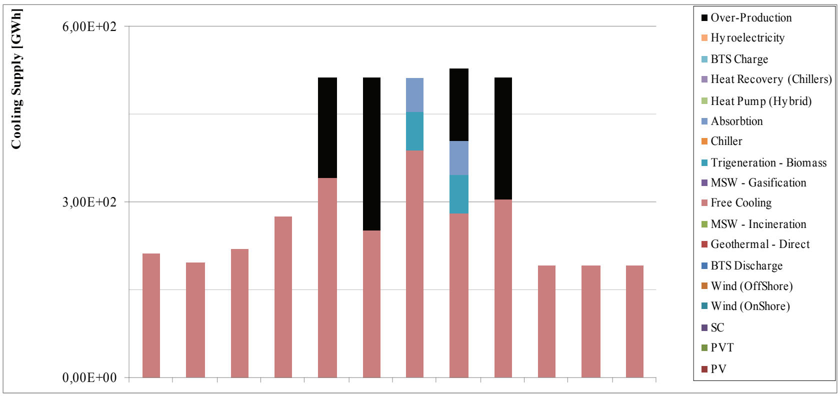


Figure 18. The cooling production for the period of a year period obtained for OS in the case of GTA (Also published in [175] by the same authors)

A detailed presentation of the proportion of each energy conversion system in the annual energy production is shown in Figure 19, Figure 20, and Figure 21.

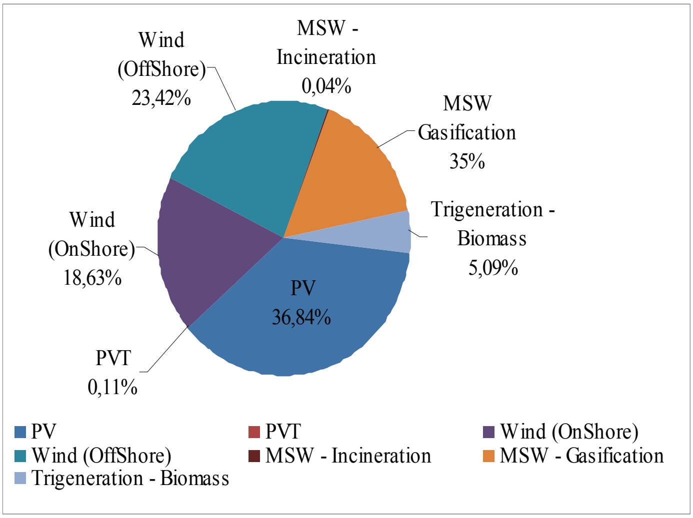


Figure 19. The proportion of the different energy conversion systems on the overall annual production of electricity in the case of GTA

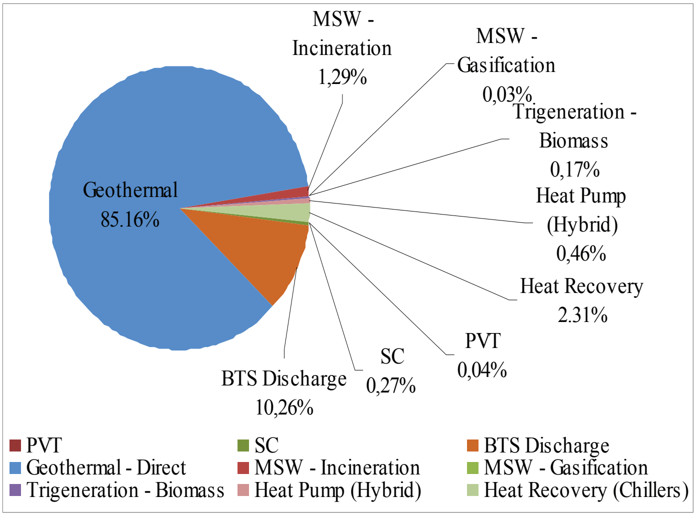


Figure 20. The proportion of the different energy conversion systems on the overall annual heat production in the case of GTA

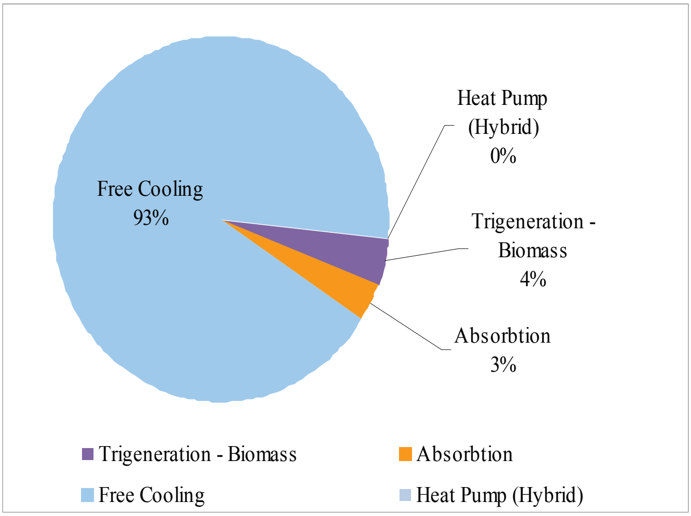


Figure 21. The proportion of the different energy conversion systems on the overall annual cooling production in the case of GTA

6.3. Environmental Assessment

The amounts of carbon dioxide emissions avoided by the utilization of RE sources as compared with use of various fossil-fuel-based energy conversion technologies are shown in Table 12.

Table 12. The amounts of carbon dioxide emissions avoided by use of RE sources of a cogeneration type as compared with use of fossil-fuel-based energy conversion technologies.

Fossil-Fuel based Energy Conversion Technologies	Emissions (CO_2) [M ton]	
	GCA	GTA
Coal fired Back-pressure steam turbine	703	1118
Coal fired Extraction-condensing steam turbine	883	1406
Natural gas fired Gas turbine	420	668
Propane fired Reciprocating engine	499	794

7. Discussion

Despite the Genetic Algorithm's being powerful for handling optimization models of virtually any type, the optimal solutions obtained were found on certain rather infrequent trials to show considerable error in their satisfaction of the constraints involved, especially when evaluating the heat supply-demand match. The thermal storage that could take place in the boreholes was considered to be a major reason for this, due to the marked differences that existed in the manner in which the heat energy that was produced was utilized, through the excessive heat produced during the summer being stored and its being discharged during the winter. Thus, manual arrangement of the variable data (in part the nominal capacities of the different systems involved but mainly of the borehole storage system) was employed in order to adjust the variation in the energy supply to match the variation in demand.

Several OSs of differing capacity and of differing overall lifecycle costs were obtained in both of the case studies. Since different aspects of OSs can affect decision making here differently, the evaluation of the OSs was carried out with use of different parameters, such as lifecycle costs, exergetic costs, and overproduction assessed on a monthly basis. In the case of GCA, one can note in Table 10 that the energy supply configuration given for OS 2 as based on certain of the energy conversions systems, namely those of offshore wind turbines, of the direct utilization of geothermal data, and of free cooling, resulted in lower overall costs than those based on most of the other OSs. However the difference between production and demand (in the sense of overproduction) here was found to be significantly greater than for the other solutions, as can be seen in Figure 5 and Figure 6. The other solution, that of OS 3, was taken as the best solution for the case study in question, due to its having the lowest cost and the least degree of overproduction; and due also to the diversity of the RE sources involved when note is taken of the security of supply, a matter not included in the algorithm of the optimization.

The exergetic costs of each energy conversion system is dependent upon several factors, such as the efficiency of the energy conversion system, together with the capacity factor, and the economic performance of the technology employed, such as the rate of gain in the economy-of-scale for investment costs, the superiority of the other economic values described in section 2.2, and the efficiency improvements that could be made through multi-generation, if the equipment available were adequate for this. One should take account also of the different exergetic costs, each of which was observed as being unique to the technology employed, and of the economy-of-scale being uniquely dependent upon the nominal capacity of the energy conversion system. For example, the borehole thermal storage systems, the direct utilization of geothermal sources, and the free-cooling technologies employed resulted in a significant reduction in exergetic costs in all OSs. This is due to the very low specific costs assigned to the systems in question. Regarding the solar-based energy conversion systems, for example, the order of size of the lifecycle cost observations obtained (i.e. of PV, PV/T, and the solar collectors) does not correlate appreciably with their exergetic cost values, where the order of size of the life cycle cost is that of $LCC_{PV/T}>LCC_{PV}>LCC_{SC}$, whereas the order of size of the exergetic costs is that of $C_{Ex,SC}>C_{Ex,PV}>C_{Ex,PV/T}$, despite the same nominal capacity being employed in both cases. A further and final point to be discussed is that of the disharmony to be noted in comparing the life cycle costs with the exergetic costs, and also with the exergetic improvement (i.e. reduction in exergetic costs) that occurred through the hybrid production of heat and electricity with use of the PV/T system that occurred. However, simply comparing the PV cells with the solar collectors does not indicate clearly how matters lie, because of the different forms of the final useable energy that they provide, the one supplying electricity and the other heat energy. This was one of the main reasons for the carrying out of a life-cycle cost analysis, which can regarded as embodying the major aim in the optimization model, rather than carrying out an exergetic evaluation, meanwhile considering evaluating the satisfaction level of energy requirements in question. Still another reason for carrying out such an analysis is that in economic terms renewable energy sources (with the exception of biomass-based systems) are free.

There was a high degree of over-production of heat energy in the summer months due in part to the increased efficiency and/or increased capacity of some energy conversion systems, such as solar systems, due in part to the recovery of heat from the waste heat of supermarket cooling plants, assumed to only be possible during the summer months, and due in addition to the reduced demand for heat then because of the lack of need for space heating and the lesser need for domestic hot water production. The borehole storage systems present appear to be the best way of overcoming the inequities between summer and winter here through their enabling the excessive amounts of heat generated during the summer months to be carried over to the cold winter months, allowing for a reduction in the nominal capacities required to satisfy demands for heat. The same sort of variation can be observed for the electricity and cooling supply. Matters of the storage of cooling were not considered in the study and there is no available technology for storing electricity for long periods of time. However satisfying the minimum demands for electricity in August was found to result in a high degree of over-production of electricity during the rest of the year, as can be seen in Figure 6, this being due to lower exergetic costs of a wind turbine system than of PV cells (both of them producing electricity alone), this despite the ability of the electricity demands during the summer months to be readily met, due to the increased solar insolation then.

The annual energy requirements in terms of the ratio of heat-to-electricity was found to be higher for GTA than for GCA, the respective values for it obtained being 3.9 and 1.1, respectively, whereas, the heat-to-cooling ratio values of the two were quite similar. The considerably larger gap between the peak and the minimum of the heat energy requirements observed for GTA can be seen as reflecting the greater use of a borehole storage system there than in the case of GCA. The nominal capacity of the biomass trigeneration system of GTA was found to be double the capacity of it for GCA. The contribution of the hydroelectric capacity results in a slight reduction in the capacity of wind farms that are established off-shore. The high rate of solar insolation, found to be higher in GTA than in GCA, showed a tendency to increase the capacity of solar energy systems, except for the capacity of the solar collector systems of GTA being reduced in regard to OS. The high level of the cooling demands in connection with GTA was found to result in a slight increase in the free cooling capacity together and in a higher degree of trigeneration based on biomass there, with use of an absorption system its installed capacity being doubled.

8. Conclusions

The major aim of the study was to investigate a novel method for determining the optimal capacities of RE based energy conversion systems that can handle different climatic conditions readily and can be used to evaluate the degree to which the energy requirements of different types for different periods of the year can be satisfied. An optimization model was formulated aimed at minimizing the overall life-cycle costs of the energy conversion system as a whole. The constraints of this optimization model, designed to, maximize the satisfaction of monthly energy requirements in terms of providing the heat energy needed for space heating and for domestic hot water production in a low-energy district heating system having a temperature scheme of 55/25°C for supply/return, for electricity energy and for cooling, were described. The lifecycle cost analysis carried out was found to provide a reasonable basis for finding an optimal solution here, rather than using an exergetic cost model taking account only of RE sources that are economically-free to make use of. It can be noted that large energy savings together with low lifecycle costs without any appreciable emission release are possible through optimizing the RE sources available locally and integrating them with city-wide distribution systems and utilizing the low-temperature operations available in a DH network. The assessment of locally available RE sources then together with the optimization of their nominal capacities which is required to meet the demands of the community can be seen as a must for any district. Borehole storage systems can be the saving element here in matching the varying heat production taking place with the varying heat requirements during the course of the year. Wind farms should be considered promising as a source of electricity due to their low exergetic costs for districts that have plain land areas or available neighboring off-shore areas. The same applies to two additional technologies that are readily available the one being the direct utilization of geothermal energy and the other being the free cooling, to meet energy requirements in terms of heating and of cooling, respectively.

