UNIVERSITY OF ZAGREB
FACULTY OF MECHANICAL ENGINEERING
AND NAVAL ARCHITECTURE

MASTER'S THESIS

Dario Čulig-Tokić

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UNIVERSITY OF ZAGREB
FACULTY OF MECHANICAL ENGINEERING
AND NAVAL ARCHITECTURE

COMPARATIVE ANALYSIS OF THE DISTRICT HEATING SYSTEMS IN CROATIA AND DENMARK

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Dario Čulig-Tokić

Zagreb, 2013.

I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have fully cited all used sources and I have only used the ones given in the list of references.

Dario Čulig-Tokić

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DIPLOMSKI ZADATAK

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Naslov rada na engleskom jeziku: **Comparative analysis of the district heating systems in Croatia and Denmark**

Naslov rada na hrvatskom jeziku: **Komparativna analiza centralnih toplinskih sustava u Hrvatskoj i Danskoj**

Opis zadatka:

Construction and development of district heating systems and technologies and heat production from a high efficient cogeneration, as well as their use and maintenance, are of the specific interest for Croatia and Denmark. District heating systems are important element of energy efficiency policy and they can help meeting the goals set by the EU Energy Efficiency Directive 2012/27/EU. New high efficient and low temperature district heating systems combined with heat storage could also support integration of renewable energy sources in energy systems. Moreover, the district heating sector has a significant green growth potential. Currently, district heat is delivered to millions of end-consumers in more than 5,000 European systems. Denmark is one of the front runners with a district heating share of approx. 50% and substantial exports of technology. At present, the Danish district heating industry employs more than 9,000 people and generates a turnover of approximately 20 billion DKK per year.

In the thesis it is necessary to complete the tasks outlined below:

a) A technology review of available literature will be completed to identify the basics of district heating systems and their possibility to integrate renewable energy sources.
b) Two district heating systems and companies that operate them, the City of Aalborg in Denmark and another one from City of Zagreb in Croatia should be compared on technical and financial parameters and their organisational structures. The parameters for comparison should at least include heat sources, primary energy used and heat produced, operating temperatures, length of pipes, number and size of substations, year of construction, price regulation, tariff models, sector ownership, profit and loss accounts, and any other publicly available data interesting for comparison.
c) Based on the analysis state the possible improvements of district heating systems in Denmark and Croatia.

Necessary data and literature could be obtained from the supervisors. In the thesis, it is also necessary to state used literature and received help.

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Zadatak zadao:
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Prof. dr. sc. Zvonimir Guzović

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NOMENCLATURE

Abbreviation	**Unit**	**Description**
DH		District heating
CTS		Centralni toplinski sustav
HEP		Hrvatska elektroprivreda
CHP		Combined heat and power
RES		Renewable energy sources
EU		European Union
EC		European Commission
P_{hp}	MW	Heat power
P_{ec}	MW	Electricity capacity
$P_{hp,ec}$	$-$	Specific heat power per unit of electricity capacity
E_{he}	TJ	Generated heat energy
E_{el}	TJ	Generated electricity
$P_{he,pe}$	$-$	Specific heat energy generated per unit of electricity
$D_{he,h}$	kWh	Average heat energy demand in a single household
$D_{he,b}$	kWh	Average heat energy demand of a business
A_{ca}	m^2	Connected area
$P_{hp,ca}$	$\mathrm{kW/m}^2$	Specific heat power per connected area
$P_{ec,ca}$	$\mathrm{kW/m}^2$	Specific electricity capacity per connected area
$E_{he,ca}$	$\mathrm{MJ/m}^2$	Specific heat energy generated per connected area
$E_{el,ca}$	$\mathrm{MJ/m}^2$	Specific electricity generated per connected area
l	km	Network length
l_{hw}	km	Hot water network length
$P_{hp,l}$	MW/km	Ratio of heat power and total length of the network
$P_{ec,l}$	MW/km	Ratio of electricity capacity and total length of the network
$E_{he,l}$	TJ/km	Specific heat energy generated per km of network length
$E_{el,l}$	TJ/km	Specific electricity generated per km of network length
L_w	m^3	Annual water loss
$A_{ca,l}$	$\mathrm{m}^2\mathrm{/km}$	Specific connected area per km
$L_{w,l}$	$\mathrm{m}^3\mathrm{/km}$	Specific annual water loss per km
$E_{w,l}$	GJ/km	Specific heat losses due to water losses per km of network length

ABSTRACT

District heating systems are one of the elements that can help meet the goals set by the EU Directives for the reduction of primary energy consumption. Therefore, they are of high interest to both Croatia and Denmark. DH systems are essential for their heat production that can be produced with a wide variety of energy sources with high efficiency. Heat energy for DH can be produced by high-efficiency cogeneration or the use of renewable energy sources like geothermal heat and heat pumps. The advantage of DH systems are substantial and include secure heat energy supply, primary energy savings, and they also have greater means of regulating energy consumption. Numbers like 63% of all Danish dwellings, and 11% of households in Croatia that are heated by district heating systems, show the relevance of these systems. This thesis compares DH systems in Zagreb and Aalborg in order to see their similarities and differences from which conclusions are drawn on how to improve the systems.

The method chosen for this thesis is the comparative analysis. Different parts of district heating system are analyzed point by point. In this way, the data is organized and structured so to allow clear and concise comparison.

The results of the comparative analysis show that Aalborg DH system is more advanced than Zagreb DH system. This advantage is prominent in aspects of supply, demand, distribution and economic spheres. As a result of this difference, more improvement could be stated for Zagreb DH than Aalborg DH.

Some of the possible improvements include lowering specific heat and water losses, which are 68%, and 36 times lower in Aalborg DH. Systematic replacements and refurbishments of the old network pipes are key to this. Supply temperature, which is correlated with heat losses, could be lower in both DH systems. Further advances in both systems must be made in heat supply. In Zagreb new CHP unit could be built and in Aalborg more excess heat from the industry should be use. Further integration of the renewable energy sources should be achieved in both systems. Technological advancements and market forces are expected to bring new technologies in heat generation in DH systems such as waste to energy plants, geothermal plants, biomass CHP, solar thermal, and heat pumps run by the electricity from wind turbines, hydroelectricity plants and photovoltaic systems.

Key words: District heating, Zagreb, Aalborg, supply, demand, renewable energy sources

SAŽETAK

Centralni toplinski sustavi (CTS) jedan su od elemenata kojima bi se mogli postići ciljevi postavljeni u EU Direktivama, o smanjenju potrošnje primarne energije. Samim time, oni su od iznimnog interesa i za Hrvatsku i Dansku. CTS-i izuzetno su bitni radi mogućnosti proizvodnje topline sa širokim dijapazonom izvora energije, s visokom razinom efikasnosti. Toplina za CTS može se proizvesti kogeneracijom ili obnovljivim izvorima energije poput geotermalne energije i toplinskih pumpi. Prednosti CTS-a znatne su, a uključuju sigurnu opskrbu energijom, štednju primarne energije te su tu također mogućnosti reguliranja potrošnje energije. Činjenice poput te da je 63% danskih kućanstva grijano CTS-om, kao i 11% hrvatskih kućanstva, govori o važnosti ovih sistema. U ovom diplomskom radu uspoređuju se CTS-i u Zagrebu i Aalborgu, kako bi se pokazale njihove sličnosti i razlike, iz kojih se mogu izvući zaključci kako poboljšati spomenute sustave.

Metoda izabrana za razradu rada je komparativna analiza. Pojedini dijelovi centralnih toplinskih sustava analiziraju se dio po dio. Na ovaj način podatci se organiziraju i strukturiraju kako bi se ostvarila jasna i koncizna usporedba.

Rezultati komparativne analize pokazuju da je CTS u Aalborgu znatno napredniji od sustava u Zagrebu. Prednost je znatna u području opskrbe, potražnje, distribucije i na ekonomskom polju. Kao rezultat te činjenice više poboljšanja moglo se predložiti za sustav u Zagrebu nego za sustav u Aalborgu. Neka od mogućih poboljšanja uključuju snižavanje specifičnih toplinskih gubitaka i gubitka vode, koji su 68% i 36 puta niži u Aalborgu. Za to su ključne sistemske zamijene i poboljšanja stare mreže cijevi. Temperatura polaza, koja je u korelaciji s gubitcima topline, mogla bi biti niža u oba analizirana sustava. Daljnja poboljšanja u dobavi topline nužna su u oba sustava. U Zagrebu bi se mogla izgraditi nova kogeneracijska jedinica, dok bi se u Aalborgu trebao više koristiti višak topline iz industrije te bi se također trebalo integrirati više obnovljivih izvora energije. Napredak u tehnologiji i „sile tržišta“ trebale bi donijeti nove tehnologije u proizvodnju topline u CTS-ima, poput modernih spalionica otpada, geotermalnih postrojenja, kogeneracija na biomasu, solarnih toplinskih kolektora te dizalice topline pogonjene električnom energijom iz vjetroelektrana, hidroelektrana i fotonaponskih elektrana.

Ključne riječi: Centralni toplinski sustavi, Zagreb, Aalborg, opskrba i potražnja toplinske energije, obnovljivi izvori energije

PROŠIRENI SAŽETAK

U današnjem globaliziranom društvu, pokretanom intenzivnom uporabom fosilnih goriva i rastućom potrošnjom energije, izuzetno je važno poticati smanjenje potrošnje primarne energije i korištenje energije iz obnovljivih izvora. Još se mnogo toga mora učinit kako bi Europa postigla cilj uštede 20% primarne energije do 2020., koji trenutačno ne ide po planu.

U mnogim je sektorima prijeko potrebno poboljšanje. Jedan od najvećih potrošača energije u EU je sektor zgradarstva, s 40% finalne potrošnje energije. U ovom su sektoru moguće znatne uštede. Jedan od načina štednje primarne energije jest visoko-efikasna kogeneracija te centralni toplinski sustavi.

Neke od znatnih prednosti centralnih toplinskih sustava (CTS) uključuju sigurnu opskrbu toplinskom energijom, štednju primarne energije te veće mogućnosti regulacije potrošnje energije. Također, jedna od prednosti jest i mogućnost integracije obnovljivih izvora energije.

Osnovna uloga CTS-a je stvaranje i održavanje toplinske ugodnosti. Vanjska temperatura najvažniji je faktor koji određuje dnevne potrebe za toplinskom energijom.

Toplinska energija može se proizvoditi putem termoelektrana, postrojenje za termičku obradu otpada, industrijskih procesa ili obnovljivih izvora energije.

Cilj ovog rada je odgovoriti na pitanje:

Na koje se načine mogu poboljšati CTS-i u Danskoj i Hrvatskoj?

Pitanje proizlazi iz potrebe za poboljšanjem i proširenjem današnjih CTS-a. Usporedbom dva CTS-a, u Zagrebu i Aalborgu, dolazi se do podataka nužnih za odgovor na to pitanje.

Svi sakupljeni podatci moraju biti organizirani i strukturirani kako bi se stvorili uvjeti za usporedbu. Za usporedbu je odabrana metoda komparativne analize. Analizirani aspekti CTS-a su opskrba i potražnja toplinske energije, distribucija te ekonomski aspekti.

Proizvodnja toplinske energije u mnogim je zemljama usko vezana na proizvodnju električne energije, obično putem kogeneracijskih postrojenja ili kombi-kogeneracijskih postrojenja.

Potražnja topline sastoji se od dvije osnovne komponente: toplinske energije i toplinske snage. U većini zgrada potražnja se sastoji od energije za grijanje prostora i potrošne tople vode. Osim potražnje u zgradarstvu, također postoji potražnja u industriji, za različite svrhe.

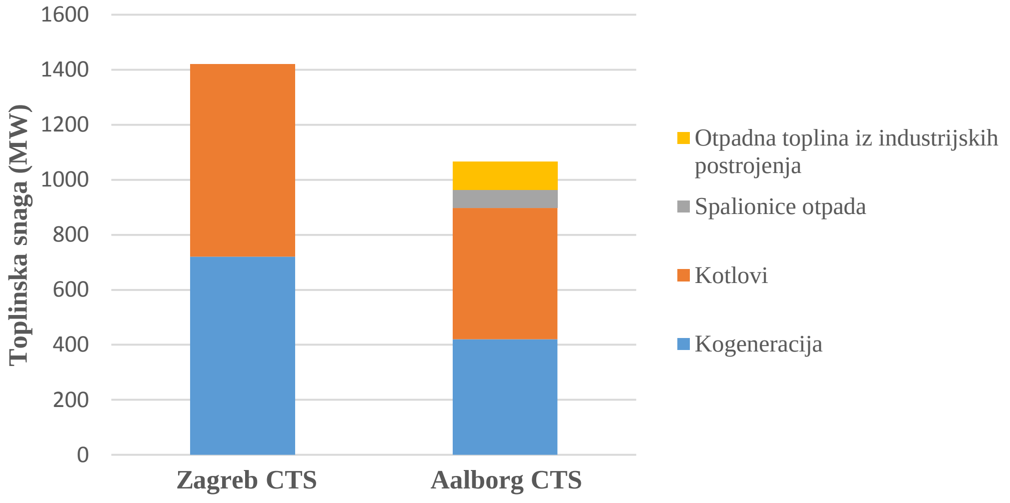
Mnoge tehnologije koristile su se za distribuciju topline, neke su se pokazale robusnije i više energetski učinkovite. Većina cijevi za distribuciju topline, polaže se podzemno, u zemlju ili u za to predviđene kanale. Konstantno se radi na razvoju novih tehnologija distribucije, kako bi se smanjili investicijski troškovi, vrijeme potrebno za ugradnju te operativni troškovi. Trenutno postoje tri generacije distribucijske tehnologije, razvijene jedna za drugom, a također se radi na istraživanjima i razvoju četvrte generacije.

Analizirane tvrtke koje se bave proizvodnjom i dobavom topline su HEP Grupa u Zagrebu i Aalborg Forsyning-Koncernen u Aalborgu.

HEP Grupa je Hrvatska nacionalna kompanija koja se bavi proizvodnjom, prijenosom i distribucijom električne energije, kao primarnom djelatnosti, ali nudi i mnoge druge usluge pa tako i usluge vezane na toplinsku energiju. HEP Grupa ima preko 4000 MW instaliranog kapaciteta za proizvodnju električne energije i preko 1900 MW instaliranog kapaciteta za proizvodnju topline. HEP Toplinarstvo d.o.o. (tvrtka kćer) zadužena je za proizvodnju i distribuciju toplinske energije. To je najveći dobavljač toplinske energije u Hrvatskoj. U 2012., toplinska energija dobavljena je za 117145 kućanstava i 6051 poslovnih subjekata, u gradovima Zagrebu, Zaprešiću, Samoboru, Velikoj Gorici, Sisku i Osijeku. Valja napomenuti da HEP Toplinarstvo ne proizvodi svu energiju koju dobavlja krajnjim korisnicima, najveći dio proizvodi HEP Proizvodnja.

Aalborg Forsyning-Koncernen je grupa za komunalne usluge, u posjedu okruga Aalborg, koja pruža usluge kućanstvima i poslovnim subjektima. Aalborg Forsyning, Varme (Aalborg centralni toplinski sustav) bavi se kupovinom, proizvodnjom, distribucijom, savjetovanjem i promocijom centralnih toplinskih sustava u okrugu Aalborg. Opskrbno područje Aalborg Forsyning, Varme sastoji se od centralnog područja i decentraliziranih područja. Decentralizirana područja imaju neovisne CTS-e koji se opskrbljuju iz malih kogeneracijskih postrojenje na prirodni plin. Centralno područje Aalborg CTS-a predstavlja 98.5% proizvedene toplinske energije u Aalborg Forsyning, Varme.

Usporedba dobave toplinske energije (Slika 1.) pokazuje da je ukupna toplinska snaga u Zagreb CTS-u oko 1420 MW, od čega kotlovi predstavljaju 49% snage, a kogeneracijska postrojenja 51%. U Aalborgu CTS-u ukupna toplinska snaga je 1067 MW, što je 353 MW manje nego u Zagreb CTS-u, navedene brojke relativno su blizu s obzirom na različitu veličinu gradova i populaciju. Aalborg CTS-u većinu instalirane toplinske snage pružaju kotlovi, 45%, kogeneracijska postojanja predstavljaju 39%, a otpadna toplina iz industrijskih postrojenja predstavlja 10%. Ostalih 6% spalionice su otpada.

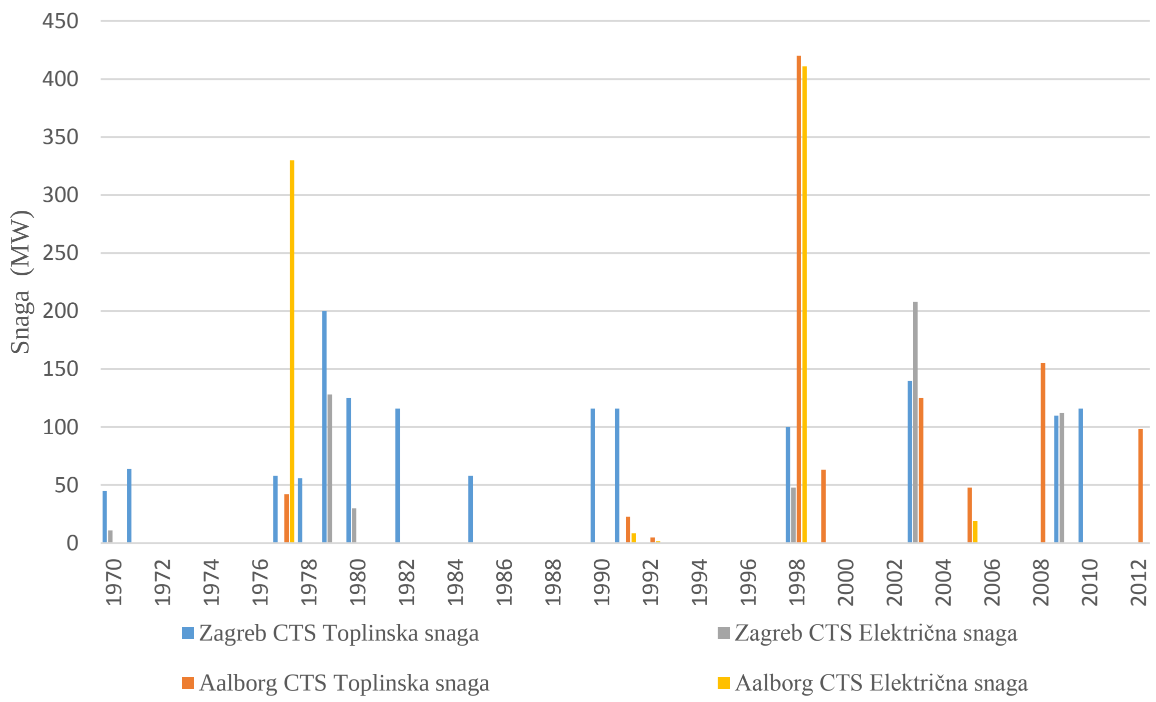


Slika 1. Instalirana toplinska snaga u Zagreb CTS-u i Aalborg CTS-u

U Zagrebu CTS-u je 14 postrojenja za proizvodnju energije, od kojih 8 proizvode samo toplinu, a 6 je kogeneracijskih postrojenja, dok je u Aalborgu CTS-u 16 postrojenja, od koji 10 proizvodi samo toplinu, a 6 su kogeneracijska postrojenja. U Aalborg CTS-u proizvodnja topline obavlja se sa 16 postrojenja na 14 lokacija, a u Zagreb CTS-u s 14 postrojenja na 2 lokacije.

Postrojenja za proizvodnju toplinske energije prema godini izgradnje prikazan su na Slici 2. U Zagrebu su postrojenja za proizvodnju toplinske energije, koja su i danas u pogonu, starija nego u Aalborgu. Važno je istaknuti izgradnju bloka 3 termoelektrane na ugljen Nordjylland, koja proizvodi većinu godišnje toplinske energije Aalborg CTS-a te izgradnju bloka K i bloka L, u TE-TO Zagreb, u 2003. i 2009., koje proizvode većinu toplinske energije u TE-TO Zagrebu. Prosječna starost postrojenja za proizvodnju toplinske energije u Zagrebu je oko 26 godina, dok je u Aalborgu oko 14 godina.

Neka od postrojenja u Zagreb CTS-u izgrađena su još 1970./1971. godine. Jedinice građene u Aalborgu u 2003., 2008. i 2012., građene su iz potrebe da se proširi kapacitet rezervi, u slučaju prestanka rada neke od većih jedinica.



Slika 2. Godina izgradnje kotlova i kogeneracijskih postrojenja

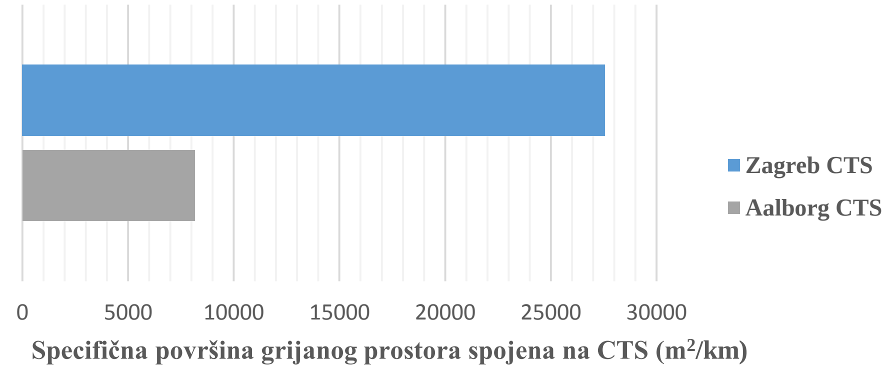
Usporedba potražnje toplinske energije pokazala je da je u Zagreb CTS-u specifična toplinska snaga po grijanoj površini 198 W/m^2, dok je u Aalborg CTS-u 94 W/m^2.

Zagreb CTS ima više instalirane proizvodne snage, toplinske snage i električne snage, dok Aalborg CTS ima veću grijanu površinu.

Kao što je napomenuto, vanjska temperatura je najbitniji faktor koji određuje potražnju za toplinskom energijom. Srednje mjesečne temperature u Zagrebu, u prosjeku su 5°C više nego u Aalborgu od ožujka do rujna. Tijekom hladnijih mjeseci, posebno zimskih mjeseci, temperature su podjednake u oba grada. U prosincu su prosječne temperature u oba grada oko 2°C, a u siječnju 0°C.