Various shortcomings of the method as described above should be taken account of in future work. The ideal energy-supply decision tool should take into consideration such matters as the following: (i) the existence of such multi-input multi-output integrated energy conversion systems as those considered in studies [29,176], (ii) there being several useable outputs or inputs (not necessarily in the form of energy) pertaining to the geographical area involved that should be considered, such as the availability of clean water, of hydrogen, and of biogas, together with storage facilities for them [177], (iii) possibilities for hourly evaluation of the demand satisfaction in connection with the requirements taken up in [1], and (iv) site-specific considerations concerning the location of local RE sources, the land area requirements of each energy technology, and geographical information regarding the area [25]. One should also note that there is a great variety of different RE sources other than what is considered in this study, such as tidal energy, wave energy and several types of energy conversion systems, such as concentrated solar electricity-production plants, that could be of relevance [20].

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the COWIfonden, Marie & MB Richters Fond, and Oticon Fonden, which provided the financial support for the external study carried out by the PhD Candidate Hakan İbrahim Tol at the UOIT, Oshawa, ON, Canada. We would also like to thank Henrik Lorentsen Bøgeskov for his guidance in accessing the data of the Danish district cooling network.

Nomenclature

LATIN LETTERS		***SUBSCRIPTS***	
A	The area of the collector	b	Brine present in the geothermal reservoir
c_1, c_2	First- and second-order heat loss coefficient for flat-plate solar collectors	*BT*	Biomass sourced trigeneration
C	Cost	c	Cooling Energy
C_p	The power coefficient for the wind turbines	Cell	The cell of PV panels
Ch	Charged heat in the borehole thermal storage system	*C*	Cooling energy
CF	Capacity Factor	*CC*	Compressor chiller
d	Depth	*DH*	District Heating
dh	Height of the dam	*DF*	Double flashing geothermal plant
D	The total energy requirement of the district	*DS*	Dry steam geothermal power plant
DisCh	Discharged heat by the borehole thermal storage system	*DU*	Direct utilization of geothermal source (i.e. for heat production)
Ex	Exergy value	DSP	Dry Steam Plants
G	Nominal Capacity	e	Energy type
I	Intensity	*fuel*	Fuel input to the cogeneration plant
n	Overall amount of the entry type of the indicated in its subscript	F	Fuel Cost
p	The end of the period (12 since month as taken as time period in this project)	*FC*	Free cooling
P	The overall production of the energy conversion systems as a whole	*Gain*	Energy gain involved for heat recovery units
r	The discount rate	h	Heat energy
Reg1, Reg2	Regression Parameters	hydro	Hydro-electric plant
t	Entry type for time	*H*	Heat energy
T	Temperature	*HHP*	Hybrid heat pump
v	the wind speed	*HR*	Heat recovery unit
W	Electrical energy	i	The index for the energy conversion system (used for the optimization)
GREEK LETTERS		in, out, /s	Input and output of the exergy for the boundary conditions of the energy conversion plant (/s refers to plurality of the inputs and outputs
$\forall$	The universal mathematical symbol indicating "for all"	I/P	Specific investment cost
β_0, β_1, and β_2	The parameters used in calculating invesment cost of hydroelectric plant	LCC,i	Life cycle cost
η	Energy Efficiency	m	Month studied
ξ	The factor representing the building facilities required for the hydro-electric plant	Max	Maximum amount of the entry type
ρ	Air density	*MSW*	Municipal Solid Waste
τ	Exergetic temperature factor	O	Outdoor temperature
Ψ	Exergetic efficiency	O&M	The operating and management cost
		PV	Photo Voltaic Unit
		PV/T	Hybrid Photovoltaic and Thermal Unit
		R	The return temperature
		subS	Geothermal sub-surface pratices
		surf	Geothermal surface plant
		S	Single production
		S,p	Salvage Cost (at the period p)
		Sol	Solar
		SF	Single flashing geothermal plant
		SR	Solar radiation
		STC	Solar thermal collector
		tdc	The temperature degression coefficient of the PV cells
		TF	Triple flash geothermal plant

REFERENCES

1) Lund H, Mathiesen BV (2009) Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy 34:524-531.
2) Duguid B (2010) Ontario's long-term energy plan - Building our clean energy future. Queen's Printer for Ontario. http://www.energy.gov.on.ca/docs/en/MEI_LTEP_en.pdf
3) Wiltshire R (2011) Low temperature district energy systems In: Proceedings of the Urban Energy Conference, Debrecen, Hungary, 14–15 October, 2011.
4) Foged M (1999) Low temperature operation, DBDH. http://www.dbdh.dk. Accessed 10 Jan 2011.
5) Olsen PK, Lambertsen H, Hummelshøj R, Bøhm B, Christiansen CH, Svendsen S et al (2008) A new low-temperature district heating system for low-energy buildings. In: The 11th international symposium on district heating and cooling, Reykjavik, Iceland, 31August–2 September 2008.
6) Paulsen O, Fan J, Furbo S, Thorsen JE (2008) Consumer Unit for Low Energy District Heating Net. In: The 11th international symposium on district heating and cooling, Reykjavik, Iceland, 31August–2 September 2008.
7) Torio H, Schmidt D (2011) Low exergy systems for high-performance buildings and communities. ECBCS - Annex 49.
8) Christiansen CH, Worm J, Jørgensen H, Thorsen JE, Bennetsen J, Larsen CT et al. (2011) Demonstration of low energy district heating system for low energy building in ringgårdens Afd. 34 in Lystrup (Demonstration af lavenergifjernvarme til lavenergibyggeri i boligforeningen ringgårdens afd. 34 i Lystrup). DEA, Århus,Denmark.
9) Thorsen JE, Christiansen CH, Brand M, Olesen PK, Larsen CT (2011) Experiences on low-temperature district heating in Lystrup - Denmark. In: Proceedings of the International Conference on District Energy International Conference on District Heating and Cooling, Portorož, Slovenia, 20–22 March 2011.
10) Christiansen CH, Paulsen O, Bøhm B, Thorsen JE, Ting Larsen C, Jepsen BK et al. (2009) Technical Report for Project Development and Demonstration of Low-Energy District Heating for Low Energy Buildings (Udvikling og demonstration af lavenergi-fjernvarme til lavenergibyggeri. Hovedrapport og bilag). Teknologisk Institut. Copenhagen, Denmark.
11) Sibbitt B, Onno T, McClenahan D, Thronton J, Brunger A, Kokko J et al (2007) The Drake Landing Solar Community project - Early results. In: Canadian solar buildings conference, Canmet Energy Technology Centre, Calgary, 10–14 June 2007.
12) Mertoglu O, Bakir N, Kaya T (2003) Geothermal applications in Turkey. Geothermics 32:419-428.
13) Olsen PK, Christiansen CH, Hofmeister M, Svendsen S, Thorsen JE, Gudmundsson O et al. (2014) Guidelines for Low-Temperature District Heating. EUDP - DEA. Denmark. 14) Schmidt D, Ala-Juusela M (2004) Low Exergy Systems for Heating and Cooling of Buildings. In: Plea, Eindhoven, The Netherlands, 23 September 2004.
15) Hasan A, Kurnitski J, Jokiranta K (2009) A combined low temperature water heating system consisting of radiators and floor heating. Energy and Buildings 41:470-479.
16) Brand M, Thorsen JE, Svendsen S (2012) Numerical modelling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of DHW with respect to service pipes. Energy 41:392-400.
17) Tol Hİ, Svendsen S (2012) Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark. Energy 38:276-290.
18) Tol Hİ, Svendsen S (2012) A comparative study on substation types and network layouts in connection with low-energy district heating systems. Energy Conversion and Management 64:551-561.
19) Tol Hİ, Svendsen S (2013) The exergetic, environmental, and economic effect of the hydrostatic design static pressure level on the pipe dimensions of low-energy district heating network. Challenges 4:1-16.
20) Dincer I, Zamfirescu C (2012) Renewable-energy-based multigeneration systems. Int J Energy Res 36:1403-1415.
21) Lund H, Möller B, Mathiesen BV, Dyrelund A (2010) The role of district heating in future renewable energy systems. Energy 35:1381-1390.
22) Sperling K, Möller B (2012) End-use energy savings and district heating expansion in a local renewable energy system – A short-term perspective. Appl Energy 92:831-842.
23) Østergaard PA, Lund H (2011) A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Applied Energy 88:479-487.
24) Mathiesen BV, Lund H, Connolly D (2012) Limiting biomass consumption for heating in 100% renewable energy systems. Energy 48:160-168.
25) Weber C, Shah N (2011) Optimisation based design of a district energy system for an eco-town in the United Kingdom. Energy 36:1292-1308.
26) Niemi R, Mikkola J, Lund PD (2012) Urban energy systems with smart multi-carrier energy networks and renewable energy generation. Renewable Energy 48:524-536.
27) Ozlu S, Dincer I, Naterer GF (2012) Comparative assessment of residential energy options in Ontario, Canada. Energy Build 55:674-684.
28) Chicco G, Mancarella P (2009) Distributed multi-generation: A comprehensive view. Renewable and Sustainable Energy Reviews 13:535-551.
29) Dincer I, Zamfirescu C (2004) Integrated multigeneration energy systems. In: Dincer I, Zamfirescu C (eds) Sustainable energy systems and applications. Springer, New York.
30) Kiani B, Hamamoto Y, Akisawa A, Kashiwagi T (2004) CO2 mitigating effects by waste heat utilization from industry sector to metropolitan areas. Energy 29:2061-2075.