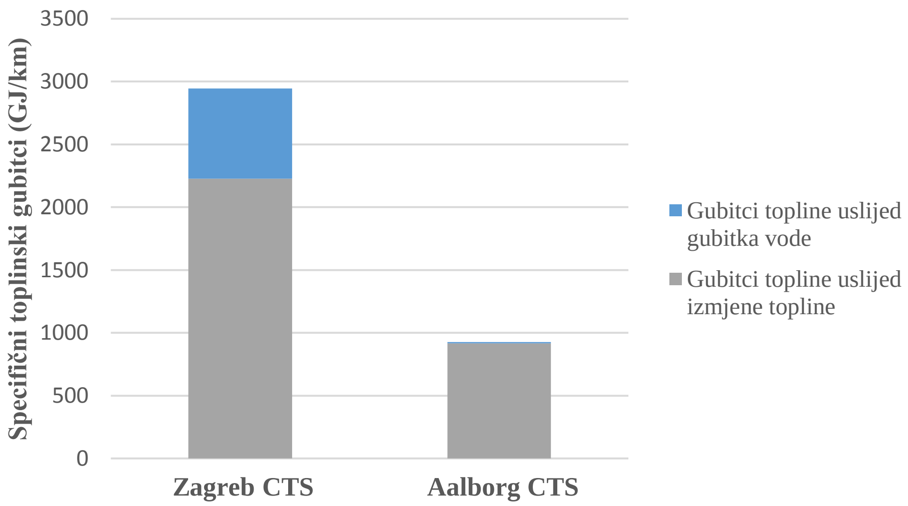
Duljina mreže u Aalborgu je 1386 km, što je gotovo 6.5 puta više od 216 km u Zagrebu. Ovakva razlika u duljini sistema, koji su slični u instaliranoj toplinskoj snazi i godišnjoj proizvodnji toplinske energije, nastaje jer je područje Zagreb CTS-a unutar samog grada, dok je Aalborg CTS pokriva i nekoliko okolnih gradova, uz grad Aalborg. Valja napomenuti da su u Zagrebu oba postrojenja za proizvodnju toplinske energije smještena unutar grada, dok su u Aalborgu neka od postrojenja smještena izvan grada, poput Nordjylland termoelektrane, smještene na 5 km od ruba grada. Osim toga postoji razlika u urbanoj gustoći na opskrbnom području.

Specifična grijana površina po kilometru duljine CTS mreže prikazana je na Slici 3. Specifična grijana površina po kilometru duljine Zagreb CTS-a je preko 27500 m^2/km mreže, dok Aalborg CTS ima oko 8100 m^2/km.



Slika 3. Specifična grijana površina po kilometru duljine CTS mreže

Ukupni specifični gubitci topline, za oba CTS-a, pokazani su na Slici 4. Specifični toplinski gubitci, nastali kao rezultat gubitka vode razmjerno su mali u oba sistema. Ukupni specifični gubitak topline u Zagreb CTS-u iznosi 2944 GJ/km, dok u Aalborgu 928 GJ/km. Ova razlika posljedica je prosječne starosti dijelova vrelovoda u Zagrebu naspram Aalborga. Općenito, starije cijevi imaju lošiju izolaciju i veće gubitke radi curenja.

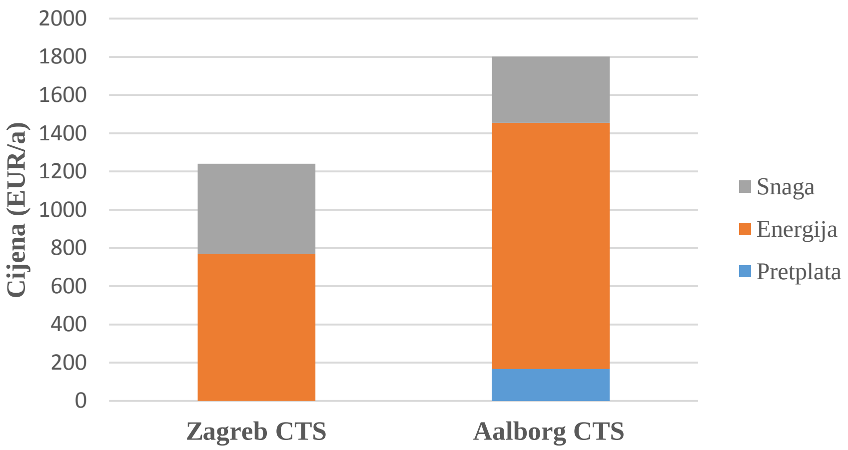


Slika 4. Ukupni specifični gubitci topline u Zagreb CTS-u i Aalborg CTS-u

Specifični gubitci topline uzrokovani izmjenom topline računati su kao razlika između ukupnog specifičnog gubitka topline i specifičnog gubitka topline uzrokovanim curenjem vode.

Ekonomska usporedba cijene grijanja u oba sustava nije mogla biti direktna uslijed različite formacije cijena u Zagreb CTS-u i Aalborg CTS-u. U Zagrebu nema pretplate, osim za zakupljenu toplinsku snagu, dok u Aalborgu ima. Energija se u Zagreb CTS-u naplaćuje po kWh, dok su u Aalborg CTS-u naplaćuje po m^3. Pretplata snage u Zagreb CTS-u naplaćuje se po kW instalirane snage, dok u Aalborgu po m^2 grijane tlocrtne površine prostora.

Godišnji troškovi toplinskih usluga za Zagreb CTS i Aalborg CTS, za identičnu obiteljsku kuću pokazani su na Slici 5. Godišnji troškovi izračunati su kao suma cijene energije, snage i pretplate u slučaju Aalborg CTS-a te sume cijene energije i snage u slučaju Zagreb CTS-a.



Slika 5. Godišnji troškovi toplinskih usluga za identičnu obiteljsku kuću u Zagrebu i Aalborgu

Analiza pokazuje, da je Aalborg CTS napredniji od Zagreb CTS-a, u aspektima opskrbe, potražnje i distribucije topline te ekonomskim aspektima. Stoga se više prijedloga može dati za unaprjeđenje Zagreb CTS-a nago Aalborg CTS-a.

Dobava topline u Zagreb CTS-u sastoji se od kogeneracijskih postrojenja i kotlova, pokretanih na mazut i prirodni plin. Omjer toplinske i električne snage te omjer proizvodnje toplinske energije i proizvodnje električne energije (samo kogeneracija) niži su u Aalborgu, što ukazuje na intenzivnije korištenje kogeneracijskih jedinica kod proizvodnje toplinske snage i energije.

U Zagrebu postoji mogućnost izgradnje spalionice otpada, kojom bi se djelomično mogao riješiti trenutni problem zbrinjavanja otpada, a takav sistem u Aalborgu ostvaruje 20% ukupne toplinske energije za CTS. Geotermalni izvori već se koriste u Zagrebu, ali ne u sklopu CTS-a, nego za bazene Mladost koji imaju direktnu toplinsku snagu geotermalnog izvora od oko 6.3 MW.

Iako Aalborg ima relativno ekološku proizvodnju topline, daleko je od potpunog prestanka korištenja fosilnih goriva, koji treba biti ostvaren do 2035. Unutar Aalborg CTS-a postoji relativno malo korištenje obnovljivih izvora energije tako da na tom području ima mnogo prostora za napredak. Postoji nekoliko projekata koji se bave ovim problemom. Preliminarni projekt Vattenfalla, za korištenje 40% suspaljivanja biomase u Nordjylland postrojenju, bio je napravljen, ali je stavljen na čekanje. Vattenfall je također proveo studije za ekstrakciju i skladištenje CO_2 iz Nordjylland postrojenja, za blok 3.

Postoje studije utjecaja proizvodnje viška topline u nula energetskim zgradama i njihov utjecaj na različite CTS-e. Glavni rezultati pokazuju da toplina proizvedena u nula energetskim zgradama povoljno utječe na smanjenje korištenja neobnovljivih goriva. Viši udjeli solarnog grijanja u nula energetskim zgradama zahtijevaju sezonsku pohranu topline.

Implementacija obnovljivih izvora energije s CTS-ima zahtjeva detaljno strateško planiranje od strane pojedinih tvrtki te lokalne vlasti, što se nažalost rijetko postiže, a pogotovo ne tako da obuhvaća sve aspekte 100% obnovljivih izvora energije.

U Zagrebu bi prioritet trebao biti smanjenje specifičnih gubitaka topline i vode uslijed curenja, koji su u Aalborgu 68% i 36 puta niži. Ključ tome je sistemska zamjena i popravak starih cijevi unutar mreže. Također, Aalborg ima nižu polaznu temperaturu, koja ujedno znači i niže toplinske gubitke. No, poboljšanja su moguća u oba sustava, budući da bi prosječna godišnja polazna temperatura mogla biti 74ºC. Snižavanje povratne temperature također je važno jer omogućuje bolju integraciju obnovljivih izvora energije.

U oba sistema gotovo da nema integriranih obnovljivih izvora energije, što se mora promijeniti ukoliko se želi ostvariti cilj gospodarstva s niskim udjelom CO_2. Većina rada u tome polju najčešće obuhvaća samo studije izvedivosti.

Daljnji napredak u tehnologiji i „sile ekonomskih tržišta“ trebale bi donijeti nove tehnologije u proizvodnju, distribuciju i pohranu toplinske energije za CTS-e. Poput postrojenje za termičku obradu otpada, geotermalnih postrojenja, kogeneracija na biomasu, solarne energije, sezonske pohrane topline i dizalica topline pokretanih električnom energijom iz vjetroelektrana, hidroelektrana ili fotonaponskih elektrana.

Integracija obnovljivih izvora energije s CTS-ima najvažniji je cilj koji tek treba biti ostvaren.

1. INTRODUCTION

In today society, driven by extensive use of nonrenewable energy sources, and with growing energy consumption, it is necessary to try to promote energy savings and renewable energy sources. If Europe is to achieve its goal of 20% saving in primary energy consumption, by 2020 that is not currently on track, a lot must be done to try to achieve it [1].

Many sectors are in desperate need of improvement, in the means of both energy sources and technology. One of the greatest energy consumers in EU are buildings, with 40% of the European Union final energy consumption [2]. This sector has a great potential for energy savings. One of the ways of saving primary energy is with high-efficiency cogeneration and district heating and cooling.

District heating is one of the ways of supplying space heating and domestic hot water to households, and heat energy to businesses and industry. In essence, it is an energy distribution network. In heat generation units, hot water is pumped to consumers where the heat form the district heating water is used, after which the water is circulated back to plant for reheating. This type of DH system is called hot water system, and it forms a closed loop, unlike some steam DH systems. The concept of district heating is to use excess heat from electricity production and different industrial processes, like waste incineration plants and cement factories, where it is needed, in households, businesses or industry.

The advantages of DH systems are considerable and include secure heat energy supply, primary energy savings, and have greater means of regulating energy consumption. District heating also has a lot of potential for integration of renewable energy sources.

Today 63% of all Danish dwellings are heated by district heating systems [3]. In Croatia, 11% of households are heated with district heating, and 15% of energy used for space heating and domestic hot water comes from district heating [4].

Through the comparative analysis of two DH systems, in Zagreb and Aalborg, their differences and similarities will be identified and discussed. The comparison results will show the potential of the two systems, and ways to improve them.

Denmark has been the leading country in this field for a long time, so a lot can be learned from their DH systems. Aalborg DH has more advanced technology than Zagreb DH, so the differences will show the steps that Zagreb DH should take to catchup with Aalborg DH.

1.1. Past and present of DH systems

The origins of district heating can be traced back to Ancient Rome, with its hot-water heating baths, the hypocaust system. District heating became popular, in Europe, in middle ages. The system in French village of Chaudes-Aigues Cantal, dating back to 14th century, is still operational today [5]. The first commercially successful district heating system was put into operation in 19th century in Lockport, New York. Birdsill Holly, the engineer, who put this system in operation, in 1877, is considered to be "the father" of district heating [6].

Denmark´s first district heating power plant was launched in 1903; this was a waste incineration plant [7]. Most countries in the Northern hemisphere have district heating systems due to their cold winter seasons. In Northern hemisphere countries, there are about 80000 systems with almost 600000 km of pipes installed [6].

The main point of district heating is to create and maintain a pleasant indoor climate, so the outdoor temperature is the most important factor that determines the daily heat demand, and yearly variations in space heat demand. The heat generation unit can be a thermal power plant, a waste incineration plant, an industrial process or renewable energy source. DH systems are going to play a far more important role in the future economies with high share of renewable energy sources.

1.2. Basics of renewable energy sources

Wind energy is used by wind turbines to produce electricity, but due to intermittency in wind power, imbalances are sometimes caused within the electric grid. This problem becomes more pronounced with higher shares of the wind turbines within power generation. There are a couple of ways to tackle this problem, and one of them is the use of heat pumps or electric boilers which can be used to balance the electricity consumption. This could be done by fewer large canalized heat pumps, that supply the DH system, or with numerous individual heat pumps. Another option is to balance the electricity generation and consumption using the hydroelectric power plants and pumped-storage.

Heat radiation from the Sun can be used by PV or solar collectors to produce electricity and heat energy. The day/night cycle causes a need for grid balancing in the case of PV and heat storage in the case of solar collectors. Electric grid balancing can be achieved by heat pumps during the summer in connection to district cooling. Space heating with solar collectors usually mandates an additional boiler, which could be replaced with DH system, and during the summer excess heat could be used by adsorption heat pumps for cooling.

Geothermal heating uses hot water or steam created below the Earth surface by extracting it and then using its heat, and usually returning the water back in the aquifer. These energy sources are sometimes at low temperature level, and it is difficult to use it directly, but the additional use of absorption heat pump can sometimes be utilized economically to solve this.

Biomass is naturally growing trees, grasses and such that can be used as fuel in CHP plants in which electricity and heat can be generated.

1.3. Brief EU legislative overview

This chapter gives brief overview of the following EU Directives:

- DIRECTIVE 2012/27/EU on energy efficiency
- DIRECTIVE 2010/31/EU on the energy performance of buildings
- DIRECTIVE 2009/28/EC on the promotion of the use of energy from renewable sources

The general goals of each Directive are described first and followed by description of section dealing with district heating, and any concerning subjects.

DIRECTIVE 2012/27/EU on energy efficiency:

Energy efficiency is a way for the European Union to deal with challenges associated with increased dependence on energy imports, limiting climate change, and battling economic crisis by assuring the reduction in primary energy consumption and decreasing energy imports. Energy-efficient economy should also facilitate technological innovation and improve competitiveness of the European Union industry and in addition create new jobs.

European Council emphasized in 2007 that the energy efficiency should be increased, in order to achieve goals of 20% saving in primary energy consumption by 2020, compared to projections so far. The Council also concluded, in 2011, that achieving 20% energy efficiency by 2020 is not on track, but it must be delivered. In regard to that conclusion, Member States are required to set national targets, and indicate how they intend to achieve them. It is also desirable for the Member States to decouple energy use from economic growth. Higher energy savings should be made in buildings, transport, products and processes.

The Energy Efficiency plan 2011 states energy efficiency policies and measures covering the full energy chain: including energy generation, transmission and distribution. The public sector should take a leading role in energy efficiency, but there is also a need for the final customers to manage their consumption.

Directive establishes a common framework to promote energy efficiency and lays down specific actions for the implementations of proposals included in the Energy Efficiency Plan 2011 that should achieve the unrealized energy saving potentials defined. Directive contributes to meeting the goals set out in Roadmap for becoming low carbon economy by 2050, and reducing greenhouse gas emissions from the energy sector, eventually accomplishing zero emission electricity production by the year 2050.

Energy saving potential should be used in an integrated approach, making savings in both the energy supply and the end-use sector. Cogeneration based on a useful heat demand in the internal energy market should be strongly promoted. Primary energy can be saved with high-efficiency cogeneration and district heating and cooling. Each Member State should assess its own potential for high-efficiency cogeneration and district heating and cooling. It should also carry out a cost-benefit analysis covering their territory. Analysis should be based on climate conditions, economic feasibility and technical suitability.

In order for the end-user to have control of their energy-use there should be the use of individual meters or heat cost allocators. New electricity generation installations and existing ones that are being refurbished should be equipped with high-efficiency cogeneration units to recover waste heat. The district heating networks should then transport the waste heat where it is needed.

DIRECTIVE 2010/31/EU on the energy performance of buildings:

Since buildings account for 40% of total energy consumption in the European Union, and the sector is expanding, increasing its consumptions, measures should be taken to reduce the energy consumption and to increase the use of energy from renewable sources. These measures in the building sector should reduce the European Union's energy dependency and greenhouse gas emissions. Measures should be based on local conditions, climate and cost-effectiveness, and should not affect other requirements such as accessibility, safety, and the use of the building.

In implementing these measures, local and regional authorities play a critical role. “Furthermore, Member States should enable and encourage architects and planners to properly consider the optimal combination of improvements in energy efficiency, use of energy from renewable sources and use of district heating and cooling when planning, designing, building and renovating industrial or residential areas.”[8]

DIRECTIVE 2009/28/EC on the promotion of the use of energy from renewable sources:

There are also opportunities for economic growth coming from innovation and sustainable competitive energy. The Member States should support development in those areas. It is important to notice that production of energy from renewable sources is often dependent on local or regional small and medium sized enterprises (SMEs). The Member States should also support decentralized energy production that utilize local energy sources and increases security of energy supply.

“It is necessary to set transparent and unambiguous rules for calculating the share of energy from renewable sources and for defining those sources.”[9]

Energy from renewable sources should be used in new and renovated buildings. That should be encouraged through building regulations and codes. The Member States should also consider measures to promote district heating and cooling from renewable sources.

1.4. Research question

The goal of this Thesis is to answer the main research question:

What are possible improvements of district heating systems in Denmark and Croatia?

This question comes from the need to improve existing and expand new district heating systems. The comparison of two DH systems, in Zagreb and Aalborg, will give some of the essential data needed to make conclusions on how to do it. By comparing the two DH systems, much better overview will be achieved of the possible improvements than if only one system was analyzed.

In the following chapter, on Methodology, the description is given of ways and tools for comparison and analysis. Besides the main research question there is a series of sub questions:

- What are the future trends in district heating?
- What renewable energy sources could be integrated in DH?
- How the renewable energy sources could be integrated?

After the comparison of DH systems in Zagreb and Aalborg, answers to these questions will be discussed, and the conclusion will give a summation on all the questions and give possible questions for further research of DH systems.

2. METHODOLOGY

After brief descriptions of the past and present DH systems, basics of renewable energy sources that can be integrated with it and EU legislative overview concerned with these subjects, the main research question was stated: what are possible improvements of district heating systems in Denmark and Croatia. This chapter elaborates research approach and tools that have been applied in order to answer the stated research question. It also explains the limitations in data collection and analysis and shows the overall structure of the thesis.

2.1. Choice of topic

District heating systems are of high interest to both Croatia and Denmark. They are essential for their heat production that can be produced with a wide variety of energy sources with high efficiency like cogeneration or the use of renewable energy sources like geothermal heat, solar thermal heating or heat pumps. These systems are one of the elements that can help meet the goals set by the EU Directives, and they have a significant green growth potential. In addition, this sector employs a significant number of people and has an important role in the economies of both Croatia and Denmark.

All these factors show the importance of district heating, and research on how to improve it. By the comparison of systems in the two countries, conclusions could be drawn on how to improve both systems and also what are the advantages and disadvantages of one compared to another. Since the subject is very relevant, and there is not enough literature dealing with it, this research aims to tap into the problem using two examples, stating the best policies for the future of district heating.

2.2. Literature overview and data collection

The framework for the thesis has been established after the available literature overview and data collection. Scientific literature deals mostly with the optimization modeling, economic analysis, development and prospects of cogeneration district heating, and low-energy district heating. There is some literature dealing with the integration of renewable energy systems in district heating. Data on respectable systems in Zagreb and Aalborg were obtained from multiple sources. Some of the data was received through personal communication with the companies, and some was found on the official websites. Most of the data was obtained from various annual reports and financial reports and different brochures.

2.3. Data analysis and processing

All this data needs to be organized and structured so to allow clear and concise comparison. This has been accomplished by combining numerous sources to show a valid cross-section of Zagreb DH and Aalborg DH. In order to draw conclusions on how to improve both systems, the method of comparative analysis was chosen.

"Comparison is a fundamental tool of analysis. It sharpens our power of description, and plays a central role in concept formation by bringing into focus suggestive similarities and contrasts among cases."[10] By the comparative analyses tool, data can be shown in sections dealing with different aspects of the subject being compared, in that way directly showing similarities and differences in one place. This type of comparative analysis is called point-by-point comparison. A paragraph, or a chapter is dedicated to one aspect of the system, analyzed first in one city, than another. After this, the comparison is made, and a short conclusion, dealing with that particular part, is drawn. This structure of comparative analysis chapters is shown Figure 1.

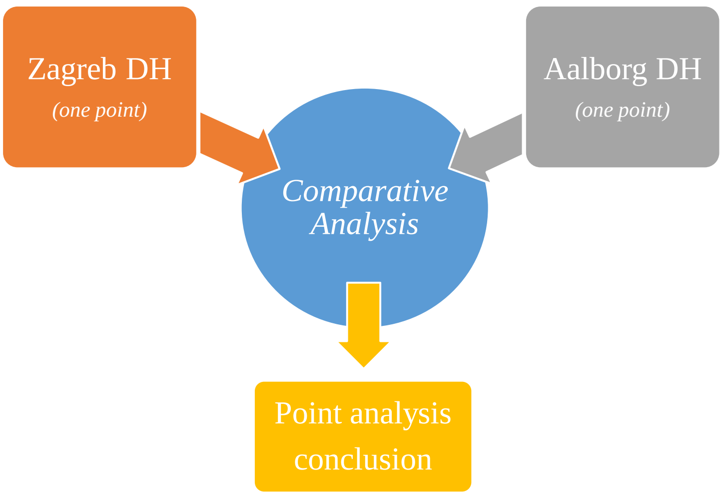


Figure 1. Structure of comparative analysis chapters

Microsoft Excel software was used, in order to interpret and process data on the two DH systems. In this way, information is visualized in the form of tables, graphs and charts, orderly and clearly comparing certain points. Some of the data visualized in this way is the data on supply, demand, distribution and economics.

2.4. Structure of the Thesis

Thesis can be dived into three main parts. First part is the introduction, showing briefly basics of district heating in general, basics on renewable sources, and a brief legislative overview dealing with EU Directives. The main research question is also stated in this first part of the thesis. The overall structure of the thesis is shown in Figure 2.

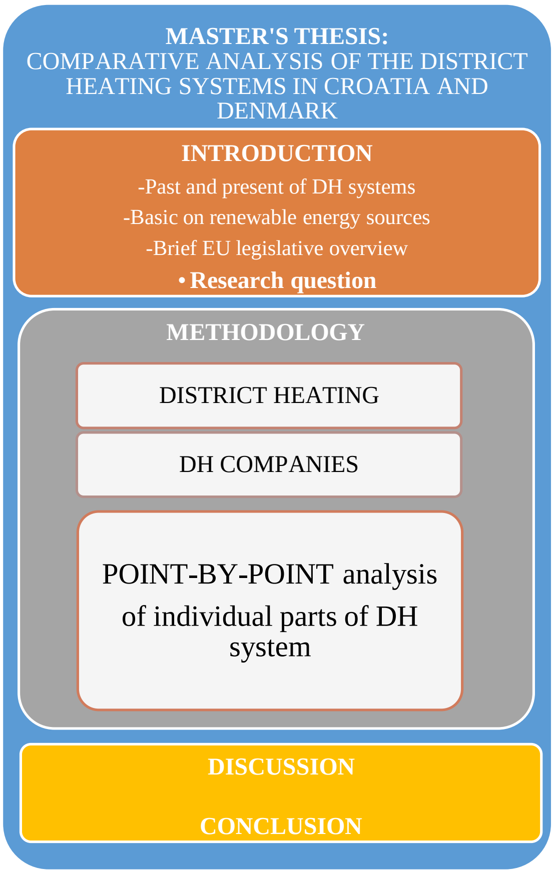


Figure 2. Overall structure of the Thesis

Second, and the most significant part of the thesis, the body of the thesis is the comparative analysis method applied to the two DH systems. In this part, after describing in part of one of the DH system, the same part of the other will be described after which a comparison of both will be presented with a short discussion of the findings. This will be done for all the relevant parts of the system.

The last major parts are Discussion and Conclusion. In this section, the brief conclusions resulting from the point-by-point analysis are synthesized into the final conclusion.

2.5. Limitations and challenges in research

This research was in parts limited by the available data. Some of the data is sensitive, and could be considered as classified, so disclosure of some of the data was severely limited.

Some of the data collected was shown for different time frames, the comparison of such data was challenging and sometimes impossible. One of the challenges was conversion of different data into same units in order to compare them using Microsoft Excel software.

Possibly the biggest challenge was the language. Data sources for Aalborg DH are mostly in Danish, with some exceptions. The same goes for the web pages that all featured short paragraphs in English, but the majority of needed data was in Danish. In order to overcome this problem, the Google Translate tool was used extensively.

3. DISTRICT HEATING

3.1. Heat supply

District heating systems are capable of a remarkable diversification and flexibility in available energy sources for heat generation. Technologies for heat generation in other industries are similar to the heat generation technology of the district heating systems. Considering the extensive use of heat energy in many industries the heat generation technology is well-developed.

In Denmark, diversification of energy sources is considerable (see Figure 3) and includes heat only boilers on biomass, fossil fuels or electricity, heat pumps, solar heat, CHP, waste incineration and surplus heat from industry.

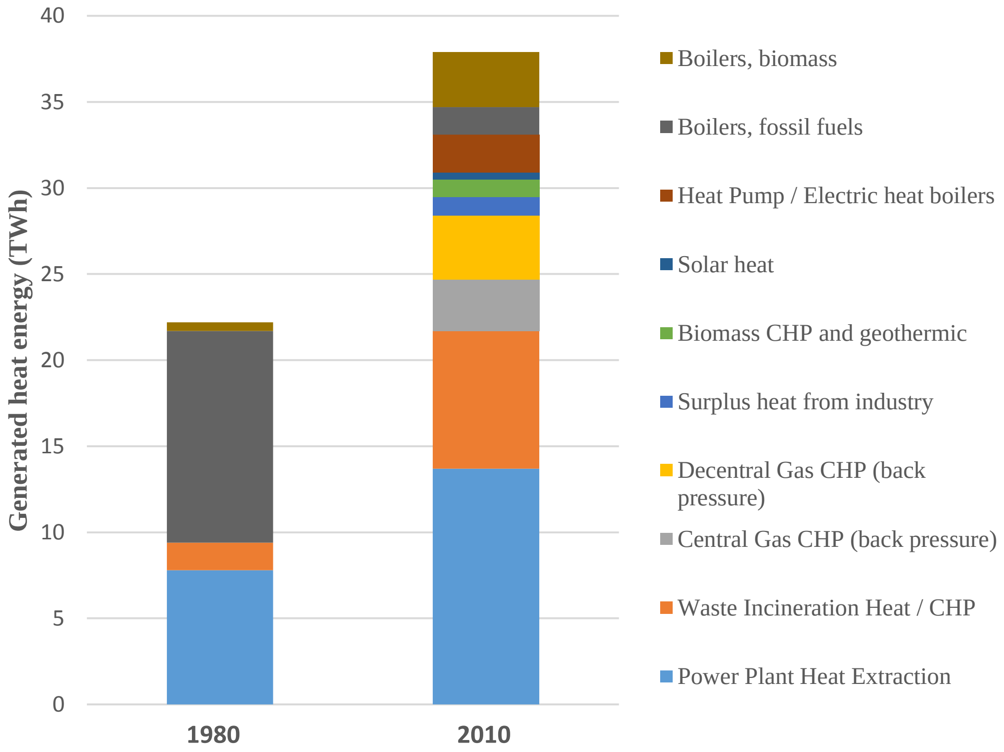


Figure 3. District heating energy sources in Denmark [6]

In the period from 1980 to 2000, there was a surge in the existing use of imported coal, and an introduction of natural gas, all in order to scale down dependence on oil for Danish DH systems. The use of boilers on fossil fuels was reduced almost in half in every five year period during this twenty year period.

This was firmly tied to the bolstered use of CHP, which lead to the expansion of DH networks in larger cities, to allow for increased extraction of heat from CHP plants running on coal. CHP plants, running on natural gas, were installed in smaller towns.

In the recent years, there has been an increase in the use of biofuels, like straw from the agriculture, mainly imported woody biomass and some use of biogas from pig farms [6]. However, recycling heat from industry does not play a significant role, considering the non-energy intensive industry in Denmark.

Heat generation in many countries is closely tied to the electricity generation, usually via CHP or Combined cycle CHP.

For most of the 20th century, large electrical power plants dominated the energy supply. This was accompanied with the expansion of power grids and the application of long-range transmission capacity. The results were lower specific initial costs, improved plant efficiency, mutual power reserves and efficient load sharing.

Figure 4 shows how in twenty year period, several thousand small-scale power-producing units have been added to larger centralized units. Most of them are wind turbines, followed by small-scale CHP, based on natural gas fired engines. Market share for district heating in Denmark has been significantly expanded by small-scale CHP.

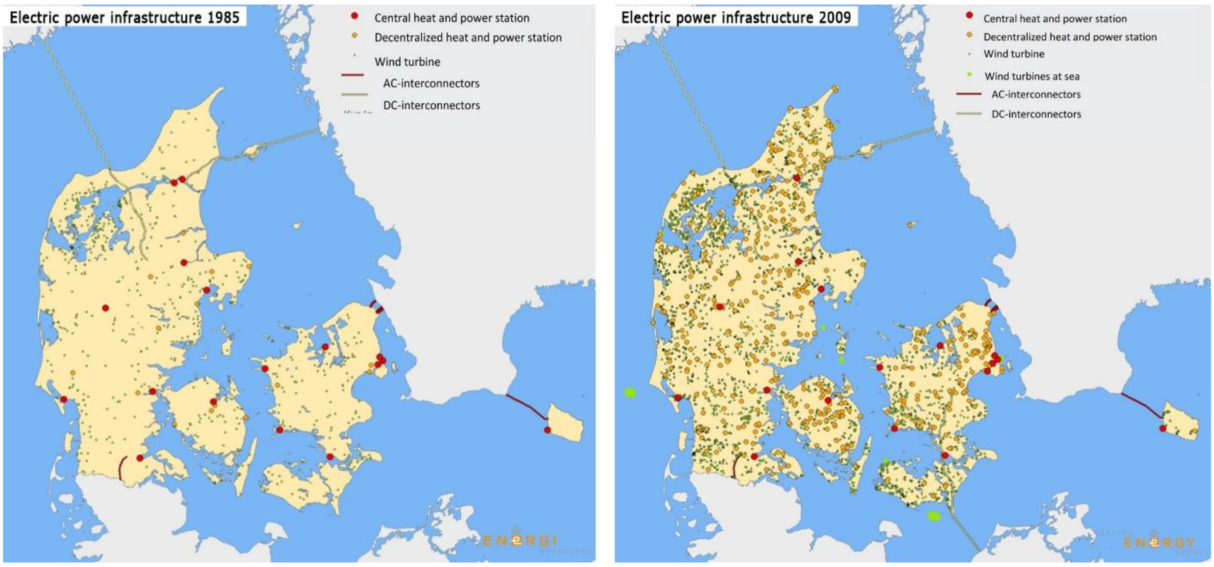


Figure 4. Distribution of Electricity generating power plants from 1985 to 2009 [11]

Development of decentralized generation has been happening in the last 30 years, as a political tool to introduce renewable energy supply and for encouraging energy savings. This has resulted in a large number of small power plants and new plant owners. It was also made mandatory by law for grid owners to buy electricity offered by small-scale producers, on favorable terms, the feed-in tariffs.

This trend of decentralization is expected to continue, along with the development of smart grids that have the possibility to match load variation with stochastic variation in generation from wind turbines.

3.2. Heat demand

Heat demand is comprised of two basic components: heat energy and heat power. In most buildings, heat demand consists of space heating and domestic hot water. Other than heat demand in buildings, there is also an industrial heat demand for different processes.

Space heating aims to create a pleasant indoor climate. The heat demand will grow when the desired indoor temperatures is higher or when outdoor temperatures are lower. The most important variable influencing heat demand is the outdoor temperature.

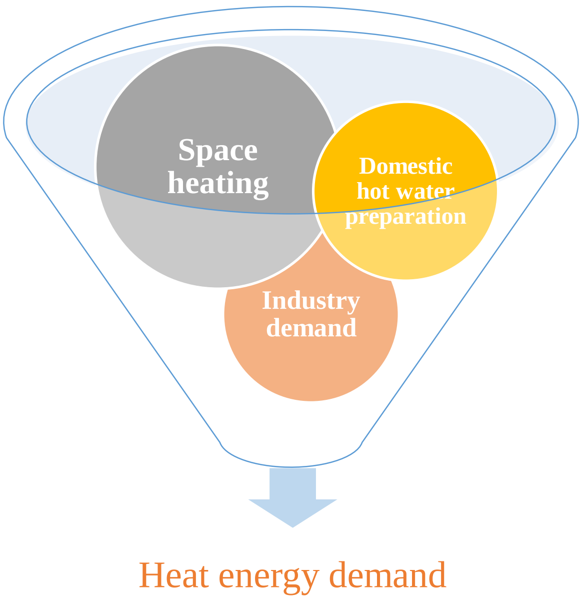


Figure 5. Heat energy demand division

The retention of desired indoor temperature depends primarily on the total boundary surface area between the outdoor and indoor space, the heat transfer coefficient and the difference between outdoor and indoor temperature. There are other influencing factors like solar gains, internal gains and wind chill. Heat transfer coefficient is composed of the transmission heat transfer coefficient and the ventilation heat transfer coefficient. Considering that the desired indoor temperature and the heat transfer coefficient are constant for a building (assuming that no renovation took place) main factor influencing the space heating annual energy consumption is the outdoor temperature.

Domestic hot water preparation represents a highly fluctuating heat demand, which is usually lower during the night and high during mornings and evenings. Higher hot water demand is higher in winters compared to summers because the degree of occupancy is higher. Hot water temperature of about 55ºC is high enough for human hygienic needs and for avoiding Legionella growth interval of 20 ºC to 45 ºC [6].

Intensity of industrial demand depends mostly on the type of industrial process heat is being delivered to. High versatility of temperature and intensity levels exist in across many countries. In 2007 in EU27 about 30% of all commercial heat deliveries was for industry activities. On the basis of temperature level industrial heat demand can be low temperature level (below 100 ºC), medium temperature level (100 ºC to 400 ºC) and high temperature level (above 400ºC).

Tendencies in modern district heating systems are to lower the supply temperature, so only part of the low temperature level industry demand can be covered. Some DH systems use steam as a heat carrier, so they are suitable even form medium temperature level industry heat demands.

3.3. Distribution of heat energy

Over the time, many technologies and designs have been used for district heating distribution. Some of them have proven to be more robust and energy efficient. Most of the pipes are installed underground, in soil or sometimes in ducts. New technologies in district heating are being developed to cut the investment cost, space demand, installation time and operating cost.

There are three generations of distribution technologies (see Figure 6) developed in sequence, with each more advanced than the last one.

In the first generation, the steam is distributed through pipes situated inside of a duct. This system was already in use a century ago, but today the hot water distribution dominates over steam distribution. In many cities the steam distribution is being replaced with hot water distribution, Copenhagen is one example, where the steam distribution is expected to be replaced with hot water distribution by 2020 [6].

Steam DH pipeline usually consists of a larger pipe which is a steam supply pipe, and the smaller one which is the return condensate pipe. Some systems lack such return pipe, so the condensate is dumped in the sewer after the heat exchange at the customers place. The problem with the condensate is that it can be corrosive because it absorbs oxygen and carbon dioxide.

The build-up of condensate due to heat losses in the supply pipe can create slugs that smash with high velocity into valves and bands. To avoid this, all pipes must slope to facilities that draw off the condensate at low points.

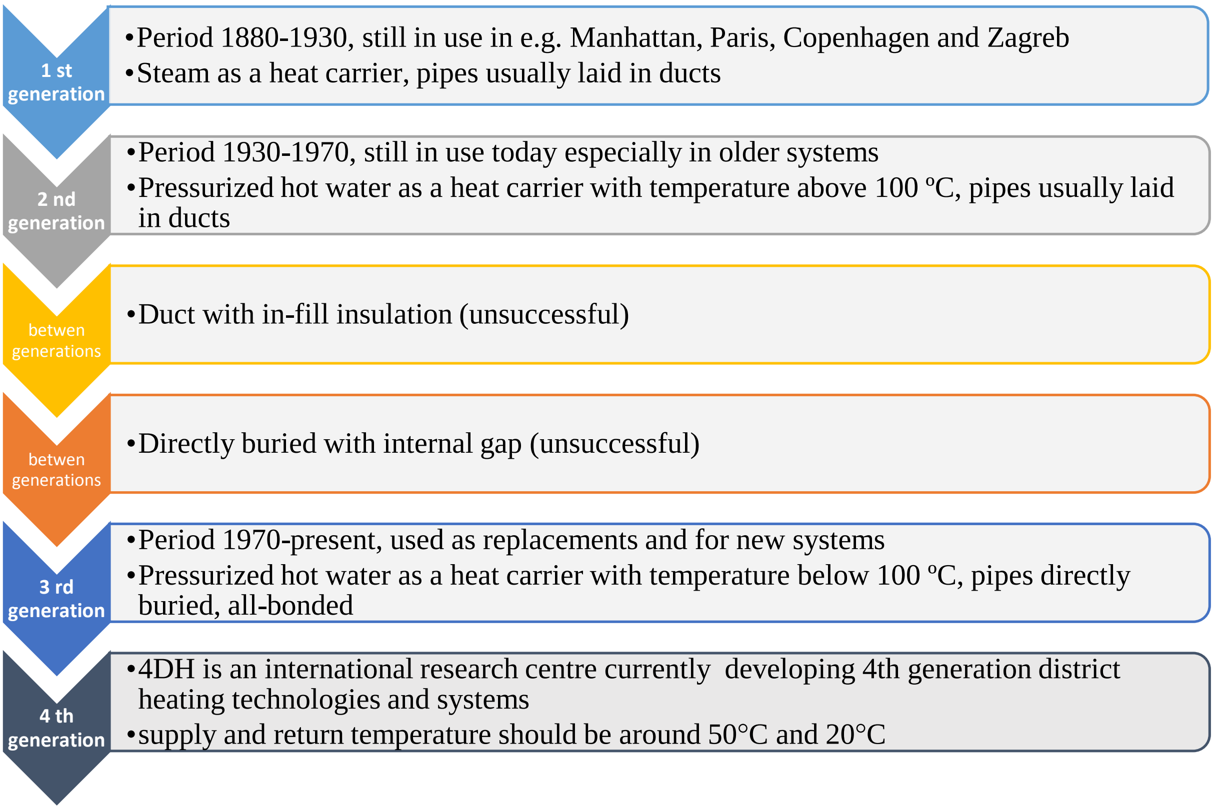


Figure 6. District heating generations [6],[49]

Pressure in steam distribution systems varies. In small systems it as low as 2 bar, and in larger systems it can be up to 20 bar, with temperatures up to 300˚C [6]. Pressure must be high in the larger system due to the specific volume of heat carrier, so the network pipes don’t become too large.

Significant energy loss in the steam system is related to pressure drops in the steam flow. Losses of this nature are on the order of 10 times the corresponding loss in hot water network representing a power demand for running pumps [6].

The advantage of steam supply is a high energy level, especially for the industry in need of heat supply at higher temperatures.

In the second generation, the design of heat distribution system is mainly the same as in the first generation, but the heat energy supply is based on the hot water distribution. There are two pipes in the hot water system, a hot water supply pipe and a cold water return pipe. The pipes are usually contained in rectangular pre-casted straight duct, made this way for speeding up the installation.

Pipes are insulated with fibrous mineral wool, in protecting wrapping, usually on site. This mineral wool is a great insulator, so the heat losses are small, as long as the insulation from the mineral wool is not damaged and is dry.

The hot water system is also designed to slope. If there are any leakages, or water originated in any other way, it accumulates at low points where it is drained. There are also inspection chambers in the system, housing both valves and compensators which allow thermal expansion and connection to the network.

Problems with this system occur with flooding, especially if the water contains salt (from roads during winter or any other source), that causes corrosion. The design was developed further, to the next generation (third generation) mainly to cut the initial costs and to allow for faster installation.

Between second and third generation two alternatives were tried, both unsuccessful in the end.

The first used various in-fill materials. Some of these materials are cellular concrete, granular plastics, or granular minerals. Most materials did not function, mainly due to the moisture in the ducts. A variant that dealt with this problem was pouring a hot bitumen substance into the duct that provided water-tightness.

The second alternative was directly buried pipes, arranged concentrically to permit axial thermal movements. With this alternative, the main problem was corrosion on the outside of pipes made of carbon steel.

The variation that is still in use is made as a steel-in-steel design, with mineral wool insulation between two layers of steel pipe. This is a very robust design, used in situations when pipes cross a river, or are buried under water, but this type of design is expensive.

The third generation is based on plastic jacket pipes. There are two types of the plastic jacket pipes, rigid and flexible. Rigid pipes are available in all pipe diameters, while flexible pipes are only available in small diameters.

Rigid pipes are designed with a carrier pipe made of carbon steel, insulation of cellular polyurethane (PUR) and the outer layer (jacket) made of high-density polyethylene (PEHD). Third generation pipes are directly buried in the ground, this means that the dimension of the system are smaller, and there are fewer components. In this generation bellow compensators are rarely used, in the case of pipes changing direction, the bend itself accounts for flexibility. There are also elastic supports at the bend, pads made of polymeric foam, or gravel. In the third generation system, there is also built-in leakage surveillance that pipes are often produced with. Built-in leakage monitoring is performed by prefabricated elements with copper wires that run along the pipe sections.

Joints represent a weak point in the network, so joint development and improvements have been one of the priorities in district heating network development. Welded joints are considered more robust, but they are also more expensive.

Fourth generation of DH is currently being developed.

2. DH COMPANIES

2.1. HEP Group

HEP Group is a Croatian national company involved in electricity generation, transmission and distribution, as the core business, but the Group offers many other services to its customers. It is organized in the form of a holding company, with a number of daughter companies (see Figure 7). The parent company of the HEP Group is HEP d.d. which performs the function of corporate management and guarantees the conditions for secure and reliable energy supply to its customers.

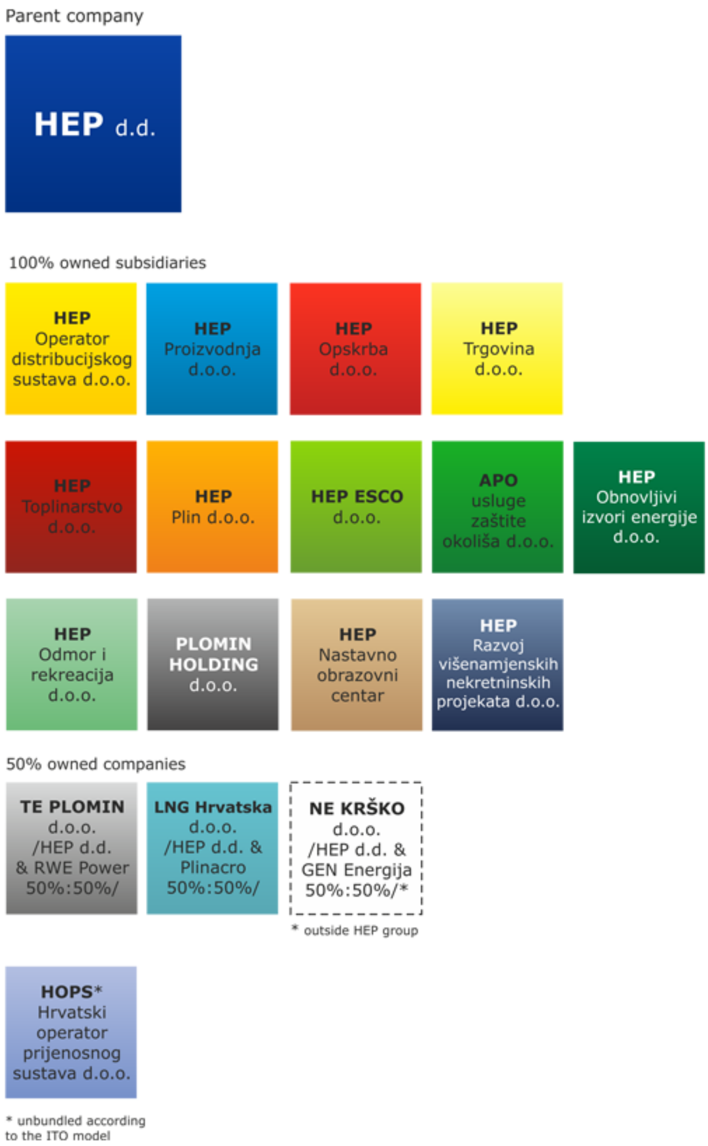


Figure 7. HEP Group [12]

HEP Group has over 4000 MW of installed capacity for electricity production and over 1900 MW of installed capacity for heat production. A brief overview of the Groups companies is presented below, with relevant ones described in more detail, and some omitted completely.