31) The Mathworks Inc. Matlab help manual optimization toolbox [disk]. Version 7.11.0.584 (R2010b). Massachusetts: Matworks Inc; 2010 Aug 16.
32) Bejan A, Tsatsaronis G, Moran M (1996) Thermoeconomic optimization. In: Bejan A, Tsatsaronis G, Moran M (eds). Thermal Design & Optimization. John Wiley & Sons, Inc, New York.
33) Bøhm B (1988) Energy-economy of Danish district heating systems: A technical and economic analysis. Laboratory of Heating and Air Conditioning, Technical University of Denmark, Kongens Lyngby, Denmark.
34) Henning D (1997) MODEST—An energy-system optimisation model applicable to local utilities and countries.
35) Werner S (2004) District Heating and Cooling. In: Cutler J. Cleveland (ed) Encyclopedia of Energy, New York: Elsevier.
36) The Danish Energy Agency, Energinet.dk (2012) Technology data for energy plants - Generation of electricity and district heating, energy storage and energy carrier generation and conversion. http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology_data_for_energy_plants.pdf. Accessed 18 June 2012
37) Kaldellis JK (2007) The contribution of small hydro power stations to the electricity generation in Greece: Technical and economic considerations. Energy Policy 35:2187-2196.
38) Downey K (2011)Power plant construction costs: Cost pressures returning. Englewood, Colorado. http://press.ihs.com/press-release/energy-power/power-plant-construction-costs-cost-pressures-returning. Accessed 23 July 2012
39) Dincer I, Rosen MA (2013) Exergy Analysis of Cogeneration and District Energy Systems. In: Ibrahim Dincer, Marc A. Rosen (eds) Exergy, 2nd edn. Elsevier.
40) Yang M, Patiño-Echeverri D, Yang F (2012) Wind power generation in China: Understanding the mismatch between capacity and generation. Renewable Energy 41:145-151.
41) Croucher M (2011) Capacity factors and solar job creation. Energy Policy 39:6914-6915.
42) Rosen MA, Le MN, Dincer I (2005) Efficiency analysis of a cogeneration and district energy system. Appl Therm Eng 25:147-159.
43) Dincer I, Rosen MA (2013) Exergy and Energy Analyses. In: Ibrahim Dincer, Marc A. Rosen (eds) Exergy, 2nd edn. Elsevier.
44) Hepbasli A, Alsuhaibani Z (2011) Exergetic and exergoeconomic aspects of wind energy systems in achieving sustainable development. Renewable and Sustainable Energy Reviews 15:2810-2825.
45) Brower M (1992) Cool Energy: Renewable Solutions to Environmental Problems. MIT press, USA.
46) Rosen M (2009) Energy and environmental advantages of cogeneration with nuclear and coal electrical utilities. In: Proceedings of 4th IASME/WSEAS International Conference on Energy & Environment, Cambridge, UK, 24-26 February, 2009.
47) CEN/CENELEC, "Manual for Determination of Combined Heat and Power (CHP)", CWA 45547, September 2004 .
48) EIA (N/A) Emission Factors and Global Warming Potentials. http://www.eia.gov/survey/form/eia_1605/emission_factors.html. Accessed 18 June 2012
49) Hepbasli A (2008) A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renewable and Sustainable Energy Reviews 12:593-661.
50) Butti K, Perlin J (1980) A golden thread: 2500 years of solar architecture and technology. Cheshire books, Palo Alto, California.
51) Bosanac M, Sørensen B, Katic I, Sørensen H, Nielsen B, Badran J (2003) Photovoltaic/Thermal solar collectors and their potential in Denmark. Final report. Copenhagen, Denmark: Danish Technological Institute, Solar Energy Centre, Novator Advanced Technology Consulting, Consulting Engineers Ltd.; 2003 May; Report No.: EFP project 1713/00-0014. 114 p.
52) Kalogirou SA (2004) Solar thermal collectors and applications. Progress in Energy and Combustion Science 30:231-295.
53) Polysun Simulation Software - User Manual [disk] (2010) Version 5.5.10.14394:123. Vinterthur, Switzerland: Vela Solaris AG, Solartechnik Prüfung Forschung.
54) Petela R (2003) Exergy of undiluted thermal radiation. Solar Energy 74:469-488.
55) Tripanagnostopoulos Y, Souliotis M, Battisti R, Corrado A (2005) Energy, cost and LCA results of PV and hybrid PV/T solar systems. Prog Photovoltaics Res Appl 13:235-250.
56) Joshi AS, Dincer I, Reddy BV (2009) Thermodynamic assessment of photovoltaic systems. Solar Energy 83:1139-1149.
57) Akyuz E, Coskun C, Oktay Z, Dincer I (2012) A novel approach for estimation of photovoltaic exergy efficiency. Energy 44:1059-1066.
58) Masters GM (2004) Renewable and Efficient Electric Power Systems. John Wiley & Sons, Inc. Hoboken, New Jersey.
59) Gunerhan H, Hepbasli A (2007) Exergetic modeling and performance evaluation of solar water heating systems for building applications. Energy Build 39:509-516.
60) Fan J, Chen Z, Furbo S, Perers B, Karlsson B (2009) Efficiency and lifetime of solar collectors for solar heating plants. In: ISES Solar World Congress, Johannesburg, South Africa. 11-14 October 2009.
61) Dinçer İ, Zamfirescu C (2011) Sustainable energy systems and applications. Springer, New York, USA.
62) Dubey S, Tiwari GN (2009) Analysis of PV/T flat plate water collectors connected in series. Solar Energy 83:1485-1498.
63) Charalambous PG, Maidment GG, Kalogirou SA, Yiakoumetti K (2007) Photovoltaic thermal (PV/T) collectors: A review. Appl Therm Eng 27:275-286.
64) Tselepis S, Tripanagnostopoulos Y (2002) Economic analysis of hybrid photovoltaic/thermal solar systems and comparison with standard PV modules. In: PV in Europe - From PV Technology to Energy Solutions, Rome, Italy. 7-11 October 2002.

65) Burton T, Jenkins N, Sharpe D, Bossanyi E (2011) Wind Turbine Installations and Wind Farms. In: Burton T, Jenkins N, Sharpe D, Bossanyi E (eds) Wind Energy Handbook: John Wiley & Sons, Ltd.
66) Østergaard PA, Mathiesen BV, Möller B, Lund H (2010) A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 35:4892-4901.
67) Gökçek M, Genç MS (2009) Evaluation of electricity generation and energy cost of wind energy conversion systems (WECSs) in Central Turkey. Appl Energy 86:2731-2739.
68) Betz A (1926) Wind-energie und ihre ausnutzung durch windmühlen. Ökobuch Verlag, Göttingen, Germany.
69) Uslu A. Europe's onshore and offshore wind energy potential - An assessment of environmental and economic constraints. Final Report. Luxembourg: European Environment Agency (EEA); 2009 Jun; Report No.: 6/2009: 90 p.
70) Ozgener O, Ozgener L (2007) Exergy and reliability analysis of wind turbine systems: A case study. Renewable and Sustainable Energy Reviews 11:1811-1826.
71) Dincer I, Hepbasli A, Ozgener L (2007) Geothermal energy resources. In: Capehart BL (ed) Encyclopedia of Energy Engineering and Technology - 3 Volume Set (Print Version), Taylor and Francis, London.
72) Lee KC (2001) Classification of geothermal resources by exergy. Geothermics 30:431-42.
73) Ozgener L, Hepbasli A, Dincer I (2006) Effect of reference state on the performance of energy and exergy evaluation of geothermal district heating systems: Balcova example. Build Environ 41:699-709.
74) Jalilinasrabady S, Itoi R, Valdimarsson P, Saevarsdottir G, Fujii H (2012) Flash cycle optimization of Sabalan geothermal power plant employing exergy concept. Geothermics 43:75-82.
75) Lako, P. Geothermal heat and power. Final Report. Paris, France: International Energy Agency - Energy Technology Systems Analysis Programme; 2010 May; Report No.: E07: 6 p.
76) Kanoğlu M. Çengel Y. Dinçer İ (2012) Efficiency Evaluation of Energy Systems. Springer, New York, USA.
77) Heberle F, Brüggemann D (2010) Exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation. Appl Therm Eng 30:1326-1332.
78) Chamorro CR, Mondéjar ME, Ramos R, Segovia JJ, Martín MC, Villamañán MA (2012) World geothermal power production status: Energy, environmental and economic study of high enthalpy technologies. Energy 42:10-18.
79) Yari M (2010) Exergetic analysis of various types of geothermal power plants. Renewable Energy 35:112-121.
80) Kanoğlu M, Çengel YA (1999) Economic evaluation of geothermal power generation, heating, and cooling. Energy24:501-509.
81) DiPippo R (2004) Second Law assessment of binary plants generating power from low-temperature geothermal fluids. Geothermics 33:565-586.
82) Coskun C, Oktay Z, Dincer I (2011) Modified exergoeconomic modeling of geothermal power plants. Energy 36:6358-6366.
83) Kanoglu M, Bolatturk A (2008) Performance and parametric investigation of a binary geothermal power plant by exergy. Renewable Energy 33:2366-2374.
84) Kanoglu M, Dincer I, Rosen MA (2007) Understanding energy and exergy efficiencies for improved energy management in power plants. Energy Policy 35:3967-3978.
85) Franco A, Villani M (2009) Optimal design of binary cycle power plants for water-dominated, medium-temperature geothermal fields. Geothermics 38:379-391.
86) Luo C, Huang L, Gong Y, Ma W (2012) Thermodynamic comparison of different types of geothermal power plant systems and case studies in China. Renewable Energy 48:155-160.
87) DiPippo R (2008) Advanced Geothermal Energy Conversion Systems. In: DiPippo R (ed) Geothermal Power Plants – Principles, Applications, Case Studies and Environmental Impact, 2nd edn, Butterworth-Heinemann. Oxford, UK.
88) Kaya E, Zarrouk SJ, O'Sullivan MJ (2011) Reinjection in geothermal fields: A review of worldwide experience. Renewable and Sustainable Energy Reviews 15:47-68.
89) Mago PJ, Fumo N, Chamra LM (2009) Performance analysis of CCHP and CHP systems operating following the thermal and electric load. Int J Energy Res 33:852-864.
90) Kanoglu M, Dincer I (2009) Performance assessment of cogeneration plants. Energy Conversion and Management 50:76-81.
91) Kizilkan O, Dincer I (2012) Exergy analysis of borehole thermal energy storage system for building cooling applications. Energy Build 49:568-574.
92) Chapuis S, Bernier M (2009) Seasonal storage of solar energy in borehole heat exchangers. In: 11th International IBPSA Conference, Glasgow, UK, 27-30 July 2009.
93) Faaij A (2006) Modern biomass conversion technologies. Mitigation Adapt Strat Global Change 11:335-367.
94) RISI (2013) European biomass review - new comprehensive analysis and forecast of the European bioenergy sector. http://www.risiinfo.com/risi-store/do/product/detail/ European-Biomass-Review.html?source=D16J. Accessed 3 June 2012
95) Patzek TW, Pimentel D (2005) Thermodynamics of energy production from biomass. Critical Reviews in Plant Sciences 24:327-364.
96) Wolf O, Crank M, Patel M, Marscheider-Weidemann F, Schleich J, Hüsing B et al. Techno-economic feasibility of large-scale production of bio-based polymers in Europe. Final report. Seville, Spain: European Commission - Joint Research Centre; 2005 May; Report No.: EUR 22103 EN, 260 p.
97) Münster M (2009) Energy systems analysis of waste to energy technologies by use of EnergyPLAN. Risø DTU - National Laboratory for Sustainable Energy, Risø, Denmark. Report No.: Risø-R-1667(EN).

98) Fruergaard T, Christensen TH, Astrup T (2010) Energy recovery from waste incineration: Assessing the importance of district heating networks. Waste Manage 30:1264-1272.
99) Werner S (2006) Possibilities with more district heating in Europe. Ecoheatcool. Report No.: Work Package 4. Brussels, Belgium.
100) Murphy JD, McKeogh E (2004) Technical, economic and environmental analysis of energy production from municipal solid waste. Renewable Energy 29:1043-1057.
101) Saidur R, BoroumandJazi G, Mekhilef S, Mohammed H (2012) A review on exergy analysis of biomass based fuels. Renewable and Sustainable Energy Reviews 16:1217-1222.
102) Young GC (2010) Municipal solid waste to energy conversion processes: economic, technical, and renewable comparisons. John Wiley & Sons, Inc, Hoboken, New Jersey.
103) Huang Y, Wang Y, Rezvani S, McIlveen-Wright D, Anderson M, Mondol J et al. (2013) A techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle. Appl Therm Eng 53:325-331.
104) Maraver D, Rezeau A, Sebastian F, Royo J (2009) Thermodynamic optimization of a trigeneration system based on biomass combustion. In: Proceedings of the 17th European Biomass Conference. Hamburg, Germany. 29 June-3 July 2009.
105) Bédard S (2009) Waste heat to power - A process integration perspective. In: ENERGY 2009 Lean and Green. Toronto, Ontario; 24-25 November 2009.
106) Pulat E, Etemoglu AB, Can M (2009) Waste-heat recovery potential in Turkish textile industry: Case study for city of Bursa. Renewable and Sustainable Energy Reviews 13:663-672.
107) Johnson I, Choate WT (2008) Waste heat recovery: Technology and opportunities in U.S. industry. Report No.: (N/A). BCS, Incorporated, Laurel, MD, USA.
108) Punte S, Repinski P (2006) Thermal Energy Equipment: Waste Heat Recovery. In: Töpfer K (ed). Energy Efficiency Guide for Industriy in Asia, Bangkok, Thailand. United Nations Environment Programme.
109) Gabrielii C (2002) The potential for heat pumps utilizing industrial waste heat (Potentialen för värmepumpar som utnyttjar industriell spillvärme). CPL, Chalmers Publication Library, Göteborg, Sweden. Report No.: N/A.
110) Samuelsson H (2009) SETatWork Goog Practice - Waste heat from industry. SETatWork Report No.: N/A.
111) Land AL, Feldhusen H, Tvärne A, Cronholm L, Sundlöf C (2002) Industrial waste heat - processes and potentials (Industriell spillvärme - processor och potentialer). The Swedish District Heating Association. Stockholm, Sweden. Report No.: FVF 02 11 49.
112) Baxter VD (2003) Advanced supermarket refrigeration/heat recovery systems. Oak Ridge National Laboratory, Oak Ridge, Tennessee. Report No.: IEA Annex 26.
113) EUREKA Wärmerückgewinnung und Kühltechnik GmbH & Co. KG (2002) Heat Recovery http://www.eureka-emsdetten.de/2-1-heat-recovery.html. Accessed 16 September 2012
114) York by Johnson Controls (2010) Optimize your facility's energy utilization with free heat. http://www.johnsoncontrols.com/content/dam/WWW/jci/be/integrated_hvac_systems/hvac_equipment/chiller_products/centrifugal-packaged/PUBL-6317_(510).pdf. Accessed 16 September 2012
115) Nieuwlaar E, Dijk D (1993) Exergy evaluation of space-heating options. Energy 18:779-790.
116) Bailer P, Pietrucha U (2004) District heating and district cooling with large centrifugal chiller - heat pumps. In: The 9th international symposium on district heating and cooling, Espoo, Finland, 30-31Aug 2004.
117) Chatterjee B, Howitt RE, Sexton RJ (1998) The Optimal Joint Provision of Water for Irrigation and Hydropower. J Environ Econ Manage 36:295-313.
118) Rosen MA, Scott DS (2003) Entropy production and exergy destruction: Part I—hierarchy of earth's major constituencies. Int J Hydrogen Energy 28:1307-1313.
119) Ertesvåg IS, Mielnik M (2000) Exergy analysis of the Norwegian society. Energy 25:957-973.
120) Rogner H (1993) Clean energy services without pain: district energy systems. Energy Studies Review 5:114-120.
121) Københavns Energi A/S (2011) KE Fjernkøling A/S http://www.ke.dk/ portal/page/portal/Fjernkoeling/ke_fjernkoeling_as?page=970. Accessed 19 September 2012
122) Ritola J, Ala-Juusela M (2004) Ground source cooling. VTT Building and Transport, Espoo, Finland, Report No.: 61-02.
123) Skagestad B, Mildenstein P (2002) District Heating and Cooling Connection Handbook. IEA, Paris, France. Report No.: Annex VI.
124) Looney CM, Oney SK (2007) Seawater District Cooling and Lake Source District Cooling. Energy Engineering 104:34-45.
125) Dalin P, Ivancic A, Tvärne A, Penthor A, Martin B, Ricci F et al. (2006) District cooling - Cooling more with less. Euroheat&Power, Brussels, Belgium. Report No.: N/A.
126) de Jager D, Klessmann C, Stricker E, Winkel T, de Visser E, Koper M et al. (2011) Financing renewable energy in the European energy market. ECOFYS, The Netherlands. Report No.: PECPNL084659.
127) Hearps P, McConnell D (2011) Renewable energy cost review. Melbourne Energy Institute, Victoria, Australia. Report No.: N/A.
128) Sherwani AF, Usmani JA, Varun (2010) Life cycle assessment of solar PV based electricity generation systems: A review. Renewable and Sustainable Energy Reviews 14:540-544.
129) Fisch MN, Guigas M, Dalenbäck JO (1998) A review of large-scale solar heating systems in Europe. Solar Energy 63:355-366.