HEP Proizvodnja d.o.o. (HEP Generation) has a task of generating electricity and heat energy. It has 26 hydroelectric power plants and 8 thermal power plants fired by coal, oil and natural gas. Electricity is also produced by Plomin thermal power plant, and Krško nuclear power plant which is located in Slovenia. Both plants are in 50% ownership by HEP Group. Some of the thermal power plants are cogeneration power plants which generate both electricity and heat energy. Cogeneration forms the majority of heat supply for district heating systems in Zagreb and Osijek. Figure 8 shows HEP Group's total installed capacity divided into 4 categories: Hydro power plants, nuclear power plants thermal power plants and thermal power, which includes cogeneration heat power and heat power of heat only boilers. Total thermal power represents 32% of the total installed capacity. Thermal power of the thermal power plants is equal to 1569 MW, and another 382 MW is installed in the heat only boilers [13]. Total electricity capacity of the hydroelectric power plants is around 2133 MW, which represent 35% of the total installed capacity while the electricity capacity of the thermal power plants is around 2020 MW or 27% of the total. [13]. Krško nuclear power plant total electricity generation capacity is around 696 MW, but only half of it belongs to HEP Generation, which represents about 6% in the overall power distribution.

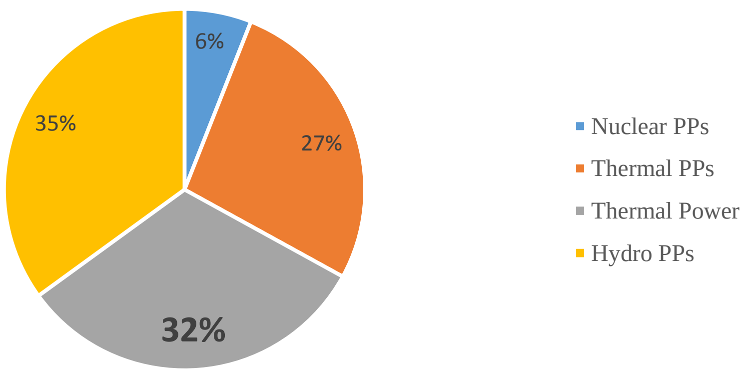


Figure 8. Installed Capacity HEP [13]

Figure 9 shows HEP Group's total generated energy in 2012, divided into four categories: hydro power plants, nuclear power plants, thermal power plants and thermal energy (energy generated by cogeneration and heat only boilers).

In 2012, hydroelectric power plants produced 17405 TJ of electricity, while the thermal power plants produced 16877 TJ, which represent 33% and 32% respectively [13]. Nuclear power plant Krško produced 9494 TJ of electricity or 18% of the total energy generation while, in the same year, CHP plants generated 8966 TJ of heat energy which represents 17% of the total energy generation [13]. Steam generation amounted to 826616 t, or 2479 TJ which was calculated using a factor of $2.9988 \cdot 10^{-3}$ TJ/t [13],[14].

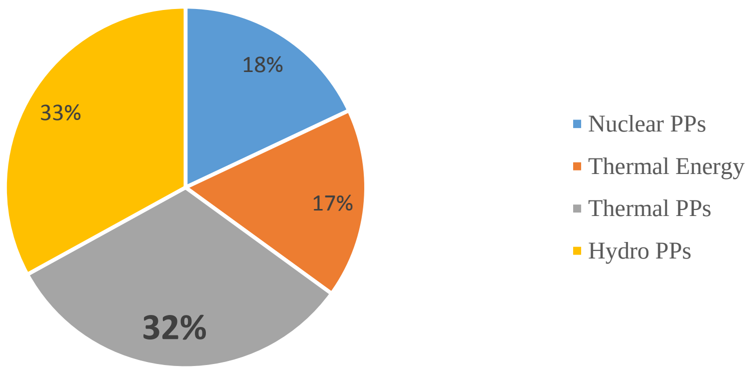


Figure 9. Generated energy HEP [13]

HEP Obnovljivi izvori energije d.o.o. (HEP Renewable Energy Sources) is involved in preparation, construction and exploitation of renewable energy sources as wind power, small waterways, geothermal heat, etc. HEP Operator distribucijskog sustava d.o.o. (HEP Distribution System Operator) is responsible for distributing electricity taken from the transmission network, ensuring reliable customer supply, managing sales, metering, billing and payment collection for electricity supplied. In addition HEP Distribution System Operator is responsible for maintenance, replacement, reconstruction and development of distribution network and plants. There are around 24000 transformer stations, and 140000 kilometers of lines of different voltage levels [12]. HEP Opskrba d.o.o. (HEP Supply) is supplying electricity to small and large business customers. HEP Trgovina d.o.o. (HEP Trade) is carrying out activities of purchase and sale of electricity, optimization of power plants operation, and trading intermediation in the domestic and international market. HEP Toplinarstvo d.o.o. (HEP District

Heating) is in charge of production, distribution and supply of heat energy in the city of Zagreb, parts of Zagreb County, Osijek, Sisak, and some local boiler plants. HEP Plin d.o.o. (HEP Gas) is in charge of natural gas supply to the customers. HEP ESCO d.o.o. (HEP Energy Service Company) provides energy services.

Operating income of HEP Group, for 2012, is 1.84 billion EUR. Operating income can be divided into categories shown in Figure 10. Electricity sales account for 83% of the total income, while sales from district heating accounts for only 4%. Gas sales accounted for 3% of the income and other activities accounted for 10%.

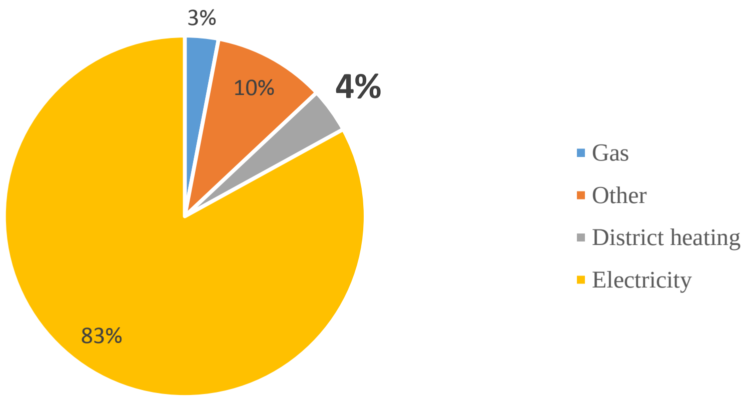


Figure 10. HEP Operating income split [13]

Number of employees in HEP Group has been decreasing in the period from 2006-2012 from 14357 in 2006 to 13585 in 2012. HEP District heating also experienced a decrease in the number of employees in the same period, from 378 in 2006, to 353 in 2012, which represents a decrease by 6.6%.

Table 1. Number of employees in HEP District Heating and HEP Group [15]

	2006	2007	2008	2009	2010	2011	2012
Total number of HEP employees	14357	14290	14375	14222	14016	13788	13585
Number of employees in HEP DH	378	386	392	355	336	351	353

As can be seen the HEP Group is a large national company that is performing multiple services for its customers, firstly electricity generation, transmission and distribution. Heat generation and distributor within HEP District Heating represents only a small part of the total operations of the company.

2.1.1. HEP District Heating

HEP District Heating is the largest provider of heat energy in Croatia, performing heat energy generation and distribution. In 2012, HEP District Heating supplied heat energy to around 117145 households and 6051 businesses, in the cities of Zagreb, Zaprešić, Samobor, Velika Gorica, Sisak and Osijek [12]. Distribution of generated heat energy in HEP District Heating by operative areas is shown in Figure 11. It is important to mention that HEP District Heating has not generated all of the energy that it is distributing. HEP Generation, sister company within the HEP Group, generates much of the energy within HEP District Heating, with its thermal power plants, TE-TO Zagreb, EL-TO Zagreb, TE-TO Osijek and TE Sisak. Special Boiler Plants are comprised of plants in Zaprešić, Samobor, Velika Gorica, and some smaller plants (heat only boilers) in Zagreb that are not connected to the central network. The term Zagreb DH will be used to designate central district heating network in Zagreb. Thermal power plants TE-TO Zagreb and EL-TO Zagreb supply all of the heat energy in Zagreb DH. Around 75% of the generated heat energy in HEP District Heating[1] is within Zagreb DH, while the Osijek Operative Area and Special Boiler Plants have around 10% of total, and Sisak Operative Area has 5% (see Figure 11).

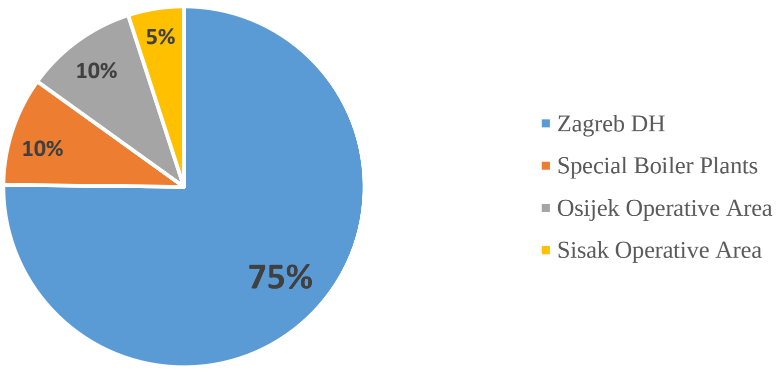


Figure 11. Distribution of generated heat energy in HEP DH by operative areas [15]

Generated heat energy distribution shown in the Figure 11 does not include generated steam. Distribution of steam generation is shown in Figure 12. Vast majority of steam is generated

[1] When it is said that Zagreb DH or HEP District Heating generated heat energy it encompasses heat generation of all relevant parties (HEP District Heating and HEP Generation)

within Zagreb DH, with about 80% of the total, while the rest is within the Osijek Operative Area. Generation in Sisak Operative Area is neglected with its 0.6%, and there is no steam generation in Special Boiler Plants. Number of customers in the Zagreb DH is the largest by far, with over 73% of the customers of HEP District Heating in all operative areas (see Figure 13). Special Boiler Plants have about 14% of the customers, while Osijek Operative Area and Sisak Operative Area have 10% and 3% respectively.

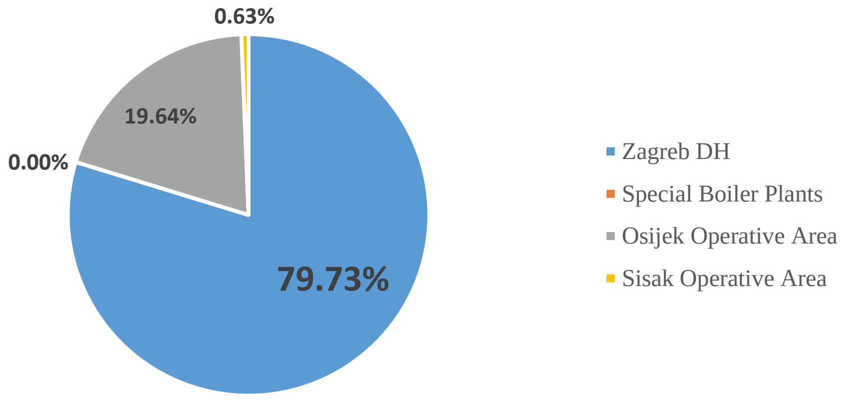


Figure 12. Distribution of generated steam in HEP DH by operative areas [15]

From this short review of the HEP District Heating, it can be seen that Zagreb DH represent the largest portion of total operations of HEP District Heating, with 75% of the heat energy generation, 80% of steam generation, and 73% of the customers. All of the further analysis presented in this work will focus on the Zagreb DH.

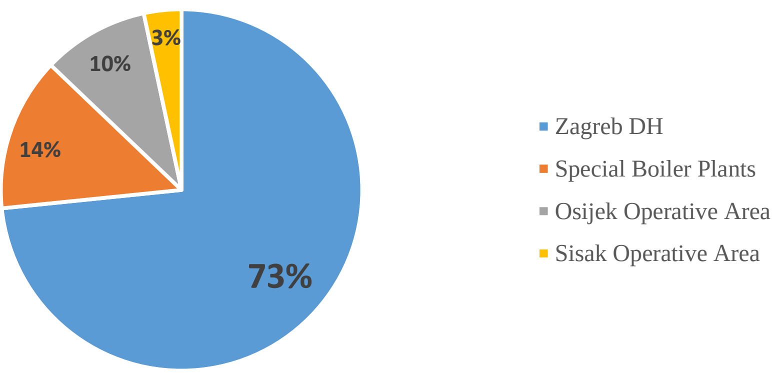


Figure 13. Distribution of the number of customers in HEP DH operative areas [15]

2.2. Aalborg Forsyning-Koncernen

Aalborg Forsyning-Koncernen (Aalborg Supply Group) is a group of utility companies owned by Aalborg Municipality that provide services to individual households and businesses. Aalborg Supply Group organizational chart is shown in Figure 14.

A brief overview of the Groups companies will be given in this paragraph. Aalborg Forsyning, Gas (Aalborg Gas Supply) is a utility company in charge of the distribution of the natural gas to customers. Aalborg Forsyning, Varme (Aalborg District Heating) is a utility company in charge of production and distribution of heat energy to its customers. Aalborg Forsyning, Renovation (Aalborg Municipal Waste) is in charge of collecting and disposing of solid municipal waste. In addition to these utility companies within Aalborg Supply Group, there is also Aalborg Forsyning, Vand A/S (Aalborg Water Supply) which provides tap water to customers, Aalborg Forsyning, Kloak A/S (Aalborg Sewage) which disposes if sewage and operates and maintains the sewers, and Aalborg Forsyning, Service A/S (Aalborg Supply Service) which handles general administrative tasks.

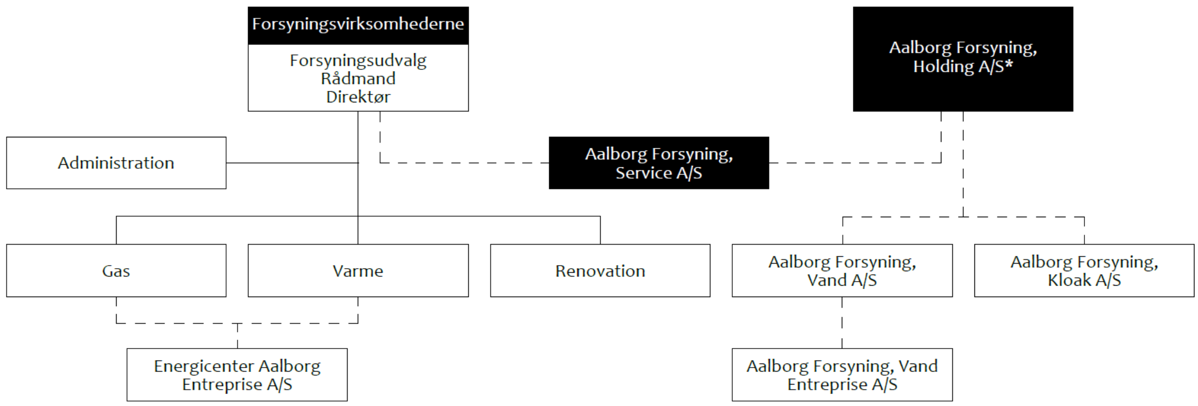


Figure 14. Aalborg Forsyning-Koncernen [16]

All these companies operate on a commercial basis, and in some areas compete with private companies, like in the area of heat energy generation for district heating in which multiple companies take part, like Aalborg District Heating, Vattenfall, Reno-Nord and Aalborg Portland.

Aalborg Supply Group also performs regulatory functions and planning on district heating, water supply and waste management. Group has approximately 480 employees and an annual turnover of approximately 200 million EUR [17]. Distribution of turnover of companies within the Aalborg Supply Group is shown in Figure 15. Aalborg District Heating has the highest stake with 47% of the total turnover in 2012, while the Aalborg Supply Sewage and Aalborg Municipal waste have 20% and 15% respectively. All other companies with the Group have smaller stakes at 6% or less.

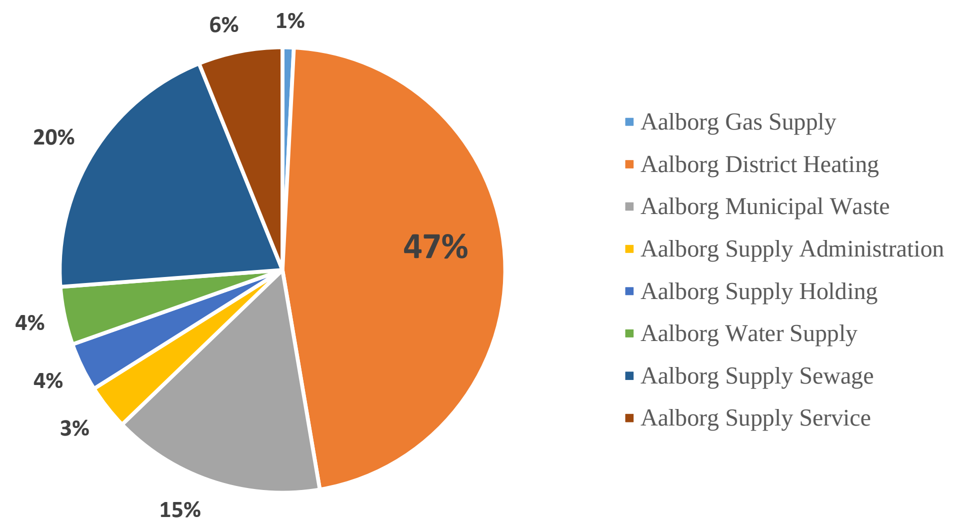


Figure 15. Distribution of turnover of companies within the Aalborg Supply Group [17]

Figure 16 shows the number of employees in companies within Aalborg Supply Group. Aalborg Municipal Waste has the most employees, at 32%, while Aalborg Supply Holding has 22%, and Aalborg District Heating has 20%. All other companies individually have less than 13%.

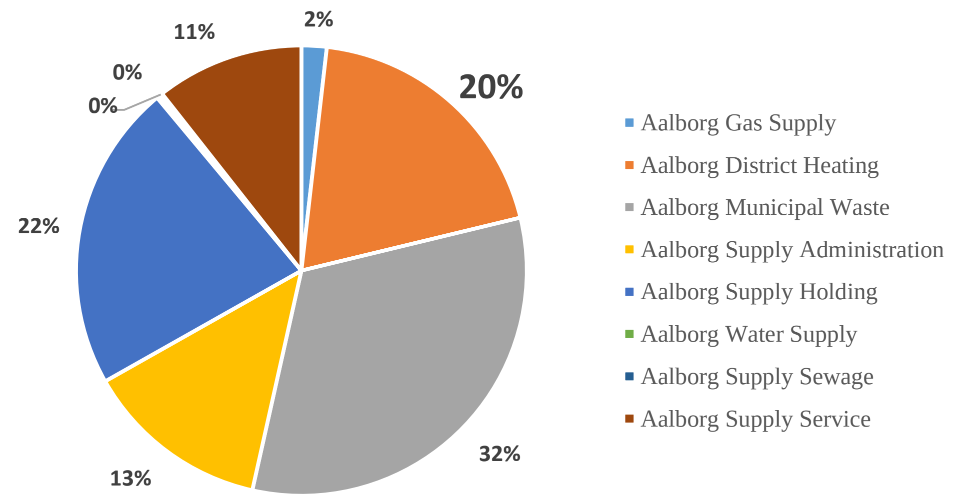


Figure 16. Number of employees in companies within Aalborg Supply Group [17]

Aalborg District Heating is one of the largest and most important company within the Aalborg Supply Group. It generates 47% of the annual turnover of the Group and represents 20% of the workforce.

The importance of district heating in Aalborg Municipality is shown in the Figure 17.

Figure 17 shows the net heat demand in the Aalborg Municipality with district heating share at 89%. Other heating alternatives have relatively small shares, such as oil with 7%, and biomass and electricity both with 2%. Natural gas and other heating alternatives have very small shares. A small fraction of houses with unregistered heating technologies are allocated proportionally to the five smallest heating technologies.

Almost everybody who had the opportunity to connect to DH is connected, especially in Aalborg as shown in the Table 16, with a coverage area of 98.6%.

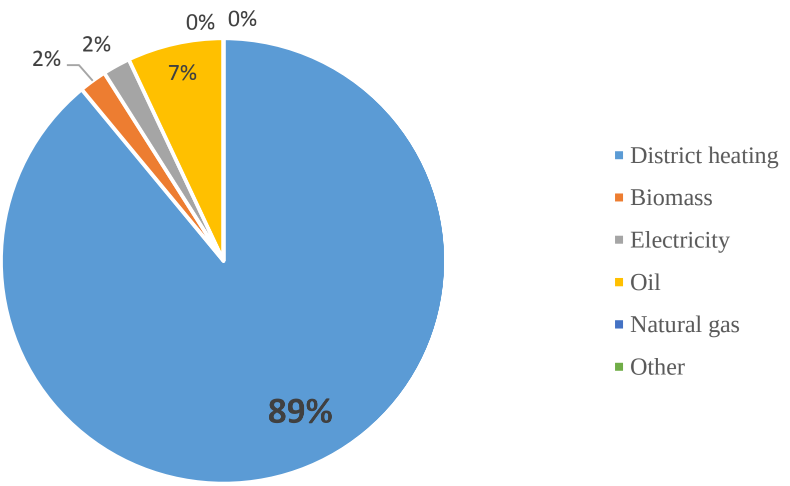


Figure 17. Distribution of the net heat demand in Aalborg Municipality [18]

2.2.1. Aalborg District Heating

Aalborg District Heating performs purchasing, production, distribution, service, consulting and marketing of DH in the Municipality of Aalborg. Aalborg District Heating comprises of the central supply area and decentralized areas. Decentralized areas have independent DH systems that are supplied by small CHP plants, run by natural gas. Central supply area will be called Aalborg DH, in further references in the Thesis. Generated heat energy in Aalborg DH is over 98.5% of the total, with the decentralized DH areas representing just over 1.4%.