130) Zhivov A, Woody A, Walker A, Croy R, Richter S, Meißner R et al.(2011) Central solar hot water systems design guide. WBDG, Washington, District of Colombia. Report No.: N/A.
131) Wiser R, Bolinger M (2010) 2009 wind technologies market report. US Department of Energy - Energy efficiency & Renewable energy, Washington, DC, USA. Report No.:N/A.
132) Ortegon K, Nies LF, Sutherland JW (2013) Preparing for end of service life of wind turbines. J Clean Prod 39:191-199.
133) Ertürk M (2012) The evaluation of feed-in tariff regulation of Turkey for onshore wind energy based on the economic analysis. Energy Policy 45:359-367.
134) Ucar A, Inalli M (2008) Thermal and economic comparisons of solar heating systems with seasonal storage used in building heating. Renewable Energy 33:2532-2539.
135) Golabi K, Scherer CR, Tsang CF, Mozumder S (1981) Optimal energy extraction from a hot water geothermal reservoir. Water Resources Research 17:1-10.
136) Rafferty K (1996) Selected cost considerations for geothermal district heating in existing single-family residential areas. GeoHeat tp93:1-28.
137) Erdogmus B, Toksoy M, Ozerdem B, Aksoy N (2006) Economic assessment of geothermal district heating systems: A case study of Balcova–Narlidere, Turkey. Energy Build 38:1053-1059.
138) Wang W (2000) The opportunity and risk of geothermal heating investment in China. In: Proceedings World Geothermal Congress, Beppu - Morioka, Japan; 28 May -10 June 2000.
139) Ozdenefe M, Atikol U (2010) Applicability of trigeneration systems in the hotel buildings: The North Cyprus case. WSEAS Transactions on Power Systems 5:98-107.
140) Pöttler R (N/A) Energy from hydropower - Innovative and regenerative. ILF Beratende Ingenieure ZT Gesellschaft mbH, Innsbruck, Austria. Report No.: N/A.
141) Mittal G (2004) Real options approach to capacity planning under uncertainty. Dissertation. Massachusetts Institute of Technology.
142) Kaldellis JK, Vlachou DS, Korbakis G (2005) Techno-economic evaluation of small hydro power plants in Greece: a complete sensitivity analysis. Energy Policy 33:1969-1985.
143) Udomsri S, Martin AR, Martin V (2011) Thermally driven cooling coupled with municipal solid waste-fired power plant: Application of combined heat, cooling and power in tropical urban areas. Appl Energy 88:1532-1542.
144) Svensson I, Moshfegh B (2011) System analysis in a European perspective of new industrial cooling supply in a CHP system. Appl Energy 88:5164-5172.
145) Murugavel V, Saravanan R (2010) Life cycle cost analysis of waste heat operated absorption cooling systems for building HVAC applications. In: Proceedings of the 10th International Conference Enhanced Building Operations, Kuwait, 26-28 October 2010.
146) Energy and Waste Management Office (2012) Metro Hall - Deep lake water cooling. Toronto, Ontario. Report No.: (N/A)
147) Lund H, Morten BB (2007) Large-scale heat pumps in sustainable energy systems: System and project perspectives. Thermal Science 11:143-152.
148) Rivas F, Khire RA, Messac A, Van Dessel S (2006) Life cycle cost based economic assessment of active building envelope (ABE) systems. In: 2nd AIAA multidisciplinary design optimization specialist conference, Newport, Rhode Island; 1-4 May 2006.
149) NRCAN (2002) Heat recovery from kitchen refrigeration. Ottawa, Ontario. Report No.: M92-242/2002-6E.
150) Sanyal SK (2004) Cost of geothermal power and factors that affect it. In: Twenty-Ninth Workshop on Geothermal Reservoir Engineering, Stanford, California. 26-28 January 2004.
151) Tester JW, Anderson BJ, Batchelor AS, Blackwell DD, DiPippo R, Drake EM et al. (2007) Impact of enhanced geothermal systems on US energy supply in the twenty-first century. Phil Trans R Soc A 365:1057-1094.
152) European Geothermal Energy Council (EGEC) (N/A) The future of geothermal development - Presentation. http://www.iea-gia.org/documents/Antics-EGEC-THEFUTURE OFGEOTHERMALDEVELOPMENT.pdf. Accessed 12 July 2012
153) INL (2006) The future of geothermal energy. Idaho Falls, Idaho. Report No.: INL/EXT-06-11746.
154) Entingh DJ, Easwaran E, McLarty L (1994) Small geothermal electric systems for remote powering. The Geothermal Division - US Department of Energy, US. Report No.: GTSMAL-3.GTD.
155) Brugman J, Hattar M, Nichols K, Esaki Y (1994) Next generation geothermal power plants. EPRI, Pasadena, CA. Report No.: EPRI RP 3657-01.
156) Lund JW, Lienau PJ (2009) Geothermal district heating. In: International Geothermal Days, Conference & Summer School, Slovakia, 26-29 May 2009.
157) Piatti, A, Piemonte, C, Szegö, E (1992) Planning of geothermal district heating systems. Kluwer Academic Publisher, Dordrecht, The Netherlands.
158) Durmayaz A (2000) An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul. Energy 25:1245-1256.
159) Elsman P (2009) Copenhagen district heating system. Københavns E, Copenhagen, Denmark. Report No.: N/A.
160) ENeRGI STYRELSEN (2010) Energy Statistic 2010 (Energistatistik 2010). Copenhagen. Report No.: (N/A).
161) CTR, Københanvs E, and VEKS (2009) Data for teknologier til produktion af varme (Data of technologies for the production of heat). Copenhagen. Report No.: N/A.

162) NRCAN (2011) Monthly market update. http://www.nrcan.gc.ca/energy/ sources/natural-gas/monthly-market-update/2258. Accessed 9 November 2012.
163) OECD (2012) Economic Outlook. http://stats.oecd.org/. Accessed 15 June 2012
164) Energy Efficiency Office (2007) Toronto's Sustainable Energy Plan. Toronto, Ontario. Report No.: N/A.
165) Laursen EV, Thomsen RS, Cappelen J (1999) Observed air temperature, humidity, pressure, cloud cover and weather in Denmark - with climatological standard normals, 1961-90. Danish Meteorological Institute, Copenhagen, Denmark.Report No.: 99-5.
166) International wind resource maps [map] (2012) NREL, Washington, DC.
167) System advisor model - Version 2.3.1 [disk] (2011). NREL, Washington, DC.
168) The Weather Network (2012) Statistics: Toronto Lester B. Pearson Int'l, ON, Canada.
169) The International Renewable Energy Agency (IRENA) (2012) Renewable energy technologies: Cost analysis series. Abu Dhabi, United Arab Emirates. Report No.: Issue 5/5.
170) Nikolaisen L (2012) Country report 2011 for Denmark. Danish Technological Institute. Report No.: IEA bioenergy task 40.
171) Oo A, Kelly J, Lalonde C (2012) Assessment of business case for purpose-grown biomass in Ontario. The Western University Research Park, Sarnia-Lambton Campus, London, ON, Canada. Report No.: (N/A).
172) Mahler A, Magtengaard J (2005) Geothermal Development in Denmark, Country Update WGC 2005. In: Proceedings World Geothermal Congress, Antalya, Turkey. 24-29 April 2005.
173) Magtengaard J, Mahler A (2010) Geothermal reserves and sustainability in the Greater Copenhagen Area. In: World Geothermal Congress, Bali, Indonesia; 25-30 April 2010.
174) Bristow D (2009) The business case for alternative energy technologies in Ontario. Dissertation. University of Toronto.
175) Tol Hİ, Dincer I, Svendsen S (2013) Regional Energy Planning Tool for Renewable Integrated Low-Energy District Heating Systems: Environmental Assessment. In: Ibrahim Dincer, Can Ozgur Colpan, Fethi Kadioglu (eds). Causes, Impacts and Solutions to Global Warming, 1st edn, Springer, New York.
176) Ahmadi P, Rosen MA, Dincer I (2012) Multi-objective exergy-based optimization of a polygeneration energy system using an evolutionary algorithm. Energy 46:21-31.
177) Ozbilen A, Dincer I, Naterer GF, Aydin M (2012) Role of hydrogen storage in renewable energy management for Ontario. Int J Hydrogen Energy 37:7343-7354.

BOOK CHAPTER II

Chapter 45
Regional Energy Planning Tool for Renewable Integrated Low-Energy District Heating Systems: Environmental Assessment

Hakan İbrahim Tol, Ibrahim Dincer, and Svend Svendsen

Abstract Low-energy district heating systems, operating at low temperature of 55 °C as supply and 25 °C as return, can be the energy solution as being the prevailing heating infrastructure in urban areas, considering future energy schemes aiming at increased exploitation of renewable energy sources together with low-energy houses in focus with intensified energy efficiency measures. Employing low-temperature operation allows the ease to exploit not only any type of heat source but also low-grade sources, i.e., renewable and industrial waste heat, which would otherwise be lost. In this chapter, a regional energy planning tool is described considered with various energy conversion systems based on renewable energy sources to be supplied to an integrated energy infrastructure involving a low-energy district heating, a district cooling, and an electricity grid. The developed tool is performed for two case studies, one being Greater Copenhagen Area and the other Greater Toronto Area, in accordance with various climate conditions and available resources in these locations, CO_2 emission savings obtained with up to 880 and 1,400 M tons, respectively.

Keywords Regional energy planning • Low-energy • Low temperature • District heating • Renewable energy • Integrated energy distribution • Renewable integrated low-energy district heating systems • Environmental assessment • Intensified energy efficiency measures • Low-grade sources • Industrial waste heat • Regional energy planning tool • Integrated energy infrastructure • Low-energy district

H.İ. Tol (✉) • S. Svendsen
Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118, 2800 Kgs. Lyngby, Denmark
e-mail: hatol@byg.dtu.dk; ss@byg.dtu.dk

I. Dincer
Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, ON, Canada L1H 7K4
e-mail: Ibrahim.Dincer@uoit.ca

I. Dincer et al. (eds.), *Causes, Impacts and Solutions to Global Warming*,
DOI 10.1007/978-1-4614-7588-0_45,

heating • District cooling • Electricity grid • Copenhagen • Toronto area • CO_2 emission savings

45.1 Introduction

As long-term energy solutions, energy supply systems based on renewable energy sources have been of considerable interest to policy makers due to such systems being more environmentally friendly than those of fossil fuels that lead to depletion [1, 2]. District heating has shown its weightiness as a sustainable solution to community-wide energy supply system due to its benefits of being energy efficient in urban scale, ease of connecting to any type of heat source, and improved comfort levels provided to houses even in cold climate conditions [3, 4]. Aims focused on reducing the residential heat consumptions, together with the increasing exploitation of renewable energy sources for providing heat, have led to a new concept of district heating systems with improved efficiency measures by means of low-temperature operation such as 55 °C in the case of supply and 25 °C in the case of return [5, 6]. Various advantages have been observed regarding low operating temperatures in district heating systems, such as (a) reduced heat loss from the network and the network equipment, (b) increased efficiency of generating heat at the production site, (c) ease of exploiting low-grade heat sources such as waste heat from industrial facilities which otherwise gets lost, and (d) improved indoor thermal comfort at the consumer site with lowered speeds of air circulation, prevented dehydration of air, and reduced risk of skin burns [6–9].

Hence, the intention of this research was directed to design an energy planning tool on the regional basis with focus being given to determining the capacities of renewable-based energy conversion systems to regional heat requirements, which involves space heating and domestic hot water production.

45.1.1 Background

It can be rewarding to provide adequate background information for a better understanding of both concepts with respect to (a) the developments presented regarding the field of low-energy district heating systems and (b) various emphases considered in the models of energy planning tools presented by some of the studies in this field.

Low-Energy District Heating Systems

A preliminary project in this field [5, 6] has presented the concept of low-temperature operation (50 °C as supply and 25 °C as return) in low-energy district heating systems with detailed analysis, in particular, being performed with respect to (a) heat demand of low-energy houses, (b) substation configurations in proper to low-temperature operation, (c) twin-pipe utilization in the district heating network, and (d) socioeconomic assessment of employing low-energy district heating systems in comparison to alternative heating option considered with equipping an individual heat pump at each house located in the district. The observations regarding the case studies taken in this research showed that low-energy district heating systems are competitive in socioeconomic perspective compared to alternative heating systems. Several successful examples of employing low-energy district heating systems have been demonstrated in case projects in Lystrup, Denmark [10, 11]; in the SSE Greenwatt Way development project in Slough in the UK [12]; in the Drake Landing Solar Community project in Okotoks, Alberta, Canada [13]; and in Munich, Germany [14].

Various analyses have been performed in order to investigate the further improvements in employing low-energy district heating systems in addition to the benefits achieved by means of low-temperature operation. Torio [15] performed exergy analysis on low-energy systems involving heating and cooling, operating in low temperatures and high temperatures, respectively, in assessing exergy performance with different scopes such as in the levels of human thermal comfort, building, community, and heat source. Christiansen [11] and Brand [16] presented detailed description of substation configurations, equipped either with storage tank or without, both in proper with low-temperature operation. Tol and Svendsen [17, 18] addressed various aspects of designing low-energy district heating systems, details being given regarding (a) determination of pipe dimensioning methods; (b) comparative assessment of substation types, either equipped with storage tank or not; and (c) the effect of consumer behavior on the energy performance of the network layouts, either branched or looped.

Regional Energy Supply Planning

Lund et al. [19] assessed expansion scenarios of renewable-based district heating in urban and rural areas located at Denmark. Their results concluded in prevailing use of district heating systems in the urban areas to be considered as the future national energy supply scheme. However, the energy supply in the rural areas was found to be relied on individual heat pump systems for the purpose of heating. Sperling and Möller [20, 21] addressed that expending the network of district heating when considered together with improved residential energy performance improves the heat production efficiency. Østergaard and Lund [22] proposed a transition period for the Frederikshavn energy infrastructure—considering electricity, heat, and fuel required for industry and transportation system—to be based totally on renewable energy. Mathiesen [23] carried out a comparative analysis focused on exploiting biomass considered either in the heat sector or in the industrial sectors. The results highlighted using biomass in industrial sectors more than heating sector. Weber and

Shah [24] presented a communal energy supply tool DESDOP with respect to meeting two different energy requirements as heating and electricity.

45.1.2 Goal and Scope Definition

This chapter presents an energy planning tool focused on determining the capacities of energy conversion systems, each sourcing from different renewable energy source and/or having different energy generation configuration considered with single generation, co-generation, and tri-generation. The latter was considered due to the efficiency gains by means of multi-generation systems in which the waste heat from one energy generation, which would otherwise be lost, is utilized in the generation of another energy form(s) [1]. Hence the focus was extended to the consideration of other energy requirements such as electricity and cooling in addition to the heating requirement. Further consideration was directed to assess the satisfaction of the energy requirements on a monthly basis since the availability of certain renewable energy sources varies stochastically through an year period (such as solar and wind energy) as well as energy requirements, each showing distinct trend of variation [24].

45.2 System Description

The regional energy supply was considered with a city-wide integrated energy system taking account of a low-energy district heating system, an electricity grid, and a district cooling. The energy source of the integrated system can be multiple energy conversion systems, each based on different renewable energy source and/or having different generation technology (Fig. 45.1).

45.2.1 Low-Energy District Heating Networks

A low-energy district heating network is considered as the prevailing heating infrastructure, when it covers the whole neighboring urban settlements in a city/ region due to its ease to connect any type of heat source. One of the successful examples of large-scale district heating systems can be illustrated by the Copenhagen district heating network which has the capacity to supply heat to 275,000 households [3]. Employing such city-wide district heating system in populated urban settlements brings the need for an energy planning scheme on the basis of infrastructure transformation with respect to new and existing settlements. New settlements can be easily employed with low-energy district heating systems. The design of the piping network, however, was considered with

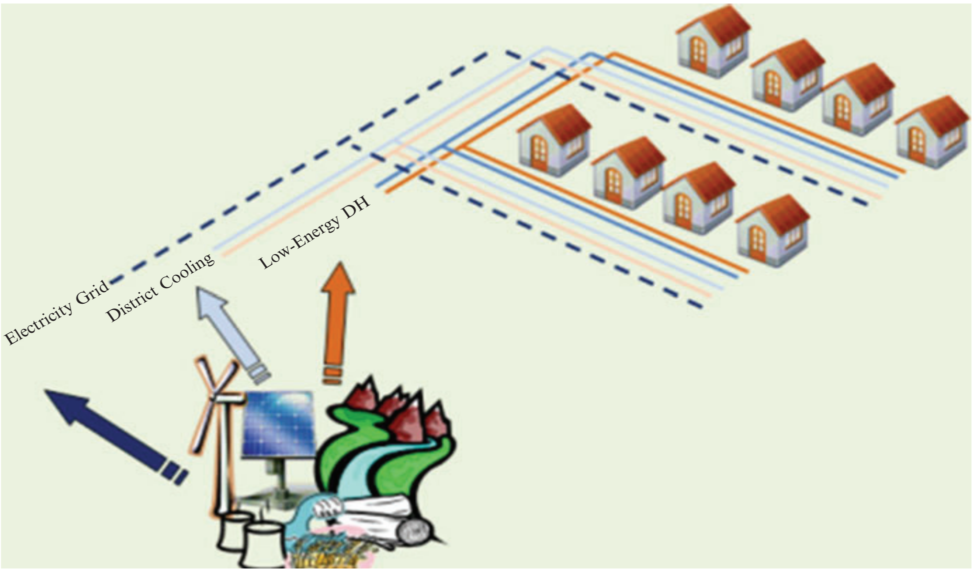


Fig. 45.1 Simplified illustration of an integrated renewable supply

optimizing the piping network being aimed at minimizing the dimensions of each pipe segment until the pressure loss through each route reaches to the head lift provided by the main pump station [17]. The existing settlements employed with either conventional district heating systems operating in high temperature configuration or natural gas grid were considered to be replaced with low-energy district heating systems. The transition period for these settlements was considered with operational control philosophy involved with boosting of the supply temperature in the peak cold winter periods. This operational strategy allowed reduction of the pipe dimensions in the design stage of low-energy district heating systems in these locations. This is due to the over-sizing of the in-house radiator systems equipped in the old houses located at the existing settlements, which was obtained with reduced mass flow requirement in case the supply temperature is boosted [25, 26].

45.2.2 Integrated Energy Supply

The efficiency improvement measure that is possible with multi-generation facilities contributes to the necessity of integrating other energy requirements to be considered with low-energy district heating systems. Hence, in this chapter, the energy forms are considered with heating, electricity, and cooling, each being provided by means of a distribution network, i.e., heat supply via low-energy district heating system, electricity via electricity grid, and cooling via district cooling system, all of which considered as the residential requirements.

Large-scale distribution systems have the advantage of utilizing economy of scale that allows lowered specific investment costs (cost per unit nominal capacity) for the energy conversion systems when they are designed in large scales.

45.2.3 Renewable Energy Conversion Systems

Various energy conversion systems are considered in this chapter on the basis of having various renewable energy sources and/or different energy generation technologies. An extensive assessment of various energy conversion systems together with exergy analysis can be found in [27].

Solar Energy

Being used by the mankind for many millenniums, solar energy is still the most used energy source, not only being the energy source to produce the useable energy forms (such as heat and electricity) but also being the passive source required for the natural life and also with its passive heating on the earth. In this chapter the solar energy is considered to be exploited by the recent conventional energy conversion systems that are photovoltaic (PV) cells, hybrid PV and thermal (PV/T) cells, and solar collectors (SC) [28–30]. PV cells convert the solar photons to electricity energy, SC recover the accumulated thermal energy to heat energy, and hybrid PV/T cells produce electricity while the thermal energy accumulated on the cells being recovered to be used as useable output of heat energy. The solar energy is dependent on the sunlight with respect to its availability and insolation rate due to a substantial level of capacity factor regarding the nominal capacities of solar energy conversion systems.

Wind Energy

Having its earlier applications by means of windmills, wind energy is a prominent renewable energy source to be considered in the future energy supply solutions. The wind turbine technology makes use of harvesting the kinetic energy of wind in order to generate electricity. The electricity generation performance by the use of wind energy is dependent on various parameters regarding the weather conditions such as wind speed together with its regularity, wind direction, and flatness of the site area where it is employed [31]. Although wind turbine technology is the same for both onshore and offshore applications, excessive variation of the cost for energy generation from onshore wind turbines are observed due to varying land prices [32].

Geothermal Energy

The geothermal energy is the hot medium that exists in the depths of the earth, either in the form of hot water or in the form of steam, or mixture of both. The temperature gradient (the temperature change per depth below earth) of the geothermal energy shows variation according to the geological conditions of the location. The quality of the geothermal energy has a significant impact on determining the energy output to be generated and/or the technology of the energy conversion system [33]. Low-quality-level geothermal sources found in low temperatures of hot water below 80 °C can be exploited by direct utilization, as heat source for district heating systems. Direct utilization shall not be mixed with the direct connection which is used for the geothermal district heating systems in which geothermal water is circulated through the whole piping network while indirect connection makes use of heat exchangers to separate the piping networks, one being the piping network circulating the geothermal mean while the other being the district heating network circulation, another heat carrier medium. There are three different energy conversion systems commonly used on the basis of the quality level of the source. In the case the brine medium in the geothermal reservoir is obtained with vapor-dominated medium, the “dry steam” technology is considered, which circulates the steam extracted from the ground directly in its plant cycle. In the case of a geothermal source embodying liquid-dominated brine medium (above 80 °C) the “binary” technology is used, which makes use of the brine energy in vaporizing the binary working fluid having low boiling temperature to be circulated in its plant cycle. In the case of a geothermal source embodying brine medium with a mixture of liquid and vapor the “flash” technology is used, which separates the steam out of the mixture of brine and directly utilizes the extricated steam in its cycle [27, 34].

Despite it being economical and sustainable, geothermal energy has some limitations such as dependency on the geological conditions of the location together with the temperature gradient existing there, and the risk of reservoir cooling after a long period of usage in the situation of stagnant brine circulation.