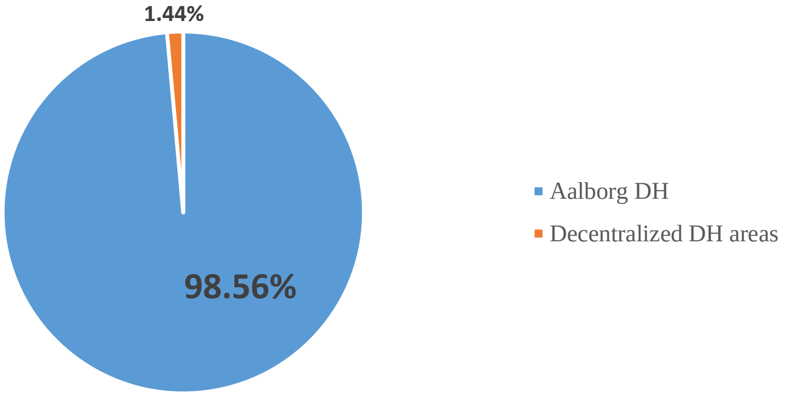


Figure 18. Generated heat energy in Aalborg DH and Decentralized DH areas [19]

Figure 19 shows installed heat power in Aalborg DH, and decentralized DH areas. Aalborg DH heat power is around 98.82% of the total, while the remaining 1.18% is the cumulative sum of decentralized DH areas.

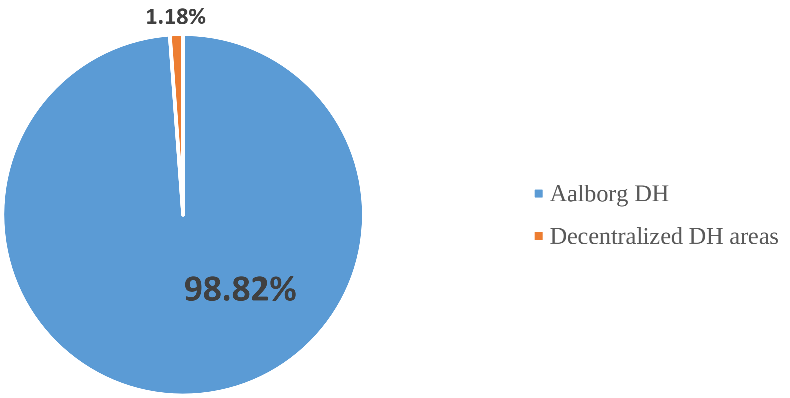


Figure 19. Installed heat power in Aalborg DH and decentralized DH areas [19]

As it has been seen the Aalborg DH represent the vast majority of the total DH business. All of the further analysis presented in this work will focus on the Aalborg DH.

3. HEAT SUPPLY

3.1. Heat supply Zagreb DH

Heat supply of the district heating in Zagreb is performed by TE-TO Zagreb and EL-TO Zagreb, both of which are thermal power plants composed of multiple units. Overall heat power of both power plants is 1420 MW, achieved by 14 units.

TE-TO Zagreb is located within the city of Zagreb, near the Sava River (see Figure 20). The power plant consists of 8 units, with overall electricity capacity of 440 MW, and heat power of 850 MW [12].

Electricity capacity and heat power of individual units are shown in the Table 2. Many of the units are quite old, and all but 2 of them have been constructed before 1990. All of the units can use natural gas as a fuel, and some can also use fuel oil. Out of the 8 units, one is a conventional CHP unit, two of them are Combined cycle CHP, and the rest are heat only boilers. There is one auxiliary steam boiler and four hot water boilers. Table 3 shows type, fuel and commission year of individual units. The newest unit is Unit L, commissioned in 2009, with nominal electricity capacity of 112 MW, and heat power of 110 MW. Unit L is a combined cycle CHP unit fueled by natural gas.

In 2012, TE-TO generated 3059 TJ of heat energy, 766 TJ of steam, and 6970 TJ of electricity. Compared to 2011, heat energy generation and steam generation, decreased by 3.5% and 1.3% respectively due to warmer heating season (see Table 14) [15].

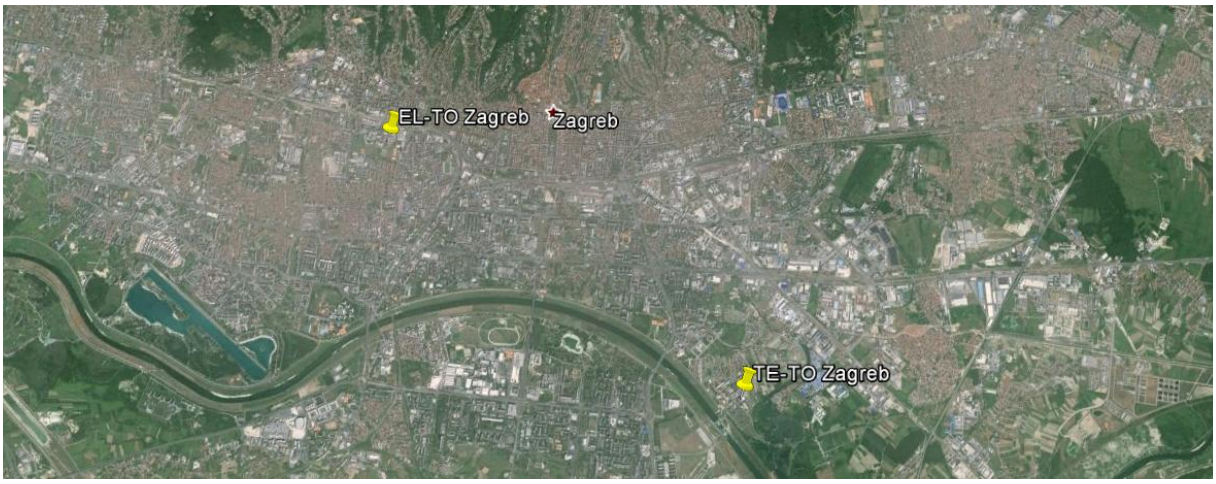


Figure 20. Location of TE-TO Zagreb and EL-TO Zagreb [20]

Since 2009, electricity generation has increased significantly due to commission of the new combined cycle CHP unit. Electricity generation increased in the period from 2009-2012 from 5591 TJ to 6970 TJ.

Table 2. TE-TO Zagreb [12]

Unit	Power	Unit type	Fuel	Commissioned
Unit C	120 MW_e /200 MW_t	CHP	Natural gas/Oil	1979
Unit D	58 MW_t	Auxiliary steam boiler	Natural gas/Oil	1985
Unit E	58 MW_t	Hot water boiler	Natural gas	1977
Unit F	56 MW_t	Hot water boiler	Natural gas	1978
Unit G	116 MW_t	Hot water boiler	Natural gas/Oil	1982
Unit H	116 MW_t	Hot water boiler	Natural gas/Oil	1990
Unit K	208 MW_e / 140 MW_t	Combined cycle CHP	Natural gas/Extra light fuel oil	2003
Unit L	112 MW_e / 110 MW_t	Combined cycle CHP	Natural gas	2009

Table 3. TE-TO Zagreb energy generation [12]

	2009	2010	2011	2012
Heat energy (TJ)	3117	3383	3168	3059
Steam (TJ)	754	770	776	766
Electricity (TJ)	5591	7301	7405	6970

During the 2009, for the generation of electricity, heat energy and steam, shown in Table 3, 93814 t of oil, $325 \cdot 10^6$ m^3 of natural gas and 137 t of extra light oil, has been used with an average heating values of 40193 kJ/kg, 33337 kJ/m^3 and 42000 kJ/kg respectively [21]. This amounted to 14605 TJ of primary energy consumption.

EL-TO Zagreb is also located within the city of Zagreb, at the district Trešnjevka. The power plant consists of 6 units, with overall electricity capacity of 89 MW and thermal generating capacity of 566 MW [12].

Table 4 shows electricity and thermal generation capacity, type, fuel, and commission year of individual units of the power plant. Again, most of the units are old, two of them being constructed in 1970 and 1971. The newest unit is auxiliary hot water boiler (Unit 6) with thermal generating capacity of 116 MW, fueled by natural gas or fuel oil, which was commissioned in 2010.

The plant consists of two conventional CHP units, one combined cycle CHP unit, and three units are heat only boilers. Two of the boilers are auxiliary hot water boilers, and there is one auxiliary steam boiler.

In 2012, EL-TO Zagreb generated 2242 TJ of heat energy (steam not included), 953 TJ of steam, and 1318 TJ of electricity. Compared to 2011, heat energy generation and steam generation decreased by 3.4% and 7.9% respectively due to warmer heating season (see Table 14).

Steam generation was constantly decreasing in the period from 2009-2012, and in 2012 it was 12.3% less than in 2009.

Table 4. EL-TO Zagreb [12],[21]

Unit	Power	Unit type	Fuel	Commissioned
Unit 1	11 MW_e / 45 MW_t	CHP	Natural gas/Oil	1970
Unit 2	30 MW_e / 125 MW_t	CHP	Natural gas/Oil	1980
Unit 3	48 MW_e / 100 MW_t	Combined cycle CHP	Natural gas	1998
Unit 4	64 MW_t	Auxiliary steam boiler	Natural gas/Oil	1971
Unit 5	116 MW_t	Auxiliary hot water boiler	Natural gas/Oil	1991
Unit 6	116 MW_t	Auxiliary hot water boiler	Natural gas/Oil	2010

Table 5. EL-TO Zagreb energy generation [12],[21]

	2009	2010	2011	2012
Heat energy (TJ)	2209	2332	2322	2242
Steam (TJ)	1087	1045	1035	953
Electricity (TJ)	1271	1328	1292	1318

Considering the EL-TO Zagreb location (see Figure 20) it doesn’t have the possibility of cooling with large amounts of water but only through four cooling towers with around 150 m^3 of cooling water. Its electricity generation is strongly correlated with heat demand [21].

During the 2009, for the generation of electricity, heat energy and steam shown in Table 5, 37907 t of oil, $132 \cdot 10^6$ m^3 of natural gas has been used, which amounted to 5924 TJ of primary energy consumption [21].

As already mentioned, electricity capacity of both power plants is 529 MW while the thermal generating capacity is 1420 MW. These capacities are achieved by 14 unit energy generating units (see Table 6). Altogether there are 3 conventional CHP units, 3 combined cycle CHP units, 4 hot water boilers, 2 auxiliary hot water boilers and 2 auxiliary steam boilers.

Conventional CHP units represent about 30.4% of electricity capacity, and about 26.0% of thermal generation capacity. Combined cycle CHP units represent about 69.6% of electricity capacity, and about 24.7% thermal generation capacity. The rest of the thermal generation capacity, which is about 49.3% of the total, is performed by heat only boilers.

Table 6. Total capacity of TE-TO Zagreb and EL-TO Zagreb

Unit type	No. of units	Electricity capacity (MW)	Heat power (MW)
CHP	3	161	370
Combined cycle CHP	3	368	350
Hot water boiler	4	0	346
Auxiliary hot water boiler	2	0	232
Auxiliary steam boiler	2	0	122
Total	**14**	**529**	**1420**

Total heat generation in 2012 was 5301 TJ (steam not included), a reduction from the previous year by 174 TJ, or 3.2% (see Table 7). In addition, power plants produced 1719 TJ of steam, a reduction from the previous year by 87 TJ or 5%.

In 2012, out of the generated heat energy of 5301 TJ, only 4687 TJ has been sold to customers which is about 88.4%. The percentage of sold heat energy has not risen during the period 2007-2012. In 2012, out of the steam generation of 1719 TJ, only 1422 TJ has been sold, which represents about 82.7%. The percentage of sold steam has risen slightly during the period 2007-2012 from the 86.5% in 2007 to 88.4% in 2012. In 2012, heat energy sales decreased by 4.2% compared to the 2011 as a consequence of slightly warmer heating season [15].

Table 7. Total heat generation of TE-TO Zagreb and EL-TO Zagreb [15]

	2007	2008	2009	2010	2011	2012
Generated heat energy (TJ)	5267	5406	5340	5713	5475	5301
Generated steam (TJ)	1918	1968	1841	1815	1806	1719
Sold heat energy (TJ)	4557	4779	4835	5087	4810	4687
Percentage of heat energy sold	86.53%	88.39%	90.55%	89.01%	87.84%	88.42%
Sold steam (TJ)	1457	1609	1469	1481	1422	1422
Percentage of steam sold	75.97%	81.76%	79.83%	81.57%	78.71%	82.74%

In 2009, total primary energy consumption in both thermal power plants was 20529 TJ using which 5339 TJ of heat energy, 1840 TJ of steam and 6862 TJ of electricity was produced.

3.2. Heat supply Aalborg DH

Generation of heat energy in Aalborg DH is predominantly performed by CHP plants, waste to energy plants and using surplus heat of industry (see Table 8).

Almost all of the CHP heat generation is performed by Nordjylland Power Station which is owned by Vattenfall and located in close proximity to the city, around 5 km to the city's outskirts (see Figure 21). The power plant generates electricity and heat energy in two separate units, Unit 2 and Unit 3 (see Table 9). Combined electricity capacity, of both units, is 706 MW, while thermal generation capacity is 462 MW [22]. Unit 4 is a diesel-fired gas turbine with electricity capacity of 25 MW, which can be used for restarting the power plant in the event of nationwide power outages [22]. Unit 2 was commissioned in 1977, while Unit 3 was commissioned in 1998. Unit 3 is the most efficient thermal power plant on coal in the world, with its combined electricity and thermal efficiency at around 91% [22].

Table 8. Heat generation in Aalborg DH [19]

	CHP	Waste to energy	Surplus heat from industry	Auxiliary boilers
2012	63%	20%	15%	2%

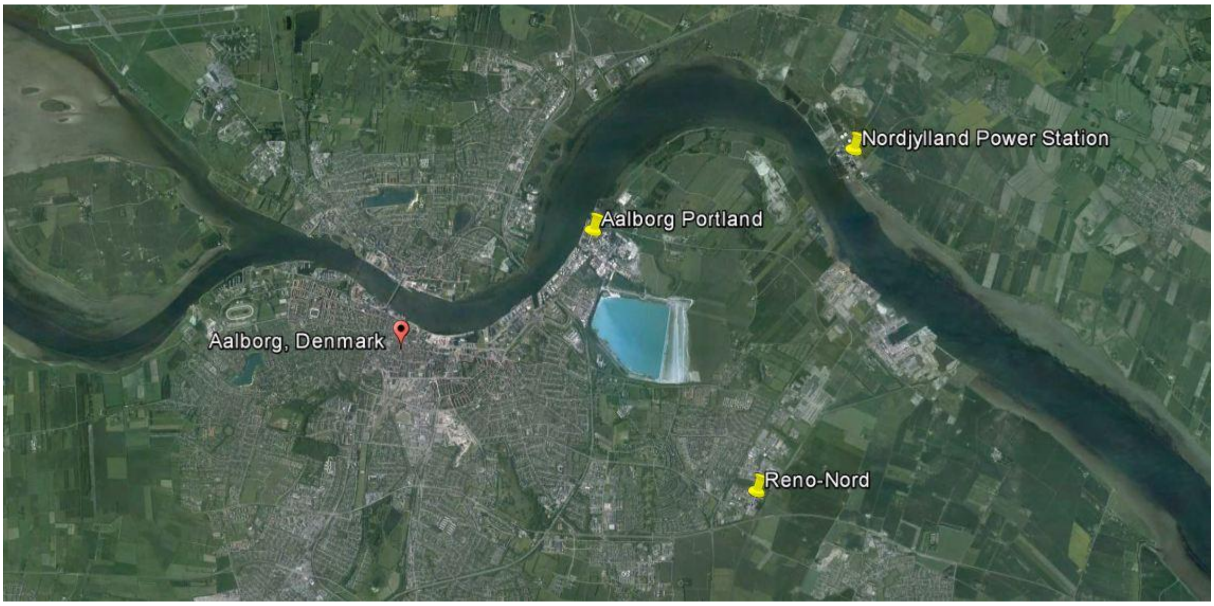


Figure 21. Locations of Nordjylland Power Station, Reno-Nord and Aalborg Portland [20]

Both units are coal fired, and when at full load, they consume 223 t of coal per hour. The Nordjylland Power Station burns around 800000 t of coal annually, which represents about 19120 TJ of primary energy (heating value of coal is 23.9 GJ/t) [22],[50]. Steam used for generating heat in district heating system is tapped from the medium pressure part of the turbine and led through two heat exchangers heating the water in the district heating system to about 80-90 ºC. To be able to optimize the operation of the power plant there is a water heat storage of about 25000 m^3. When there is a need for electricity, heat production can be stopped temporarily, and all of the steam will be used for electricity production. In that case, after exiting the turbine, steam is led to condenser where it is cooled by water from Limfjord.

Table 9. Nordjylland Power Station [22]

Nordjylland Power Station	Unit 2	Unit 3	Unit 4	Total
Type of unit	CHP	CHP	Gas turbine	
Commissioned	1977	1998	1977	
Electricity generating capacity (MW)	305	411	25	741
Heat generating capacity (MW)	42	420		462
Coal consumption at full load (t/h)	105	118		223
Steam pressure (bar)	198	289		
Steam temperature (ºC)	535	582		
Heat storage tank (m^3)	25000			

Reno-Nord is an energy company which deals with waste incineration in waste-to-energy plants located within the city (see Figure 21). Waste is gathered from households and businesses in five municipalities (Broenderslev, Jammerbugt, Mariagerfjord, Rebild and Aalborg municipality) in North Jutland [23].

Reno-Nord has two waste incineration lines, Line 3 and Line 4, both of which produce electricity and heat energy (see Table 10). In times when received waste exceeds incineration capacity, the waste is stored in the temporary depot. Both the electricity generation capacity and heat generation capacity are valid for the heating value of 10.7 GJ/t of waste. Total waste capacity of both lines is 32.5 t/h, with electricity generating capacity of 25 MW and thermal generation capacity of 67 MW. In 2012, Reno-Nord received 184414 t of waste which translates to 1973 TJ of energy (heating value 10.7 GJ/t of waste) [24]. Line 3 was commissioned in 1991, and has an overall total efficiency of 80% to 83%; electrical efficiency is around 20% to 22%. Line 4 was commissioned in 2005 and has an overall total efficiency of 97%-100%, and an electrical efficiency of 26% to 27%. Line 4 can incinerate up to 180000 t of waste per year [24].

Table 10. Reno-Nord Waste-to-Energy Plant [24]

	Line 3	Line 4	Total
Waste capacity (t/h)	10	22.5	32.5
Commissioned	1991	2005	
Steam pressure (bar)	50	50	
Steam temperature (°C)	425	425	
Electricity generating capacity (MW)	7	18	25
Heat generating capacity (MW)	19	48	67
Total efficiency (%)	80-83	97-100	
Electrical efficiency (%)	20-22	26-27	

Aalborg Portland is a company that manufactures cement that has an annual capacity of 2.8 million tonne of cement products, and it is located within the city (see Figure 21) [25]. Surplus heat is supplied to the Aalborg DH system. Annual heat energy delivered to Aalborg DH is around 1746 TJ, which is equivalent of meeting the heating needs of around 36000 households [25].

Heat energy supplied to the Aalborg DH is the waste heat recovered from flue gases in the cement plant. Aalborg Portland currently has two heat recovery systems, one with the heat power of 70 MW and other with 32 MW [26]. Sulphur dioxide is removed from the flue gases at the same time. The plant has been in service since the early 1990s and has regularly been improved and upgraded to optimize energy efficiency and make the flue gas emissions even cleaner.

Aalborg Forsyning owns 11 heating stations and 3 CHP plants (see Table 11), with total thermal generation capacity of 465 MW and electricity capacity of 7.7 MW.

All of the heating stations and CHP plants have been environmentally approved, except the ones that do not have to be, because their thermal generation capacity is below the limit for environmental approval.

Average fuel efficiency of the heating stations is around 90%, while the CHP units combined efficiency is around 90-95% [19].

As can be seen from the Table 11, all of the heating stations are intended for auxiliary use only except for two (Gasværksvej and Vadum), which are also used for peak loads and the five CHP units in Langholt, Grindsted, Tylstrup, Hou, and Farstrup. It is important to note that supply area of Tylstrup, Hou and Farstrup-Kolby are not connected to the central district heating system.

Most of the heating stations are powered by petroleum gas, while one of the stations is powered by natural gas and one by petroleum gas or bio oil. All of the CHP plants are powered by natural gas.

All of the heating stations are relatively new, constructed within the last 15 years, and four of them are newer than 2008. CHP plants are somewhat older, from the period of 1991 till 1994.

Table 11. Power plants and boilers owned by Aalborg Forsyning [19]

	Aux.	Peak load	CHP	Power (MW)	Fuel	Constructed
Svendborgvej	X			98.3 MW_t	Natural gas/Bio oil	2012
Gasværksvej	X	X		125 MW_t	Petroleum gas	2003
Lyngvej	X			86.5 MW_t	Petroleum gas	2008
Borgm. J. vej	X			69 MW_t	Petroleum gas	2008
Vikingevej	X			17.5 MW_t	Petroleum gas	1999
Vadum	X	X		7.3 MW_t	Natural gas	1999
Vestbjerg	X			8 MW_t	Petroleum gas	1999
Højvang	X			20 MW_t	Petroleum gas	1999
Vodskov	X			10.6 MW_t	Petroleum gas	1999
Langholt			X	1.58 MW_e / 4.9 MW_t	Natural gas	1991
Grindsted			X	1.58 MW_e / 4.9 MW_t	Natural gas	1992
Tylstrup			X	2.3 MW_e / 6.6 MW_t	Natural gas	1994
Hou			X	0.9 MW_e / 2.97 MW_t	Natural gas	-
Farstrup			X	1.32 MW_e / 3.1 MW_t	Natural gas	-

By the end of 2012, total installed heat power in Aalborg DH was 1067 MW [19]. Total generated heat in Aalborg DH is shown in the Table 12. Heating stations perform only peak power coverage and reserve functions, so their heat energy generation is around 2% of the total.

Aalborg Portland heat production has decreased due to lower demand for cement caused by the slowdown in construction. Overall heat production is lower in 2011, compared to 2012, due to a warmer heating season (see Table 17).

Table 12. Total heat energy generation in Aalborg DH [19]

	2008	2009	2010	2011	2012	Avg. 2008-2012
Nordjylland Power Station (TJ)	3193	3966	5076	3701	4255	4038
Reno Nord (TJ)	1374	1346	1158	1344	1339	1312
Aalborg Portland (TJ)	1417	1129	1158	1200	1038	1188
Heating stations (TJ)	196	12	57	206	140	122
Total (TJ)	6181	6451	7450	6452	6771	6661

3.3. Heat supply comparison

Total heat power in Zagreb DH is around 1279 MW, out of which heat only boilers represent 49% of the total, and CHP plants represent the rest (see Figure 22).

In Aalborg DH total heat power is 1067 MW, which is 353 MW less than that of Zagreb DH, but figures are relatively close considering the different size of the cities and their population.

In Aalborg DH, heat only boilers represent 45% of the installed heat power, CHP plants represent about 39% (not including waste-to-energy plants), surplus heat from industry represents about 10%, and the remaining 6% is represented by waste-to-energy plants.

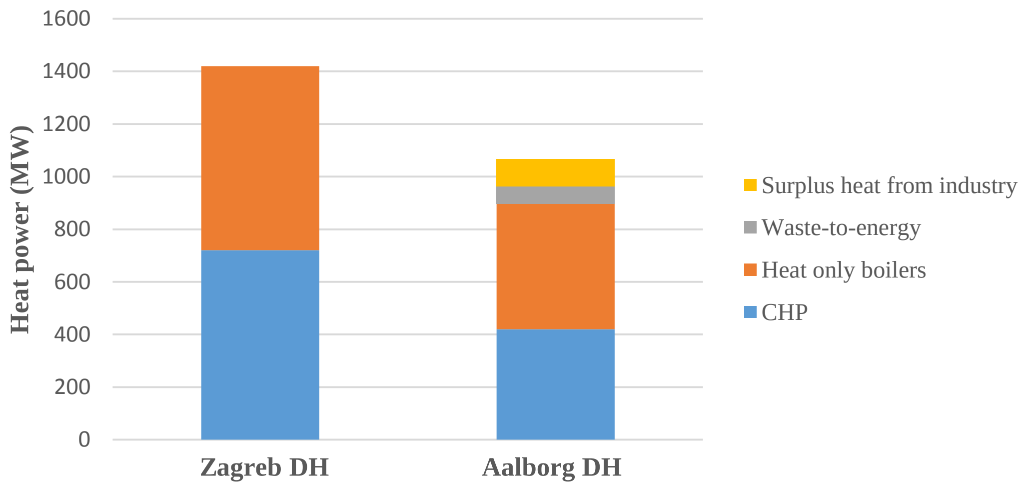


Figure 22. Heat power in Zagreb DH and Aalborg DH

Total electricity capacity of CHP plants in Zagreb DH is 529 MW while the total electricity capacity in Aalborg DH is 436 MW (see Figure 23).

CHP plants in Zagreb are fueled by oil or natural gas, while, those of Aalborg DH are fueled by coal, natural gas and waste.

Waste-to-energy CHP plant represent about 5.7% of the total CHP electricity capacity of Aalborg DH.

Specific heat power installed per unit of electricity capacity has been calculated (1) as the ratio of total heat power and total electricity capacity in individual DH systems respectively.

$$P_{hp,ec} = \frac{P_{hp}}{P_{ec}} \tag{1}$$

In Zagreb DH specific heat power installed per unit of electricity capacity is around 2.68 MW_t/MW_e, and that of Aalborg DH is around 2.45 MW_t/MW_e, which means that, in Aalborg DH, CHP units have more installed electricity capacity per unit of heat power than that of Zagreb DH.

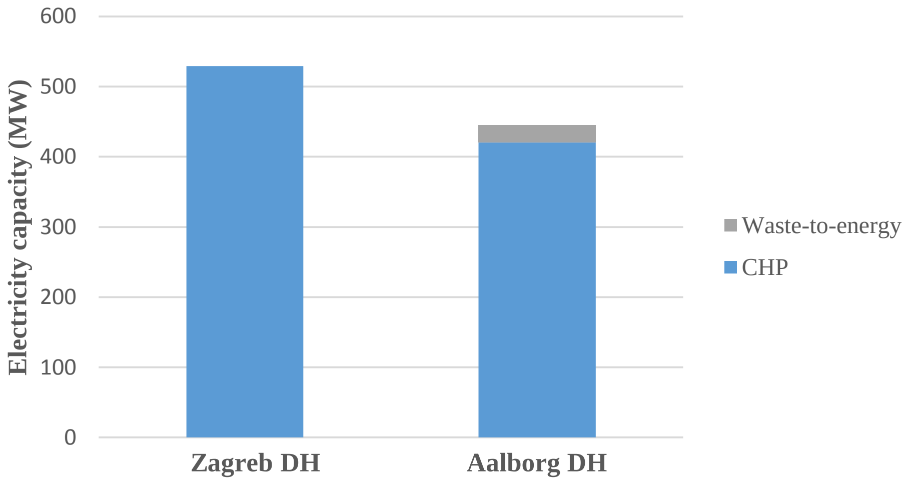


Figure 23. Electricity capacity of CHP plants in Zagreb DH and Aalborg DH

Figure 24 shows the number of heat only units and CHP plants, in both Zagreb DH and Aalborg DH.

In Zagreb DH, the total number of energy generation units is 14, out of which 8 are heat only generation units, and 6 CHP units, while in Aalborg DH there are a total of 16 energy generation units out of which 10 are heat only units, and 6 are CHP units.

Considering the fact that Zagreb DH has more installed heat power, and smaller number of heat generating units, the distribution of heat power per heat energy generation unit is lower.

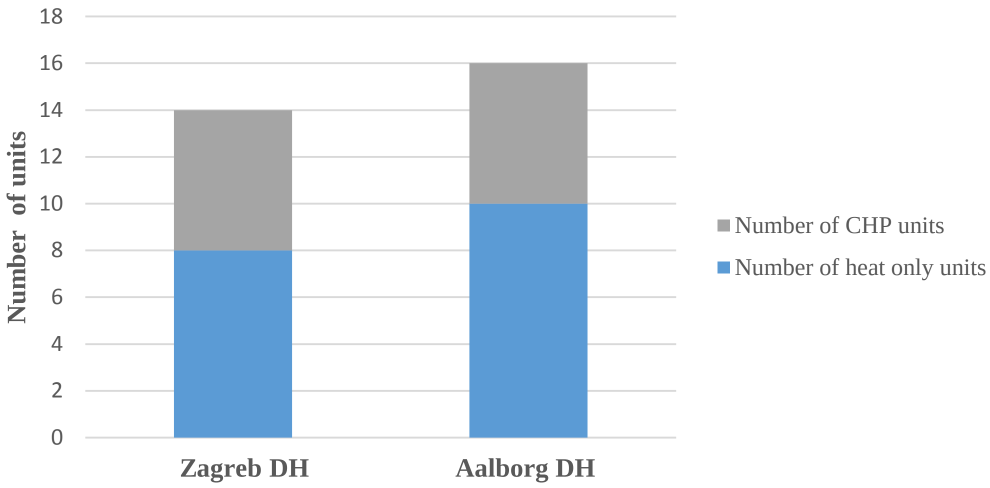


Figure 24. Number of energy generation units in Zagreb DH and Aalborg

Total heat energy and electricity generated in Zagreb DH, and Aalborg DH is shown in Figure 25.

Total heat energy generated in Zagreb DH is 7019 TJ, while the heat energy generated by Aalborg DH is 6771 TJ, which is 3.7% more than Zagreb DH.

Electricity generation of CHP units in Zagreb DH is 8287 TJ, while electricity generation in Aalborg DH is 10541 TJ, which is 27.2% more than in Zagreb DH.

Specific heat energy generated per unit of electricity is calculated as the ratio (2) of heat energy generated and the generated electricity of the individual DH systems respectively.

$$E_{he,el} = \frac{E_{he}}{E_{el}} \qquad (2)$$

In Zagreb DH, specific heat energy generated per unit of electricity is 0.85, and in Aalborg DH it is 0.64, which means that, in Aalborg DH, CHP units have a higher share in heat generation. This higher share is desirable, because CHP units have higher fuel utilization than conventional plants.

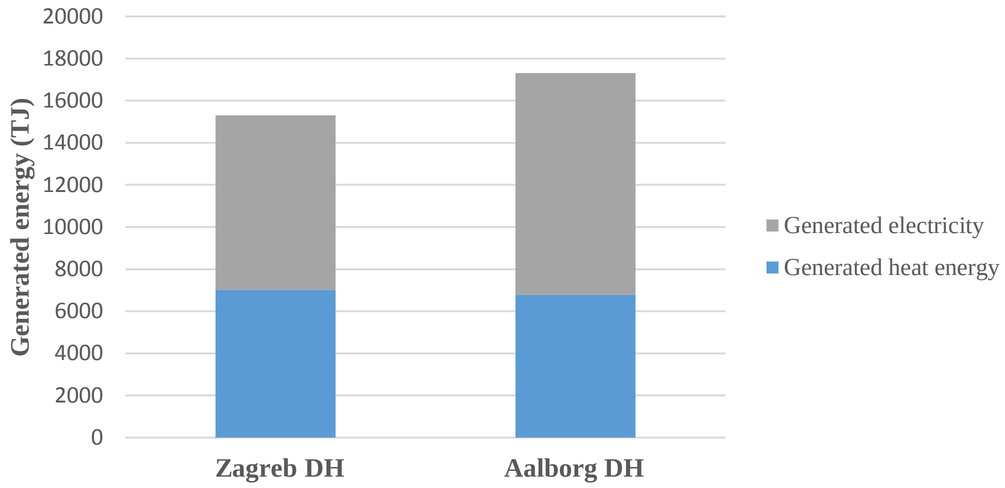


Figure 25. Generated heat energy and electricity

Figure 26 show distribution of generated heat energy to hot water and steam in both DH systems. In Zagreb DH there are both hot water and steam DH and the generation of heat energy in hot water system is about 5301 TJ, while the generation for the steam system is about 1719 TJ, which represents 24.5% of the total. Aalborg DH is comprised of only hot water system which generates around 6771 TJ of heat energy.

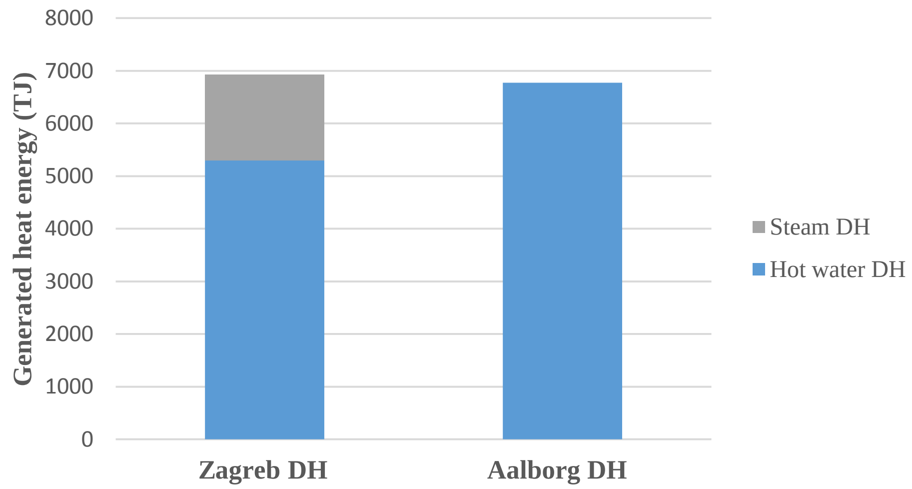


Figure 26. Distribution of generated heat energy to hot water and steam DH

Distribution of heat generating units by commission year is displayed in Figure 27. It can be seen that average commission date of heat generation units, that are still in operation today, in Aalborg DH is not as far back as those in Zagreb DH.

It is important to point out the commission of the Unit 3 in Nordjylland Power Station in 1998, which supplies most of the annual heat energy of the Aalborg DH, and commission of the Unit K and Unit L in TE-TO Zagreb, in 2003 and 2009 respectively, which supply most of the heat energy in Zagreb DH.

Average age of heat generating units in Zagreb DH is around 26 years, while the heat generating units in Aalborg DH are somewhat newer, with an average age of 14 years. Some of the Zagreb DH heat generation units still in operation today, were commissioned in the 1970/1971.

Aalborg District Heating has set its goal to expand the reserve capacity, so that there is enough heat production capacity even in the case of two of the largest units being out [17]. Heat generation units commissioned in the 2003, 2008 and 2012, in the Aalborg DH are the direct result of this goal.

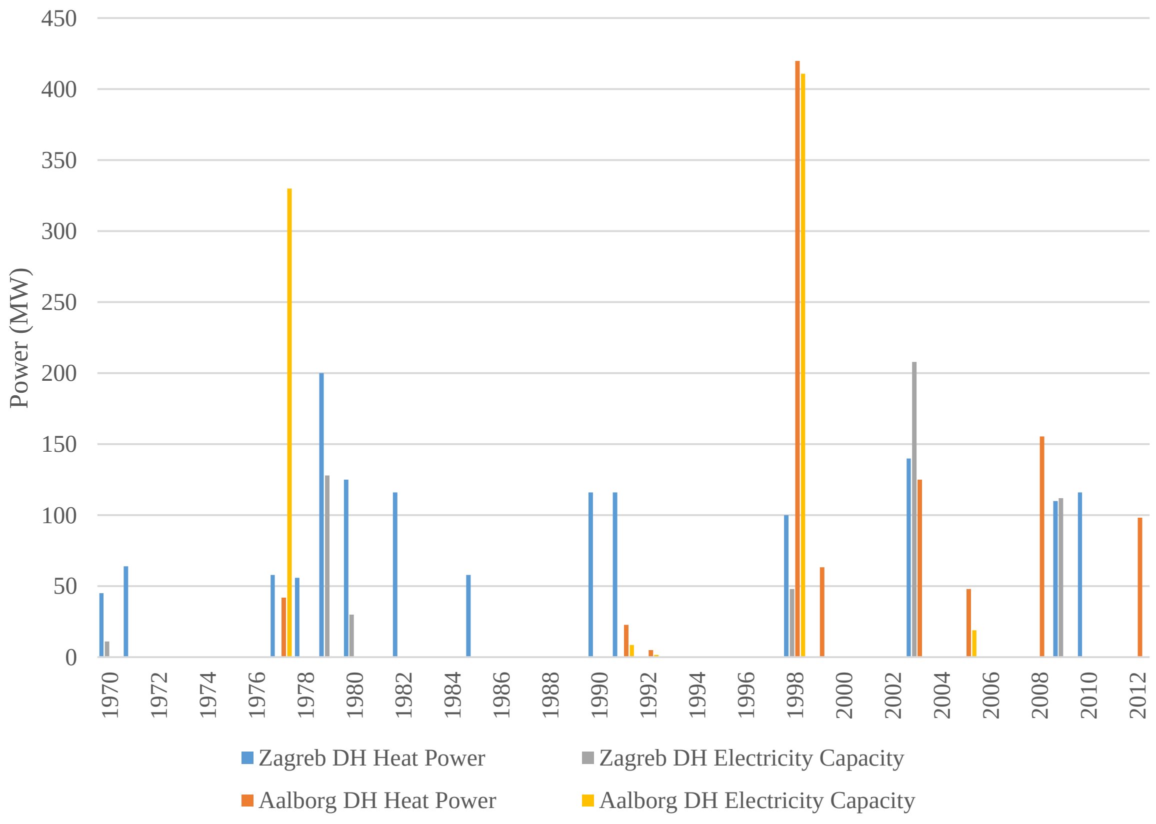


Figure 27. Commission year of heat only boilers and CHP plants

4. HEAT DEMAND

4.1. Heat demand Zagreb DH

Number of customers in Zagreb DH has been rising in the past years, from 88072 customers in 2007, to 90396 customers in 2012, which represents 2.64% increase (see Table 13). Average increase in the period from 2007 to 2012 is around 0.53% per year.

Table 13. Number of customers in Zagreb DH [15]

	2007	2008	2009	2010	2011	2012
Number of the customers	88072	88969	89367	89735	89996	90396
Growth (%)	-	1.02%	0.45%	0.41%	0.29%	0.44%

Out of the total number of customers there are 86358 households and 4038 businesses [14].

Business customers usually have much bigger space heating area and more intensive heat energy consumption. Business customers share of energy consumption is around 40%, while the remaining part, of 60%, is consumed by the households for space heating and domestic hot water preparation [12].

In the Zagreb area, there are 8331809 m^2 of connected area in DH systems out of which there is approximately 7165356 m^2 of connected are within Zagreb DH [4]. This approximation is based on the total number of connected area in DH systems in Zagreb, and the ratio of heat generation in the Zagreb area DH systems, and Zagreb DH.

Average heat energy consumption in a single household has been calculated (3) on the basis of total heat energy sold multiplied by the household share and divided by the total number of households, and it is around 11791 kWh.

$$D_{he,h} = \frac{0.6 \cdot E_{he,s}}{N_h} \tag{3}$$

Heat energy consumption per business consumer has been calculated (4), and it is around 168104 kWh.

$$D_{he,b} = \frac{0.4 \cdot E_{he,s}}{N_h} \tag{4}$$

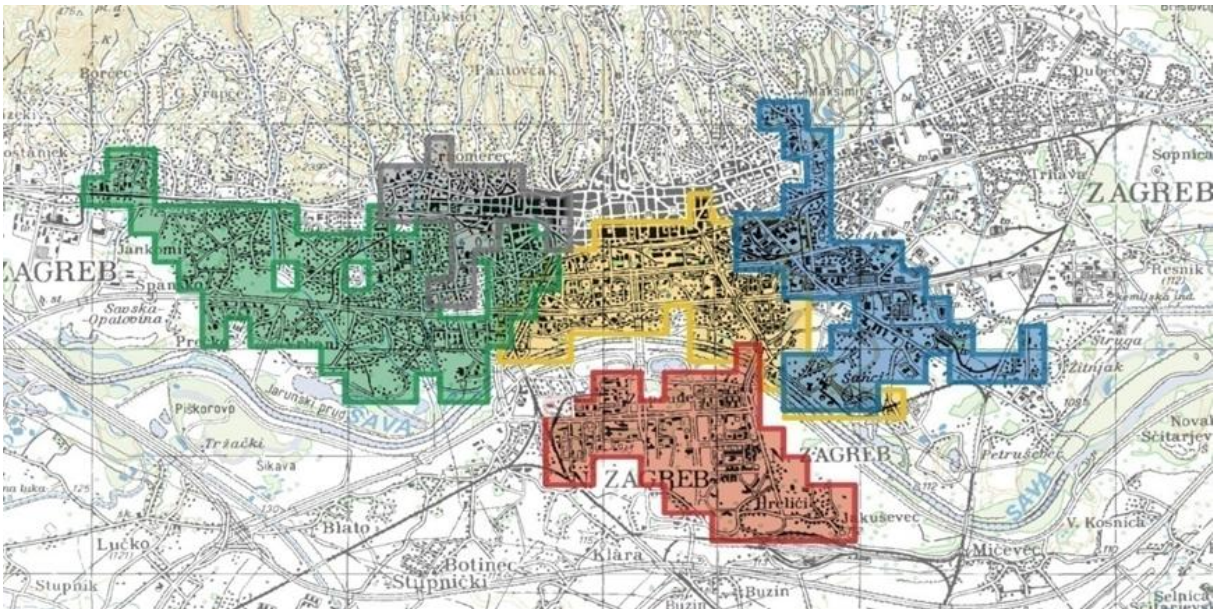
Total heat consumption, by all the households, is around 1018 GWh while the heat consumption of all the businesses is around 679 GWh.

Contracted power in both thermal power plants by households and businesses is around 912 MW out of the total installed thermal power of 1420 MW [14]. During 2012, 14 MW of new consumers were connected to the district heating systems [14].

Steam DH system is supplying heat energy to industry and customers in households, businesses and social institutions.

The city of Zagreb has a total population of 792875 people living in a 304681 households [27]. Share of the DH among the households is approximated as the ratio of the number of households supplied by DH and the total number of households, and it is around 28.3%. There are 2.6 people per household which means that Zagreb DH supplies around 225000 people in those households [27].

Zagreb DH is divided into five district heating areas out of which three are hot water district heating and two are steam district heating (see Figure 28). Hot water district heating is divided into DH area "West", DH area "North", and DH area "South" while steam district heating is divided into: DH steam "West" and DH steam "East".



Green – **district heating area "West"**

Yellow – **district heating area "North"**

Red – **district heating area "South"**

Grey – **steam district heating area "West"**

Blue – **steam district heating area "East"**

Figure 28. District heating areas in Zagreb [28]

Outdoor temperature, which is the most important parameter in determining heat energy needed for maintaining comfortable indoor temperature, is shown in the Table 14. The data in Table 14 shows average monthly temperatures for the 2011, 2012 and the nominal year.

Year 2012 has been a bit warmer than the 2011 which is one of the reasons for decreased demand in Zagreb DH (see Table 7) [15].The last two years have also been warmer than the nominal year, by around 1 ºC looking at the average annual temperature.

Outside temperature influence on the heat power of TE-TO Zagreb, and EL-TO Zagreb, is shown in the Figure 35.

Table 14. Average monthly temperatures in Zagreb [29],[30]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.
T_{2011}(ºC)	1	1	7	13	16	20	22	23	20	10	3	3	11.58
T_{2012}(ºC)	2	-3	9	12	16	21	23	23	18	12	9	0	11.83
$T_{nominal}$(ºC)	-0.1	1.9	6.3	11.1	15.8	19.2	20.9	20.2	16.1	10.8	5.8	1.4	10.78

Figure 29 shows the correlation of sold heat energy and the heating degree days in the year 2012. Heating degree days, for the year 2012, have been approximated as the product of the number of days in a month and the difference of indoor and average monthly temperatures (see Table 14). An indoor temperature of 20 ºC has been used.