The earth mass can also be utilized for storing the energy of hot water, its heat energy being generated by means of other renewable sources when excessive production more than consumption is possible. Borehole storage technology consisting of aggregated circulation holes can be referred as natural storage option despite being man-made [35]. Its application is commonly based on storing the excessive heat produced during summer period when the heat requirement is low and discharging the heat stored in the peak winter periods to be supplied to district heating network [36].

Biomass

Being obvious as the most mature renewable source due to its existence based on the discovery of fire, biomass fuel has been having recent interest by most as being the alternative solution instead of using coal when considered together with its benefit of being found easily in the nature [37]. However, it should be noticed that the increasing demand on biomass by not only the heating sector but also other industrial sectors may cause a shortage of biomass supply. Biomass utilization can be considered as renewable when the biomass fuel is harvested from a farm (not a forest) in which the following biomass plants have to be grown sequentially. If not (if the consumption of biomass exceeds its production), then it could not be renewable any more [23, 38]. In the case of municipal solid waste (MSW), it cannot be considered as biomass and renewable unless the fossil fuel-based plastics are replaced with bio-based polymers [39].

In this chapter, biomass-based energy conversion technologies (being assumed to be totally renewable) are considered with three different technologies as MSW co-generation with incineration and with gasification, and as biomass tri-generation, their details being presented in [40–42].

Waste Heat Recovery

Despite its possibility of sourcing from fossil fuels, recovering of the waste heat (also called as surplus heat) from industrial facilities can be rewarding due to it being a savior for the waste heat that is easy to be utilized and gets lost if not recovered. Waste heat energy, if recovered in high qualities, is better to be utilized in the same industrial cycle. If it cannot be utilized in the industrial cycle then it should be considered to be exploited in the production of electricity (if found in high quality level) or in the production of heat to be supplied to district heating system or neighboring heating facility (if found in low quality level) [43, 44]. In this chapter, waste heat recovery technology is considered as heat recovery facilities in connection to medium- or low-scale industry refrigeration cycles (details given in [45]), the recovered heat being considered to be supplied to low-energy district heating system.

Large-scale hybrid heat pumps are also considered in this chapter. Hybrid heat pumps based on tri-generation technology were considered to be sourced by the waste heats from medium-scale industries, operating in tri-generation mode in summer periods and in co-generation mode in winter periods [46, 47].

Hydroelectricity

Hydroelectric plants are the efficient way of producing electricity allowing rapid response to spontaneous electricity requirements by means of taking advantage of the potential energy of the previously stored river water behind the dam. The electricity production of hydroelectric plants differs significantly between seasons, i.e., the peak production occurs in winter period that is significantly higher than summer period (in the northern sphere) [48]. On this basis, capacity factor was considered in the monthly basis for this technology. The hydro-energy plant technology is considered in small-scale applications in this chapter due to already overspreading existing large-scale applications on the available river sites.

Cooling Systems

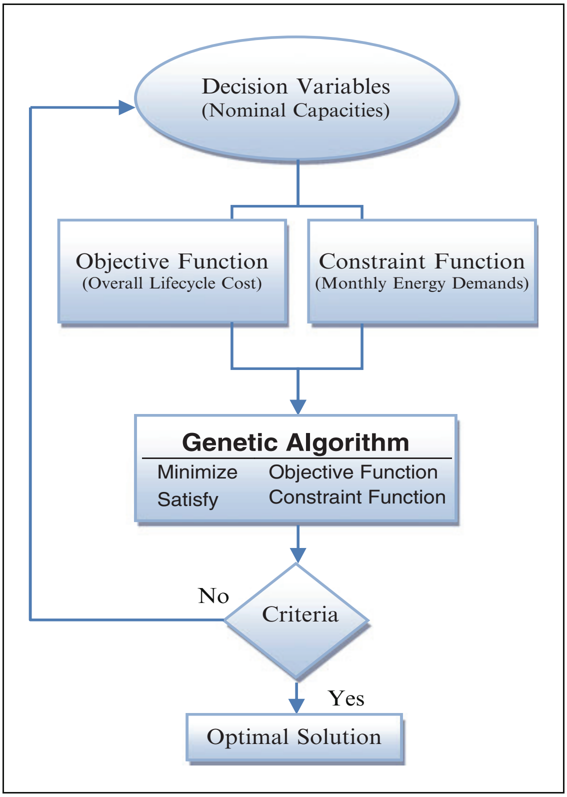
Being similar in the concept-manner with direct utilization of the geothermal energy in district heating systems, free cooling energy conversion systems become trendier as a source for the district cooling systems due to it being economical and having simpler technology compared to alternative cooling technologies. Associating free cooling with the direct utilization of geothermal is due to similar operations being observed between them. For example, in the case of free cooling, the passively cooled water mass existing in the depths of water bodies (such as sea, lake, and river) is being directly utilized as a cooling source for the district cooling network, as well as in the case of direct utilization of geothermal energy in which the brine medium is the heating source for district heating network [49, 50]. The variation in the temperature of water bodies has to be measured in order to assess the capacity factor for the use of free cooling. Hence the peak-period energy conversion technologies have to be considered in accordance with the variation of water temperature, especially for the summer period. The energy conversion systems for the peak cooling period are considered with compressor chillers which make use of electricity, and with absorption chiller which makes use of heat (recovered from industrial facilities); their details are given in the studies [51–53].

45.3 Energy Planning Considerations

The most important consideration in energy planning, above all, is estimating the energy requirements of the region (as the focus in this chapter on heat, electricity, and cooling) wisely, in particular considering the energy demands (of the regional houses) by taking account of the current demands together with their expected values in future and with the expected population growth. Another consideration has to be directed to the determination of the heat load (on the distribution network) by taking account of simultaneity factor that is based on the phenomenon that each consumer in a district does not consume energy at the same time nor at the same rate [54]. Energy losses from the DH network also have to be considered due to its considerable effect on the heat production site. However, in the case of employing a low-energy district heating system as the prevailing heating infrastructure at the region, heat saving is possible due to significant reductions of the heat loss from the network, thanks to the low-temperature operation [17]. The energy planning has to be based on an analysis formulated with evaluation of the energy requirements in shorter periods than an year period assessment. The reason behind this is the variable nature of most energy requirements together with the dissimilar variation of the renewable energy production [24].

After determining the most plausible energy requirements of the region in focus, it can be beneficial to use a regional energy planning tool that determines the nominal capacities of the energy conversion systems that exploit the locally

Fig. 45.2 Optimization flow chart, as defined for the energy planning tool



available renewable sources, considered with prevention of having over-dimensioned energy conversion systems and also lack of security of supply. Hence, an energy planning tool was modelled in this research work with an optimization method involved with the genetic algorithm (details presented in [55]). As shown in Fig. 45.2, the objective function of the optimization method in question was formulated with minimization of the overall life cycle cost of the entire regional energy conversion systems while an expression being modelled for the constraint function as evaluation of monthly energy requirements.

In order to maintain a general basis as comparative degree for all of the energy conversion systems, life cycle cost calculation was involved with various economic considerations. The specific investment cost expression was derived by taking account of the economy of scale for each energy conversion system [53]. The reason behind this is to include the effect of the nominal capacity on the investment cost for each energy conversion system. Salvage cost values were involved in the economic calculations since each energy conversion system has quite different lifetime and salvage value at the end of its lifetime. Due to the variation in the lifetimes, a base period was considered for the net present value (NPV) method on the account of the energy conversion technology with the shortest lifetime, and the salvage costs of the energy conversion technologies are allocated accordingly.

(Further details are presented elsewhere [56]). Annual costs were considered with O&M cost for all technologies and, exceptionally, with also fuel cost for the case of biomass-based tri-generation system.

As a general impression, efficiency measures are not generally of any interest since there is no need to concern fuel costs when renewable energy sources are considered (except for biomass). However, the nominal capacity being determined in the design stage of an energy conversion system is significantly dependent on efficiency measures as well as the availability of the renewable source. Besides, the seasonal weather conditions can also affect the performance of the energy generation to a lesser or a greater degree, dependent on the energy conversion system in focus. This seasonal effect was involved in the performance calculations by means of capacity factor considerations. The capacity factor was considered with monthly variation for the case of energy conversion systems, their renewable source varying significantly amongst months, while in the case of other energy conversion systems, the capacity factor accounted as same value for each month.

Heat supply was exclusively considered with long-term energy storage option in order to overcome the supply/demand mismatch amongst seasons due to the significant gap between the excessive heat energy produced in summer and the intensive heat demand in winter periods. The seasonal mismatch in terms of electricity was not considered in this study with long-term storage option due to limitations of the current technology.

45.4 Environmental Assessments

In this section, environmental issues regarding the use of renewable energy sources and the major savings compared to use of traditional fossil fuel-based energy conversion systems are described.

45.4.1 Environmental Issues

Renewable sources are known to be “green” due to their environmental impact being excessively low or nonexistent during their operation. However, some energy conversion systems have some minor impacts to environment either in their manufacture or during their operation. For example, PV cells can be hazardous due to the materials used and/or the fossil fuels consumed during the manufacturing process [57]. One should note that during the drilling of the geothermal wells, underground gases can leak to the atmosphere and the waste geothermal medium, after its heat content utilized, should be re-injected back to the underground reservoir [58]. Onshore wind farms are known with the environmental issues as noise pollution and as risk of killing the birds and bats during the operation [32]. In the incineration application of MSW, the fossil fuel-based plastic materials should be

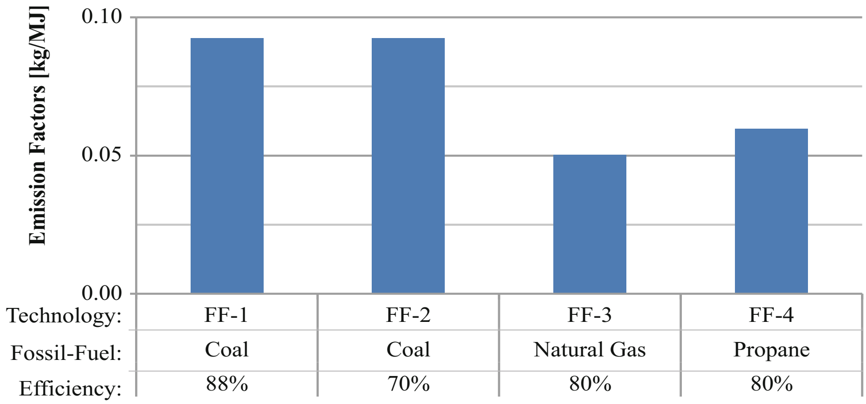


Fig. 45.3 The emission factors and thermal efficiencies, as assumed for four different fossil fuel-based energy conversion systems, based on [61]

removed from the solid waste by means of recycling before the incineration [39]. The debate regarding the environmental effect of biomass is due to the risk of losing the soil nutrients, and soil erosion occurring due to rainfalls after harvesting of biomass farm [59]. Employing the free cooling technology should be considered with special attention about the temperature increment on the water body [60].

45.4.2 Emission Savings

Besides their minor environmental effects, utilizing renewable energy sources can save significant amount of emissions in comparison to the fossil fuel-based technologies. For the case the same amount of energy requirements were provided by them instead of renewable-based technologies, the emission impacts were assessed for four different traditional fossil fuel-based energy conversion technologies, being defined as (FF-1) coal-based back-pressure steam turbine with a thermal efficiency of 88 %, (FF-2) coal-based extraction-condensing steam turbine with a thermal efficiency of 70 %, (FF-3) natural gas-based gas turbine with a thermal efficiency of 80 %, and (FF-4) propane-based reciprocating engine with a thermal efficiency of 80 %, as shown in Fig. 45.3 [61].

45.5 Results

In this chapter, the developed energy planning method is applied on two case areas: the Greater Copenhagen Area (GCA) and the Greater Toronto Area (GTA), where the annual heating degree-hours being, respectively, 1,807 and 2,400 and the cooling degree-hours in summer season being, respectively, 30 and

Table 45.1 Optimal nominal capacities, as obtained for the case areas GCA and GTA

Color labels[a]	Renewable technology		Nominal capacity GCA	GTA	Units[b]
■	PV cells		–	2.1e+7	m^2
■	PV/T cells		4.0e+6	5.0e+4	m^2
■	SC		5.0e+6	–	m^2
■	Wind—onshore		1.1e+3	8.5e+2	MW
■	Wind—offshore		1.0e+3	8.0e+2	MW
■	Hydroelectric		–	1.0e+5	MW
■	Geothermal direct		6.1e+2	4.3e+3	MW
■	Charge	BTS	4.9e+5[c]	1.1e+6[c]	m^3
■	Discharge				
■	Waste heat—chillers		2.5e+4	8.0e+5	kW
■	Hybrid heat pump		1.0e+3	1.1e+2	kW
■	MSW—incineration		2.9e+6	5.3e+3	tpa
■	MSW—gasification		3.0e+6	1.0e+6	tpa
■	Biomass—tri-generation		5.5e+5	9.5e+5	tpa
■	Free cooling		1.5e+2	5.4e+2	kW
■	Absorption		4.2e+4	8.0e+4	kW
■	Compressor chiller		1.1e+4	–	kW
■	Overproduction[d]		–	–	–

[a]The color labels are used, as same, in Figs. 45.4 and 45.5
[b]The unit of each nominal capacity is given in the last column
[c]The nominal capacity of borehole storage while the color labels given for charge and discharge
[d]The overproduction refers to the excessive energy produced more than the demand, shown in black color in the figures

370, respectively (units in [°C-h]). Hydroelectric energy conversion system is not considered in GCA due to the absence of rivers in this location [3]. Biomass fuel prices are assumed to be 166 €/ton in the GCA case, whereas it is assumed to be 130 €/ton for GTA (due to the vast amount of land and biomass fuel), the values being derived from [62, 63]. Moreover, both case areas have the geothermal source with a temperature gradient of 30 °C/km [64, 65]. Table 45.1 shows the nominal capacities for each of the case areas GCA and GTA, obtained with overall life cycle costs of 19 and 24 B€ (billion euro), respectively.

The energy supplies by each of the energy conversion systems, their nominal capacities shown in Table 45.1, are given in terms of the energy requirement types—electricity, heating, and cooling, respectively, in subsections (a), (b), and (c)—in Fig. 45.4 for the case of GCA, and in Fig. 45.5 for the case of GTA.

The CO_2 emissions were observed with respect to the case in which the same amount of energy requirements were produced by means of fossil fuel-based energy conversion systems, as shown in Table 45.2.

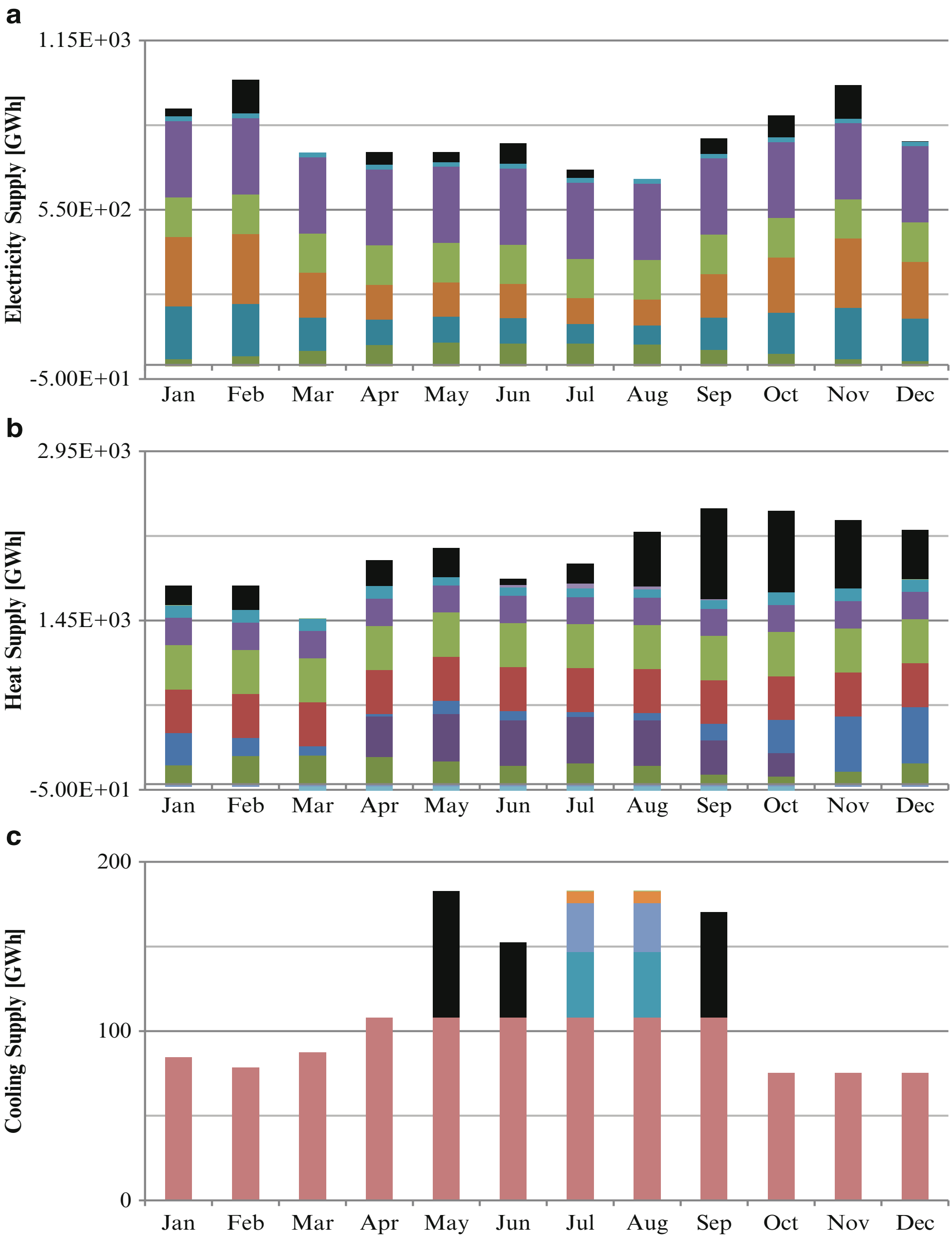


Fig. 45.4 The energy supplies in terms of electricity, heat, and cooling, as obtained for GCA (see Table 45.1 for the labels)

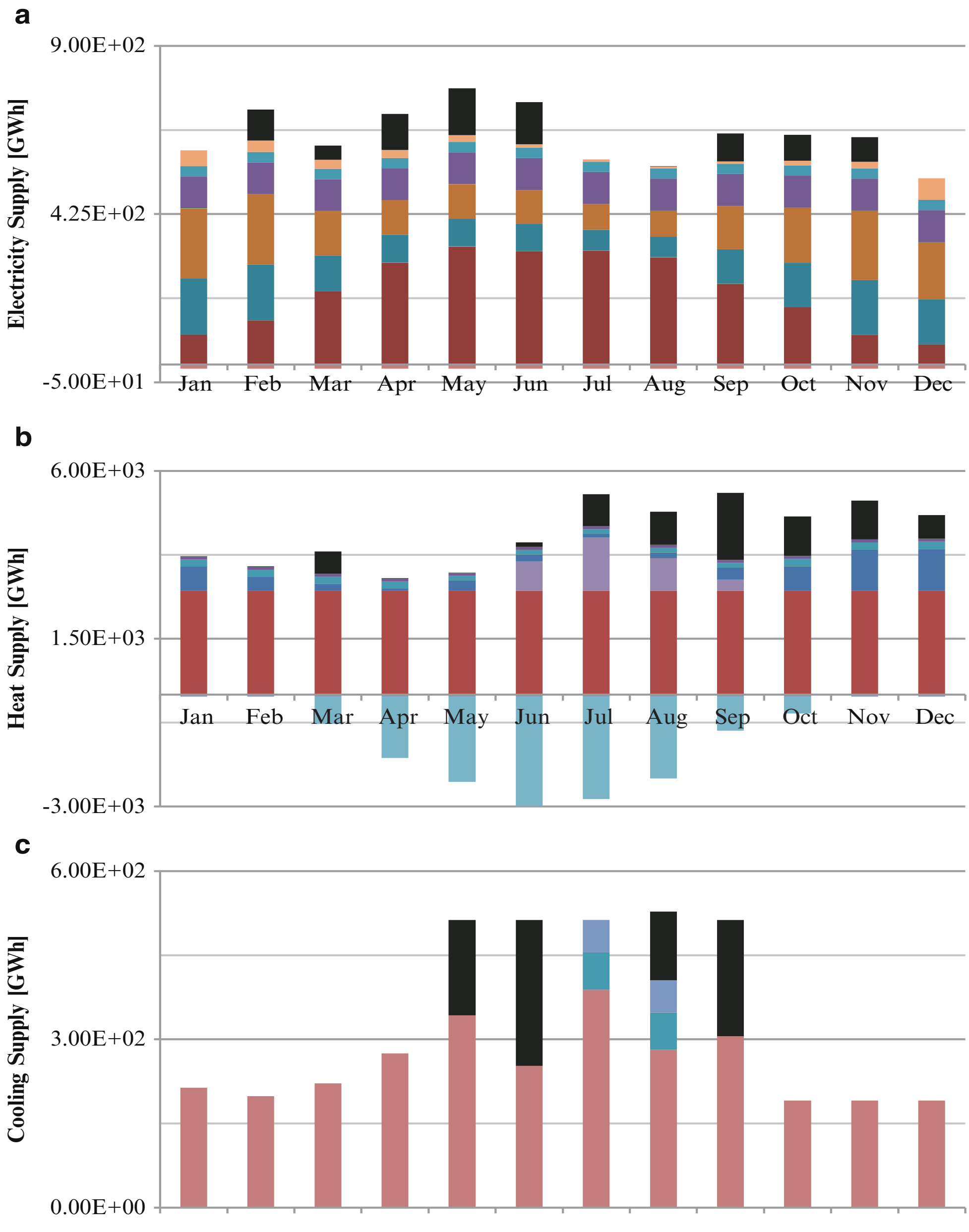


Fig. 45.5 The energy supplies in terms of electricity, heat, and cooling, as obtained for GTA (see Table 45.1 for the labels)

Table 45.2 CO_2 emissions, as obtained for each of the four technologies based on fossil fuels

	Emissions (CO_2) [M tons]	
Technologies	GCA	GTA
FF-1	703	1,118
FF-2	883	1,406
FF-3	420	668
FF-4	499	794

45.6 Discussions

This chapter provides an energy planning method considered with solely renewable energy sources supplying various energy types via an integrated energy distribution network. The integrated distribution network considers low-energy district heating network, district cooling, and electricity grid, as the scope of this chapter. The optimal capacities of renewable energy conversion systems obtained exclude the existing renewable sources exploited in the case areas in question since a general method can be drawn for assessing the locally available renewable energy sources and in determination of the requiring energy conversion systems for any focused case. Integrated city-wide distribution networks allow having the advantage of economy of scale considering the investment cost of each energy conversion system. This can be the basis behind the relatively small difference observed between the overall life cycle costs of two difference case areas in question, as can be seen in Table 45.1. The relatively small increment at the life cycle cost for the case of GTA, for example, could be due to the economy-of-scale effect despite colder and hotter climate conditions enduring, respectively, in winters and in summers in the case of GTA than in the case of GCA. The climatic nature of a case area has its influence on the optimal solutions in two manners, one being its effect on the energy requirements and the other being the availability of the renewable energy sources together with the variation of energy generation rate through an year period by use of them.

The energy planning method in question can result with several solutions, each being obtained with another optimization run despite the same modelling of the case area employed. However each solution obtained could not necessarily be the optimal solution considering the security of supply and the overproduction of each energy form together with the overall life cycle cost. The solution involving a reasonable variety of renewable sources and having the minimum overall life cycle cost is considered as the optimal solution, which is observed with also the least degree of overproduction in most, as seen in Fig. 45.4 for GCA and in Fig. 45.5 for GTA. The saving of CO_2 emissions in comparison to the case of the same input values of energy requirements supplied by traditional fossil fuel-based energy conversion systems can be seen in Table 45.2, which can account significantly in the carbon emission reduction targets when considering only meeting the residential energy requirements.

45.7 Conclusions

This chapter presents a novel method for determining the optimal capacities of RE-based energy conversion systems in focus with handling different climatic conditions and satisfaction of the energy requirements of various types for different periods of the year. A number of general conclusions not yet taken up can be drawn. One is that employing a city-wide distribution network supplying the energy forms required for the case area in focus can be beneficial due to the reduced unit costs achieved by means of the large-scale application of energy conversion systems together with the efficiency improvements possible with multi-generation systems. In addition, the borehole storage option can be considered for balancing the mismatch of heat production to heat demand between different seasons in long-term periods. One can note that significant environmental benefits can be achieved in proper with the national emission reduction targets of most by use of the proposed optimization method in an urban district in which the residential buildings are planned to be in focus with improved efficiency measures and potentials of the local renewable energy sources being comprehensively assessed.