As can be seen in the Figure 29, the data is well correlated. Heat energy generated during the summer period is mostly used for domestic hot water preparation.

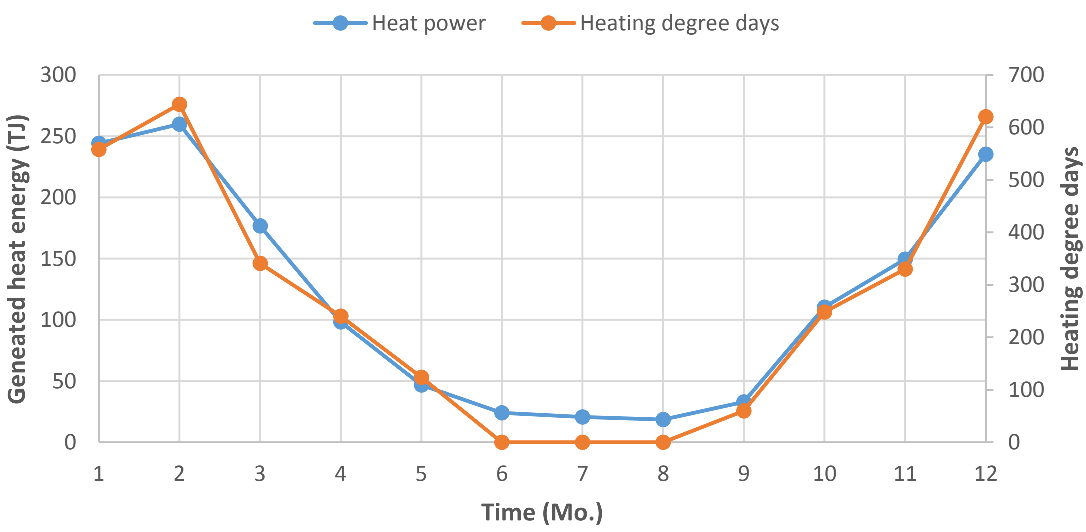


Figure 29. Correlation of generated heat energy and heating degree days

4.2. Heat demand Aalborg DH

Total number of people in Aalborg Municipality is 203475, while the city of Aalborg has a population of 106916, without the Nørresundby which has a population of 21728 [31]. Aalborg DH had 32243 customers in 2012. Compared to the previous year, the number of customers increased by 535, or 1.69% (see Table 15). Average increase of the number of customers, in the period from 2009 to 2012 was at 1.26% or 1184.

Out of the total number of customers business customers represent almost 7%, with a total number of 2239 [32]. There are 437 customers that use heat energy for purposes other than space heating [26]. The number of customers refers to the number of meters and a single customer may, in fact, be a cooperative housing society with a large number of individual consumers. For this reason, better parameter for DH size and growth, other than the number of customers, is the growth of the connected area (see Table 16) [33].

Table 15. Number of customers in Aalborg DH [26]

	2009	2010	2011	2012
Number of the customers in Aalborg DH	31059	31403	31708	32243
Growth (%)	-	1.11%	0.97%	1.69%

Total connected area in 2008 was 10.5 million m^2 while, in 2012, it was 11.3 million m^2 which represent an increase of 7.3%. Average annual increase in the total connected area, in the period from 2008 until 2012, is around 1.8%.

Out of the total connected area 2773251 m^2 are businesses and the remaining 8531749 m^2 are households and small businesses representing over 75% of the total connected area [32].

Growth of the DH heat demand share can be seen in the Table 16.

By the end of 2012, 98.6% of the heat demand within the Aalborg DH supply area has been covered by DH. Already in 2008, the share of DH has been 98.3%, and had rose to 98.6% in 2012, which represents a total increase of 0.3% (see Table 16).

Table 16. Connected area of Aalborg DH [19]

	2008	2009	2010	2011	2012
Connected area (m^2)	10535000	10836000	10982000	11106000	11305000
Growth of connected area (%)	-	2.86%	1.35%	1.13%	1.79%
DH heat demand share (%)	98.3	98.3	98.5	98.6	98.6

Average household annual demand is around 400 m^3. This translate to approximately 18275 kWh, taking into account winter supply temperature of 82ºC and the average cooling of 40ºC (see Figure 41).

Aalborg DH supply area is shown in the Figure 30, where all orange areas belong to Aalborg DH while the purple ones are decentralized DH systems with CHP plants. Green areas show decentralized DH systems with heat only boilers.

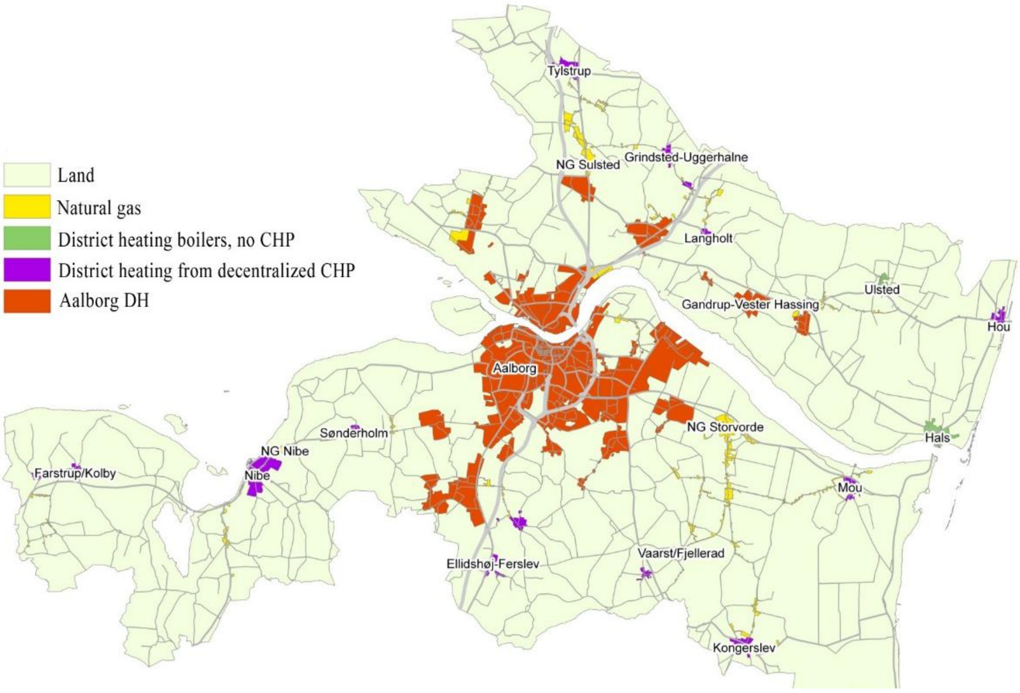


Figure 30. Aalborg DH supply area [34]

Outdoor temperature is shown in the Table 12. The data in Table 12 shows average monthly temperatures for the 2011, 2012 and the nominal year.

Year 2011 was a bit warmer than the 2012, which influences the heat demand so the overall produced heat in 2011 was lower than in 2012 (see Table 12). Both years were warmer than the nominal year.

Table 17. Average monthly temperature in Aalborg [29],[35]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.
T_{2011}(ºC)	0	-1	3	10	11	15	17	17	14	10	7	4	8.92
T_{2012}(ºC)	2	-1	7	6	12	13	16	17	13	8	6	-1	8.17
$T_{nominal}$(ºC)	-0.4	-0.4	1.9	5.6	10.7	14.4	15.7	15.5	12.3	8.9	4.3	1.3	7.48

4.3. Heat demand comparison

Specific heat power and specific electricity capacity per connected area, of both DH systems are shown in the Figure 31.

Specific power per connected area (space heating area) has been calculated (5) as the ratio of total heat power and total connected area of the individual DH systems respectively.

$$P_{hp,ca} = \frac{P_{hp}}{A_{ca}} \tag{5}$$

In Zagreb DH specific heat power per connected area, is 198 W/m^2, while that of Aalborg DH is 94 W/m^2.

Specific electricity capacity per connected area has been calculated (6) as the ratio of total electricity capacity and the total connected area of the individual systems and is equal 74 W/m^2 in Zagreb DH, while in Aalborg DH, it is 39 W/m^2.

$$P_{ec,ca} = \frac{P_{ec}}{A_{ca}} \tag{6}$$

Both of this differences are due to the fact that Zagreb DH has more generating power (both heat power and electricity capacity) installed, while Aalborg DH has more connected area. It also means that overall capacity factor of CHP plants is much higher in Aalborg DH than in Zagreb DH, with 75%, and nearly 50% respectively. Heat generation units (including CHP) capacity factor is also lower in Zagreb DH than in Aalborg DH, with 16%, and 20% respectively.

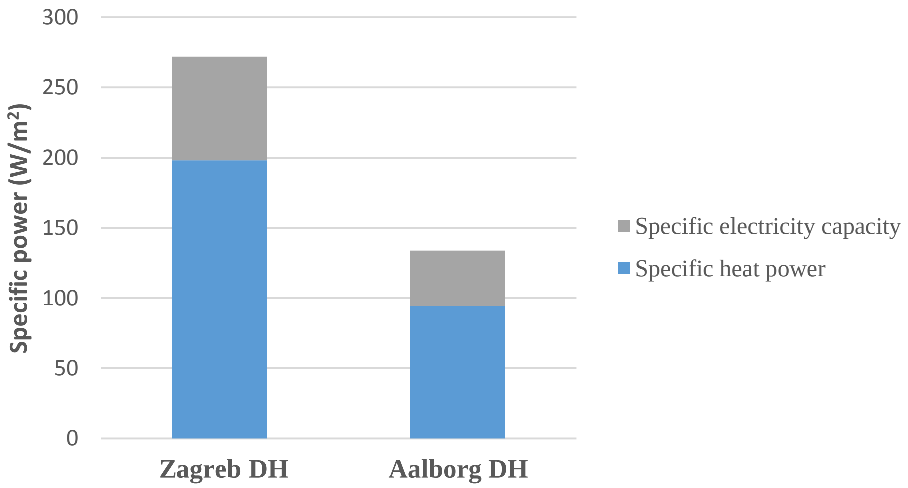


Figure 31. Specific heat power and specific electricity capacity per connected area

Specific heat energy and electricity generation per connected area are shown in the Figure 32. Specific heat energy generation per connected area has been calculated (7) as the ratio of total heat energy generation and connected area of the individual DH systems.

$$E_{he,ca} = \frac{E_{he}}{A_{ca}} \tag{7}$$

In Zagreb DH specific heat energy generation per connected area is 980 MJ/m^2, while that of Aalborg DH is 600 MJ/m^2. It is worth mentioning that this is not the energy for space heating, because it does not include heat energy for domestic hot water preparation, and it does not include heat and water losses. Businesses and industry are included.

Specific electricity generation per connected area has been calculated (8) as the ratio of total electricity generation and connected area in individual systems respectively.

$$E_{el,ca} = \frac{E_{el}}{A_{ca}} \tag{8}$$

In Zagreb DH specific electricity generation per connected area, is 1156 MJ/m^2 while, in Aalborg DH, it is 932 MJ/m^2.

Both the specific heat energy and specific electricity generation per connected area is higher in Zagreb DH. This is probably due to the fact that more industry and business consumers are connected in Zagreb DH than in Aalborg DH.

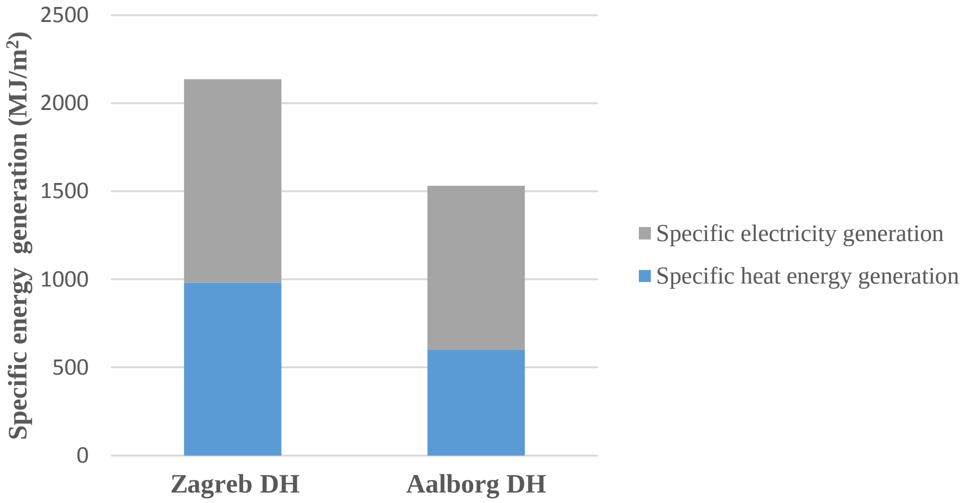


Figure 32. Specific heat energy and electricity generation per connected area

Figure 33 shows variations in average monthly temperatures in Zagreb and Aalborg, for the 2012, and the nominal year.

Temperatures in Zagreb are in average 5°C warmer than in Aalborg from March until September. In winter months, the temperature averages are much closer together, and in December and January, temperature averages are practically identical, at 2°C in December and 0°C in January.

Average national thresholds for the start of the heating season, vary between 10°C and 15 °C. So, the heating season in Northern Europe usually lasts from August/September to May/June, and in Southern Europe from November/December to February/March.

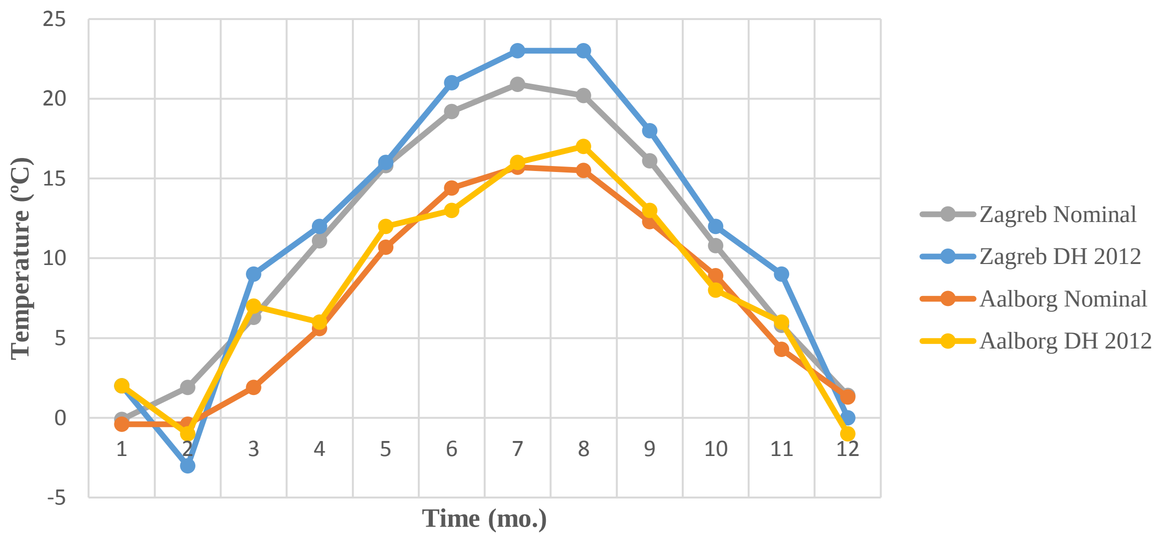


Figure 33. Monthly temperatures during the year

5. DISTRIBUTION

5.1. Distribution Zagreb DH

District heating systems have a long history and tradition in Croatia and especially in the capital Zagreb. First hot water district heating system has been constructed and commissioned in 1954, connecting EL-TO Zagreb and the Rade Končar factory [36]. First steam district heating system was constructed, and commissioned in 1958, which supplied heat energy to Mladost public pools [36]. The biggest expansion of district heating systems happened in the period between 1962 and 1970 after the new cogeneration units were constructed in both thermal power plants (TE-TO Zagreb and EL-TO Zagreb) [36].

Network structure of the district heating area "West" is shown in the Figure 34 (see Figure 28 for area distribution within Zagreb). District heating area "West" is directly connected to the EL-TO Zagreb. It can be seen that the coverage of the district heating system is not as widespread as it could have been considering the urban density.

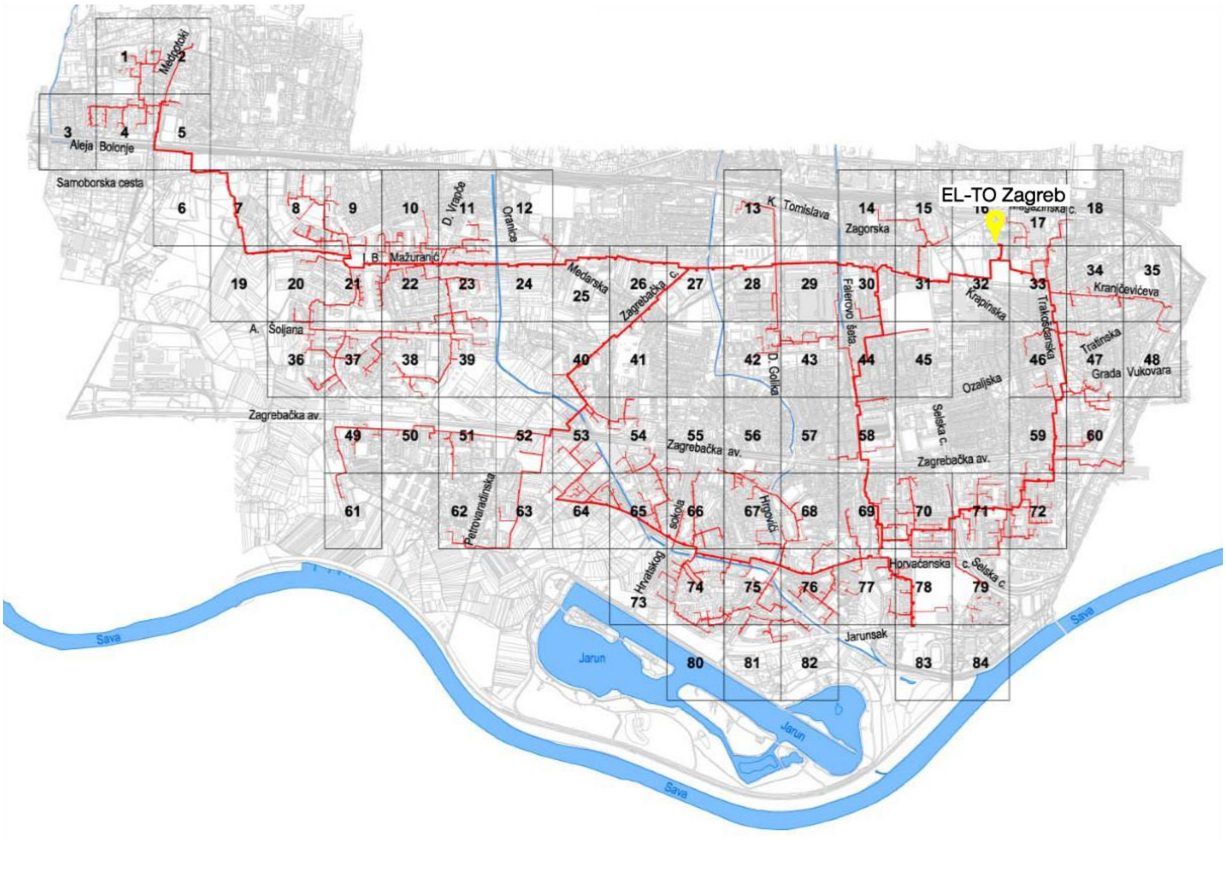


Figure 34. Network structure of district heating area „West"[28]

Pipeline length of hot water district heating, and steam district heating networks are shown in the Table 18. Total length of hot water district heating network is around 216 km, with 2509 substations. Total length of steam district heating network is 45 km, with 91 substations. Total volume of the distribution network is 20000 m^3, divided into TE-TO Zagreb part of the network that has a volume of 12000 m^3 and EL-TO Zagreb part of the network with the volume of 8000 m^3 (see Table 19).

Table 18. Pipeline length and number of substations in DH Zagreb [14]

	Hot water district heating		**Steam district heating**	
	Pipeline length (km)	Number of substations	Pipeline length (km)	Number of substations
TE-TO	128	1599	23	36
EL-TO	88	910	21	89
Total	216	2509	44	125

Hot water district heating system in Zagreb has a two pipe system, which is composed of mineral wool insulated steel supply and return pipes that are placed in concrete ducts. Newly installed pipes are pre-insulated steel pipes. Maximum diameter in the hot water district heating network is 850 mm (see Table 19).

Outside temperature correlation, to supply and return temperatures, and heat power of TE-TO Zagreb is shown in the Figure 35. In the winter period, during the coldest days, hot water supply temperature is 130 ºC, and return temperature is around 64 ºC (see Figure 35). The hot water is pressurized at 10.5 bar in the winter period [14].

The connection of the east network (TE-TO Zagreb part) with the west network (EL-TO Zagreb part) allows for the use of only one thermal power plant in the summer period when the heat energy from the grid is used only for domestic hot water preparation. In such a way newly constructed CHP units have been optimally utilized. In the summer period operating supply temperature is around 65-75 ºC, which is considerably lower than in the winter period, when the supply temperature can reach over 130 ºC [14][36],[37].

Lower supply temperatures during the summer also contribute to lower heat losses from the network grid. Temperature difference, between supply and return temperature, vary significantly form 66 ºC, in the winter time, to 25 ºC in the summer time. Price of heat energy is the same in both winter and summer periods.