Acknowledgements Financial supports, partially granted by COWIfonden, Marie & MB Richters Fond, and Oticon Fonden, are gratefully acknowledged.

References

1. Dincer I, Zamfirescu C (2012) Renewable-energy-based multigeneration systems. Int J Energ Res 36:1403–1415
2. Lund H (2010) Renewable energy systems: the choice and modeling of 100 % renewable solutions. Elsevier Science & Technology, MA, USA
3. Lund H, Mathiesen BV (2009) Energy system analysis of 100 % renewable energy systems—the case of Denmark in years 2030 and 2050. Energy 34:524–531
4. Persson U, Werner S (2011) Heat distribution and the future competitiveness of district heating. Appl Energ 88:568–576
5. Olsen PK, Lambertsen H, Hummelshøj R, Bøhm B, Christiansen CH, Svendsen S et al (2008) A new low-temperature district heating system for low-energy buildings. In: The 11th international symposium on district heating and cooling, Reykjavik, Iceland, 31 Aug to 2 Sept 2008
6. Paulsen O, Fan J, Furbo S, Thorsen JE (2008) Consumer unit for low energy district heating net. In: The 11th international symposium on district heating and cooling, Reykjavik, Iceland, 31 Aug to 2 Sept 2008
7. Danfoss (N/A) 8 steps—control of heating system. http://www.heating.danfoss.com/Content/61078BB5-1E17-4CA2-AC498A7CAC2BA687_MNU17424997_SIT54.html. Accessed 10 Nov 2011
8. Foged M (1999) Low temperature operation, DBDH. http://www.dbdh.dk. Accessed 10 Jan 2011
9. Østergaard PA, Mathiesen BV, Möller B, Lund H (2010) A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 35:4892–4901

10. Thorsen JE, Christiansen CH, Brand M, Olesen PK, Larsen CT (2011) Experiences on low-temperature district heating in Lystrup—Denmark. In: Proceedings of the international conference on district energy international conference on district heating and cooling, Portorož, Slovenia, 20–22 Mar 2011
11. Christiansen CH, Worm J, Jørgensen H, Thorsen JE, Bennetsen J, Larsen CT et al (2011) Demonstration of low energy district heating system for low energy building in ringgårdens Afd. 34 in Lystrup (Demonstration af lavenergifjernvarme til lavenergibyggeri i boligforeningen ringgårdens afd. 34 i Lystrup). DEA, Århus, Denmark
12. Wiltshire R (2011) Low temperature district energy systems (2011) In: Proceedings of the urban energy conference, Debrecen, Hungary, 14–15 Oct 2011
13. Sibbitt B, Onno T, McClenahan D, Thronton J, Brunger A, Kokko J et al (2007) The drake landing solar community Project—early results. In: Canadian solar buildings conference, Canmet Energy Technology Centre, Calgary, 10–14 June 2007
14. Bodmann M, Mangold D, Nußbicker J, Raab S, Schenke A, Schmidt T (2006) Solar unterstützte Nahwärme und Langzeit-Wärmespeicher. Forschungsbericht zum BMWA/BMU-Vorhaben (Februar 2003 bis Mai 2005), Universitetät Stuttgart and Technische Universitetät Braunschweig, Stuttgart
15. Torio H, Schmidt D (2011) Low exergy systems for high-performance buildings and communities. ECBCS—Annex 49
16. Brand M, Thorsen JE, Svendsen S (2012) Numerical modelling and experimental measurements for a low-temperature district heating substation for instantaneous preparation of DHW with respect to service pipes. Energy 41:392–400
17. Tol Hİ, Svendsen S (2012) Improving the dimensioning of piping networks and network layouts in low-energy district heating systems connected to low-energy buildings: a case study in Roskilde, Denmark. Energy 38:276–290
18. Tol Hİ, Svendsen S (2012) A comparative study on substation types and network layouts in connection with low-energy district heating systems. Energ Convers Manag 64:551–561
19. Lund H, Möller B, Mathiesen BV, Dyrelund A (2010) The role of district heating in future renewable energy systems. Energy 35:1381–1390
20. Sperling K, Hvelplund F, Mathiesen BV (2011) Centralisation and decentralisation in strategic municipal energy planning in Denmark. Energy Policy 39:1338–1351
21. Sperling K, Möller B (2012) End-use energy savings and district heating expansion in a local renewable energy system—a short-term perspective. Appl Energ 92:831–842
22. Østergaard PA, Lund H (2011) A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energ 88:479–487
23. Mathiesen BV, Lund H, Connolly D (2012) Limiting biomass consumption for heating in 100 % renewable energy systems. Energy 48:160–168
24. Weber C, Shah N (2011) Optimisation based design of a district energy system for an eco-town in the United Kingdom. Energy 36:1292–1308
25. Tol Hİ, Svendsen S (2012) Optimal dimensioning of low-energy district heating networks with operational planning—case study for existing buildings. In: 11th international conference on sustainable energy technologies, Vancouver, Canada, 2–5 Sept 2012
26. Tol Hİ, Svendsen S (2012) Operational Planning of low-energy district heating systems connected to existing buildings. In: International Conference on Renewable Energy: Generation and Applications, Al-Ain, United Arab Emirates, 4–7 Mar 2012.
27. Hepbasli A (2008) A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 12:593–661
28. Bosanac M, Sørensen B, Katic I, Sørensen H, Nielsen B, Badran J (2003) Photovolta-ic/thermal solar collectors and their potential in Denmark. Danish Technological Institute, Novator Advanced Technology Consulting, and Esbensen Consulting Engineers Ltd., Denmark
29. Kalogirou SA (2004) Solar thermal collectors and applications. Progr Energ Combust Sci 30:231–295

30. Fisch MN, Guigas M, Dalenbäck JO (1998) A review of large-scale solar heating systems in Europe. Sol Energ 63:355–366
31. Burton T, Jenkins N, Sharpe D, Bossanyi E (2011) Wind Turbine Installations and Wind Farms. In: Wind Energy Handbook: John Wiley & Sons, Ltd 2011:525–564
32. Blanco MI (2009) The economics of wind energy. Renewable and sustainable energy re-views 13:1372–1382
33. Lee KC (2001) Classification of geothermal resources by exergy. Geothermics 30:431–442
34. Coskun C, Oktay Z, Dincer I (2011) Performance evaluations of a geothermal power plant. Appl Therm Eng 31:4074–4082
35. Kizilkan O, Dincer I (2012) Exergy analysis of borehole thermal energy storage system for building cooling applications. Energ Build 49:568–574
36. Chapuis S, Bernier M (2009) Seasonal storage of solar energy in borehole heat exchangers. In: Eleventh international IBPSA conference, 27–30 July 2009
37. Vallios I, Tsoutsos T, Papadakis G (2009) Design of biomass district heating systems. Biomass Bioenergy 33:659–678
38. O'Kelly G, Rahikainen A (2011) European biomass review—new comprehensive analysis and forecast of the European bioenergy sector. RISI
39. Wolf O, Crank M, Patel M, Marscheider-Weidemann F, Schleich J, Hüsing B et al (2005) Techno-economic feasibility of large-scale production of bio-based polymers in Europe. European Communities, Prague
40. Michalski ML (2006) Biomass, biogas and municipal waste as alternative energy sources for historical cities. Environ Prot Eng 1:41–49
41. Murphy JD, McKeogh E (2004) Technical, economic and environmental analysis of energy production from municipal solid waste. Renew Energy 29:1043–1057
42. Fruergaard T, Christensen TH, Astrup T (2010) Energy recovery from waste incineration: assessing the importance of district heating networks. Waste Manag 30:1264–1272
43. Bédard S (2012) Waste heat to power: a process integration perspective. CanmetENERGY, Devon
44. Johnson I, Choate WT (2008) Waste heat recovery: technology and opportunities in U.S. industry. BCS, Memphis
45. Baxter VD (2003) Advanced supermarket refrigeration/heat recovery systems - Final report volume 1 - Executive summary. IEA Annex 26
46. Lund H, Morten BB (2007) Large-scale heat pumps in sustainable energy systems: system and project perspectives. Therm Sci 11:143–152
47. Westerlund R, Chiba T, Åstrand LE (1987) Heat pumps for district heating applications. In: Zimmerman KH, Powell RH (eds) Heat pumps—prospects in heat pump technology and marketing. LEWIS PUBLISHERS, INC., Orlando, FL, pp 427–452
48. Pöttler R. Energy from hydropower—innovative and regenerative. http://www.ilf.com.pl/fileadmin/user_upload/publikationen/13_Energy_from_Hydropwer_Innovative_and_regenerative.pdf. Accessed 15 Dec 2012
49. Bøgeskov H (2012) KE Fjernkøling A/S (KE Cooling A/S). Københavns E. http://www.ke.dk/. Accessed 1 Dec 2012
50. Looney CM, Oney SK (2007) Seawater district cooling and lake source district cooling. Energ Eng 104:34–45
51. Bailer P, Pietrucha U (2006) District heating and district cooling with large centrifugal chiller—heat pumps. In: Proceedings of 10th international symposium on district heating and cooling, Hanover, Sept 2006
52. Dalin P, Ivancic A, Tvärne A, Penthor A, Martin B, Ricci F et al (2006) District cooling—cooling more with less. Euroheat Power 32
53. Werner S (2004) District heating and cooling. In: Cleveland CJ (ed) Encyclopedia of energy. Elsevier, New York, pp 841–848

54. Winter W, Haslauer T, Obernberger I (2001) Simultaneity surveys in district heating net-works: results and project experience (Untersuchungen zur Gleich-zeitigkeit in Nahwärmenetzen: Ergebnisse und Projekterfahrungen). Euroheat Power 30:42–47
55. Ghaebi H, Saidi MH, Ahmadi P (2012) Exergoeconomic optimization of a trigeneration system for heating, cooling and power production purpose based on TRR method and using evolutionary algorithm. Appl Therm Eng 36:113–125
56. Sundberg G, Karlsson BG (2000) Interaction effects in optimising a municipal energy system. Energy 25:877–891
57. Kammen DM (2004) Renewable energy, taxonomic overview. In: Cleveland CJ (ed) Encyclopedia of energy. Elsevier, New York, pp 385–412
58. Kaya E, Zarrouk SJ, O'Sullivan MJ (2011) Reinjection in geothermal fields: a review of worldwide experience. Renew Sustain Energy Rev 15:47–68
59. Patzek TW, Pimentel D (2005) Thermodynamics of energy production from biomass. Crit Rev Plant Sci 24:327–364
60. Eliadis C (2003) Deep lake water cooling – a renewable technology. Presented at electrical line, 26 May to 8 June 2003
61. Fuel emission coefficients (2012) EIA. http://www.eia.gov/oiaf/1605/emission_factors.html. Accessed 10 Aug 2012
62. Nikolaisen L (2012) Country report 2011 for Denmark. Danish Technological Institute - IEA bioenergy task 40
63. Oo A, Kelly J, Lalonde C (2012) Assessment of business case for purpose-grown biomass in Ontario. The Western University Research Park, Sarnia-Lambton Campus, 44
64. Magtengaard J, Mahler A (2010) Geothermal reserves and sustainability in the greater Copenhagen area. In: Proceedings World geothermal congress, Bali, Indonesia, 25–29 Apr 2010
65. Bristow D (2012) The business case for alternative energy technologies in Ontario. Civil Engineering, University of Toronto. http://www.trca.on.ca/dotAsset/51366.pdf. Accessed 6 June 2012

This PhD thesis presents the results of various cases about municipal energy planning, which are common for Denmark. The first situation is about determining the design method of low temperature district heating systems for new settlements planned to be built with low-energy houses. The second situation is about investigating the existing settlements if they can be supplied by low temperature district heating systems. The last situation is about determining the required capacities of locally available renewable energy sources to be considered as the only sources for the energy production plants.

DTU Civil Engineering
Department of Civil Engineering
Technical University of Denmark

Brovej, Building 118
2800 Kgs. Lyngby
Telephone 45 25 17 00

www.byg.dtu.dk

ISBN: 9788778773685
ISSN: 1601-2917