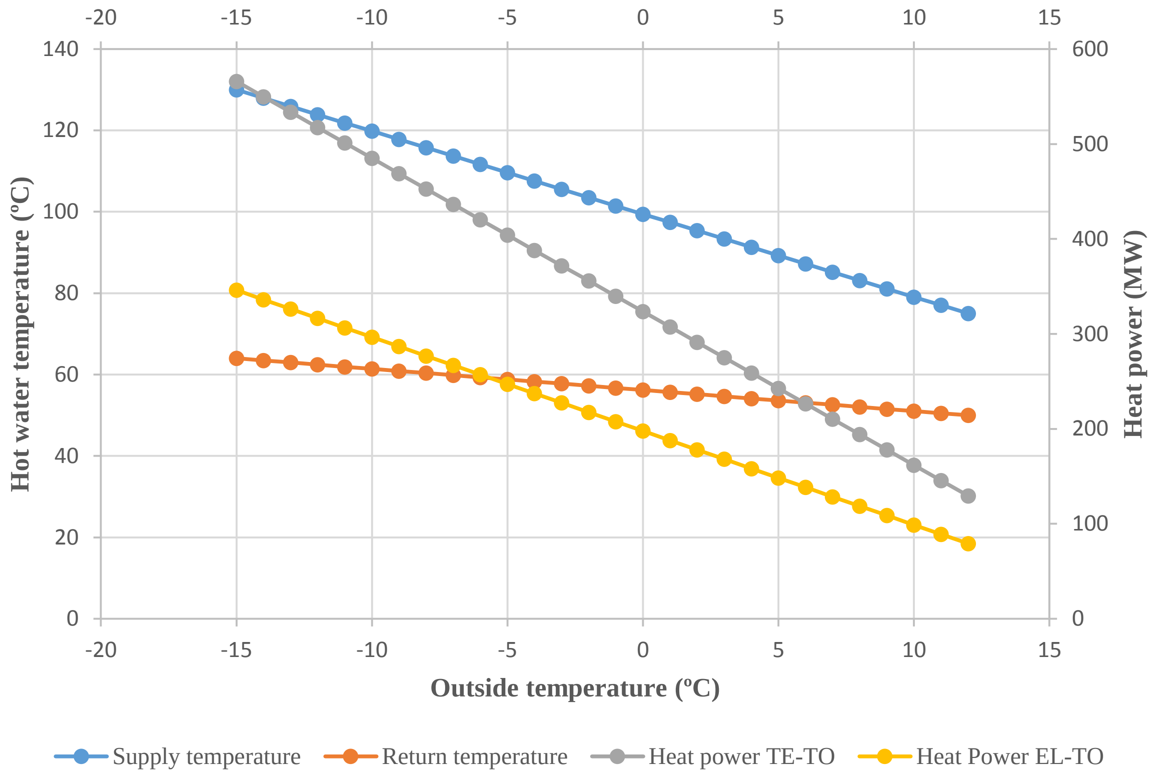


Figure 35. Outside temperature relation to supply and return temp. and heat power [14]

Steam district heating system is a one pipe system, meaning that there is no return pipe. Supply pipes are pre-insulated steel pipes placed in ducts, with a maximum diameter of 600 mm. Steam pressure in the TE-TO part of the distribution network is 9 bar, with a supply temperature of 235 °C, while EL-TO part of the distribution network is operating at 17 bar, and 250 °C.

Table 19. Hot water district heating in Zagreb [14],[36],[38]

Hot water DH system	TE-TO	EL-TO
Pipeline type	Two pipe system	
Pipe laying method	Inside concrete ducts	
Pipes	Mineral wool insulated steel pipes	
Max diameter (mm)	850	
Volume of the distribution network (m^3)	12000	8000
Temperature (°C)	130/70	130/70
Pressure (bar)	7-10	7-10
Max temperature (°C)	150	
Max pressure (bar)	16	

Table 20. Steam district heating in Zagreb [14],[36],[38]

Steam DH system	TE-TO	EL-TO
Pipeline type	One pipe system	
Pipe laying method	Inside concrete ducts	
Pipe type	Mineral wool insulated steel pipes	
Max diameter (mm)	600	
Steam pressure (bar)	9	17
Steam temperature (°C)	235	250

Most parts of the district heating network are quite old, with an average age of around 27.5 years. Some parts of the network have been used for more than 35 years without major refurbishments [12],[36]. Considering this, and taking into account that life expectancy of pipelines laid in the ducts is around 35 to 40 years, it is clear that the efficiency of such system is not as high as in many other countries in Europe [36]. Older pipes are mostly ones in the diameter range up to 400 mm [36].

Average losses, in the hot water distribution network, are around 12% due to heat losses and leakages in the pipeline system [14].

Average annual loss of water from the system due to leakage, are around 52 m^3/h in the winter period, and 30 m^3/h in the summer period in the part of the network connected to TE-TO [14]. In the part of the network connected to EL-TO, loss of water is around 37 m^3/h in the winter period, and around 12 m^3/h in the summer period [14]. Average water losses have been approximated as the sum of arithmetic means of the water losses in the summer and winter periods for TE-TO Zagreb and EL-TO Zagreb respectively. Average water losses amounted to 66.25 m^3/h or 580350 m^3 annually.

Efficiency of the steam DH system is relatively low due to age of the network system, and decreasing demand for steam, which contributes to unfavorable operating conditions. Losses of the network part connected to EL-TO Zagreb are around 18% while the part connected to TE-TO Zagreb has losses around 16% [14].

Revitalization of the oldest pipe sections out of which there are some older than 45 years, has begun in 2006 and lasted till 2012. In that period, 20.5 km of the pipe sections were replaced [12]. The refurbishment has been paid in part by the World Bank and HEP District Heating.

5.2. Distribution Aalborg DH

Since its inception in 1954, DH in Aalborg had a constant annual growth in the number of connections, and it is expected that this growth will continue. It should continue mostly as a geographical expansion of the supply area, but also with connections of new and existing buildings within the current supply area [26].

Network structure of Aalborg DH is shown in the Figure 36. Only the main pipeline is shown without the branching pipes. Figure 36 also shows the location of heating companies and heat only boilers as the heat generation units, and the location of pumping stations within the supply area.

As can be seen, the DH coverage is very high at around 98.6%, in the supply area designated by dashed lines in the Figure 36.

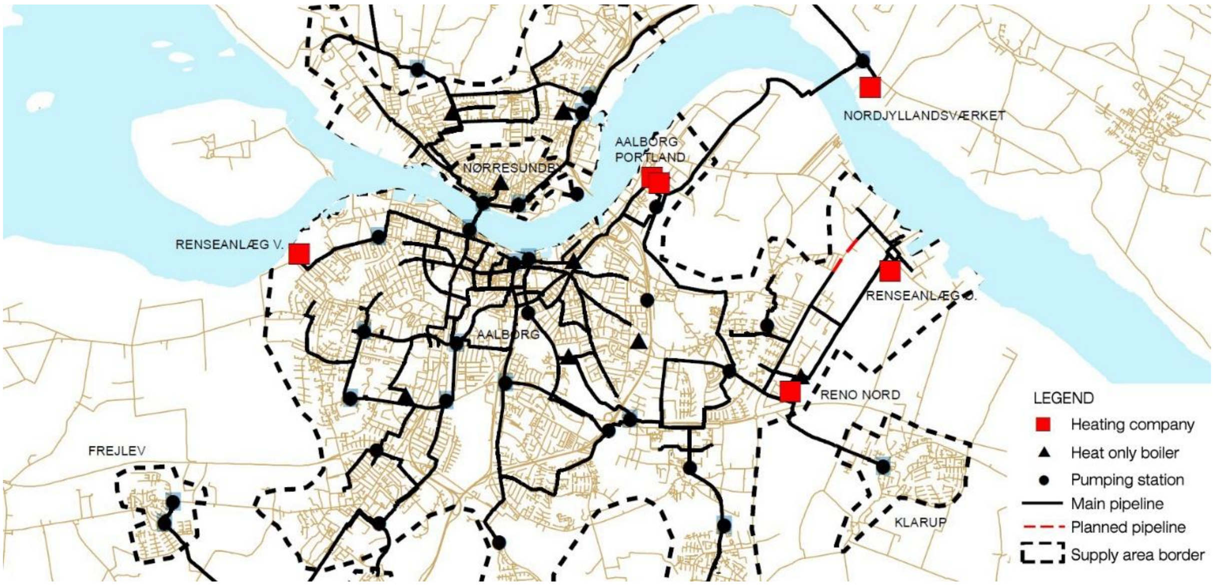


Figure 36. Network structure of Aalborg DH [26]

Total length of the hot water network, in 2012, was 1386 km (see Table 21). During the period from 2009-2012, total length of the network increased by 52 km, or 3.62%. This represents an annual increase of about 1.24%.

Hot water DH system, in Aalborg, is a two pipe system which is mostly composed of pre-insulated solid foam steel supply and return pipes. Approximately 65% of the main pipes have leakage monitoring alarm system.

Table 21. Total length of hot water network in Aalborg DH [26]

	2009	2010	2011	2012
Total length of the network (km)	1349	1360	1373	1386
Expansion of the network (km)	11	13	14	14

Supply temperatures vary during the winter time from 82-90 ºC, and after cooling the temperature returned to the plants is at around 40 ºC [17]. The pressure within the pipes can occasionally reach 6.5 bar [17].

DH systems supply temperature varies during the year in relation to the heat demand, and during the summer period is around 75 ºC [17]. Average yearly temperature is, therefore, around 80 ºC [26]. Sometimes the temperature within the supply pipe is only about 60 ºC [17]. With that reduction of supply temperature heat losses are lowered.

In every DH system, there is a water loss, which has to be replaced with new feedwater. Average water loss in recent years was around 110000 m^3 [19]. Feedwater consumption in Aalborg DH was around 102000 m^3 in 2012. Variations of feed water consumption in the period from the 2008-2012 can be seen in the Table 22.

It can be seen, that the feedwater consumption was lower, in 2012, than in all other years in the period from 2008-2012, except in the year 2011. But, due to the uncertainty why this is so a more relevant parameter, the specific feedwater consumption per km network length is intoduced (see Table 22).

Specific feedwater consumption was reduced from 92 m^3/km, in 2008, to 73 m^3/km in 2012 which represents a reduction of almost 21%. A clear downward trend is visible that is due to systematic refurbishments of the grid. Most of the new feedwater comes from the Nordjylland Power Station, and a small portion from the heating station Vikingevej [19].

Table 22. Feedwater and specific feedwater consumption of Aalborg DH [19]

	2008	2009	2010	2011	2012
Feedwater (m^3)	121000	110000	111000	117000	102000
Specific feedwater consumption (m^3/km)	92	81	78	78	73

Heat losses form the Aalborg DH system have been decreased, from more than 30% in 1985 to around 19% in 2002 (see Figure 37). This reduction in heat losses was accomplished with systematic replacement of the most poorly isolated pipes with new pre-insulated pipes and the introduction of low temperature heating in 1993. Figure 37 also shows water losses and total heat loss, corrected by heating degree days difference from the nominal year, which is defined as the average of the last 10 years.

Heat losses increased slightly, in 2012, compared to 2011, which is due to the fact that 13 km of new pipeline has been installed, and only 9.3 km of the old pipeline has been refurbished [17].

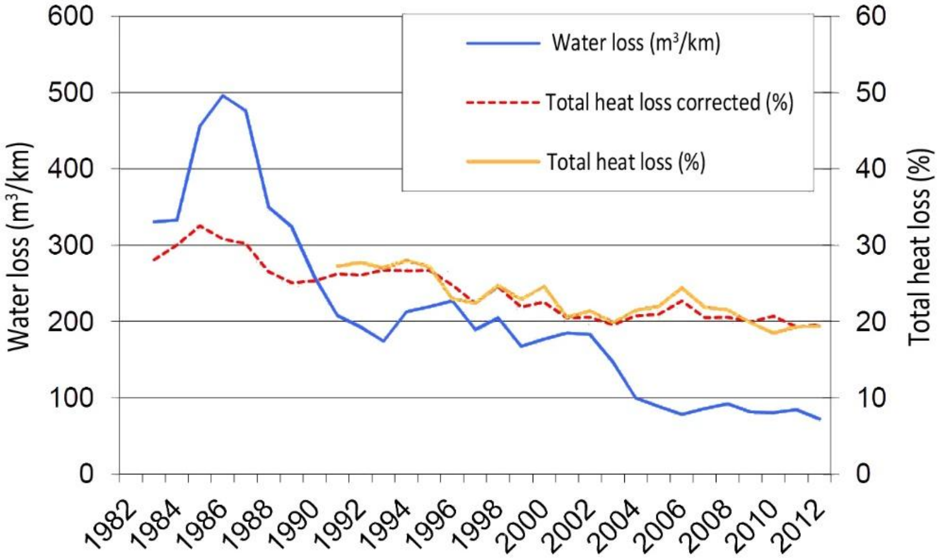


Figure 37. Heat losses in the period from 1982 to 2012 in Aalborg DH [19]

Since 1983, there has been a systematic replacement of the oldest and most poorly insulated pipe sections with new pre-insulated solid foam pipes [26].

From 1983 to 2012, there has been replaced around 700 km of main and laterals, which has had a positive impact on net loss and water loss [26]. Table 23 shows the number of kilometers of pipe sections that have been refurbished in recent years.

There is only 12 km of pipes left that are older than 32 years [26]. Technical lifetime of pipes mounted since 1981 is estimated to be around 50 years, but due to rising energy prices, they could be replaced with new pipes with smaller heat losses [26].

Pipes with extra insulation have been installed since 1999, and after 2010, twin pipes have been installed, which further reduce heat losses compared to older designs, by up to 20% [6],[19]. Average age of the main pipes is around 17 years [17]. Pipe breakage is very rare, which translates to a high level of security for an uninterrupted heat supply of customers.

Table 23. Refurbishment of Aalborg DH [19]

	2008	2009	2010	2011	2012
Refurbishment of Aalborg DH (km)	14.9	10.4	11.4	13.3	9.4
Change (%)	-	-30.20%	9.62%	16.67%	-29.32%

Planned annual replacements of the oldest parts of the network, is mostly conducted in the daytime on weekdays and during the summer. The planned cuts are usually announced a few days in advance, so customers can manage to take precautions.

Future refurbishments will diminish, considering that almost all old sections have been replaced, and it is predicted that future replacements and refurbishments will be around 5 km annually [26].

Hot water is pumped into the district heating network loop by a number of pumping stations which respond to the changes in the operating conditions. There are about 65 pumping stations [17]. Larger pumping stations are located within the larger heat generating units, such as those of Nordjylland Power Station, Reno-Nord and Aalborg Portland [26].

Electricity consumption for pumping is heavily dependent on the number of the heating degree days in the year, and it is continually optimized through monitoring and controlling pumps. In 2012, electricity consumed by the pumping stations was 18473 MWh.

5.3. Distribution comparison

Total length of the DH systems is shown in the Figure 38. Network length of the Aalborg DH is 1386 km, which is almost 6.5 times more than the 216 km of the Zagreb DH.

This difference will affect nearly all of the specific indicators described below, many of which are ratios of network length. Such a vast difference in the length of the systems, that are relatively similar in installed thermal power, and the overall annual heat energy generation, is due to the fact that Zagreb DH supply area is only within the city itself, while the Aalborg DH supply area covers several nearby towns, and the city of Aalborg.

One more thing to point out is that both thermal power plants that generate heat energy in Zagreb DH are within the city, and some of the generating units of Aalborg DH are located outside of the city like the Nordjylland Power Station, which is about 5 km from the city outskirts and the hot water pipes pass beneath the Limfjord. There is also a difference in urban density in the supply area.

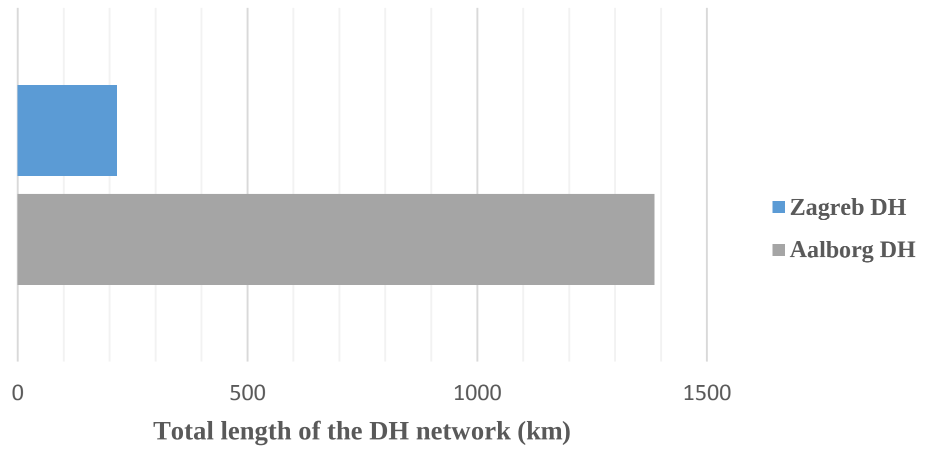


Figure 38. Total length of the Zagreb DH and Aalborg DH distribution networks

Specific heat power and electricity capacity per kilometer length of both DH systems are shown in the Figure 39.

Specific heat power per km has been calculated (9), for both DH systems as a ratio of heat power and total length of the network of the individual systems.

$$P_{hp,l} = \frac{P_{hp}}{l} \tag{9}$$

Specific heat power of the Zagreb DH is around 5.46 MW/km, while that of Aalborg DH is around 0.77 MW/km.

Specific electricity capacity has been calculated (10) as the ratio of electricity capacity and the total length of the network of the individual systems.

$$P_{ec,l} = \frac{P_{ec}}{l} \tag{10}$$

Specific electricity capacity of Zagreb DH is 2.03 MW/km, and that of Aalborg is 0.31 MW/km.

These numbers differ so much because of the very different total length of the each DH system with Aalborg DH having total length almost 6.5 times of that in Zagreb DH. It is important to note that the heat power and electricity capacity of the individual system is very similar (see Figure 22 and Figure 23).

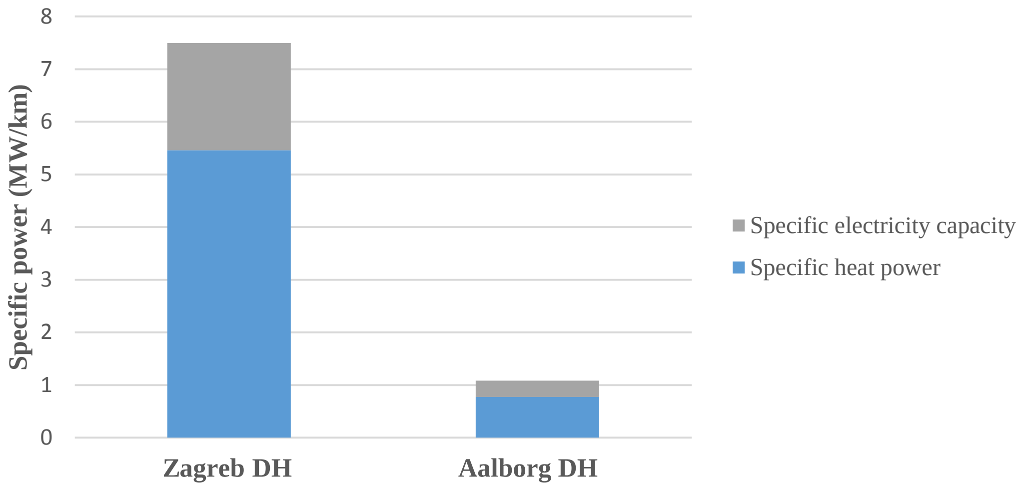


Figure 39. Specific heat power and electricity capacity per km

Specific heat energy and electricity generation per kilometer length are shown in the Figure 40.

Specific heat energy generated per km has been calculated (11) as the ratio of the total heat energy generated divided by the total length of the individual system respectively.

$$E_{he,l} = \frac{E_{he}}{l} \tag{11}$$

Specific heat energy generation of the Zagreb DH is around 27 TJ/km while that of Aalborg DH is around 4.9 TJ/km.

Specific electricity generated per km has been calculated (12) as the ratio of the total heat energy generated and total length of the individual system respectively.

$$E_{el,l} = \frac{E_{el}}{l} \tag{12}$$

Specific electricity generation of Zagreb DH is 31.9 TJ/km, and that of Aalborg is 7.6 TJ/km.

Same thing applies to the specific installed power; the difference is due to the total length of the individual systems in Zagreb and Aalborg, and also due to high specific connected area see Figure 42. Similarities in the heat energy generation and electricity of both systems can be seen in the Figure 25.

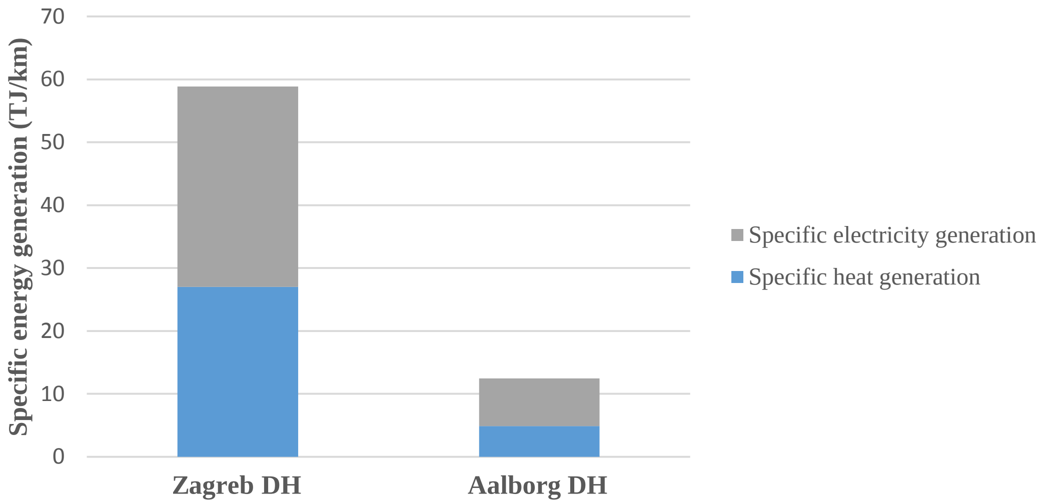


Figure 40. Specific heat energy and electricity generation per km

Hot water energy content is shown in the Figure 41.

Hot water energy content has been calculated (13) as a product of the water density, specific thermal capacity and temperature difference.

$$E_{hwec} = \rho \cdot c_w \cdot \Delta t \qquad (13)$$

Considering the temperature dependence of water density and specific heat capacity, they have been calculated as the arithmetic mean between the values for supply and return temperatures of the individual systems respectively.

Supply temperatures have been taken, for the winter period, during the coldest days which are 130 ºC in Zagreb DH and 90 ºC in Aalborg DH.

Data for water density and specific thermal capacity have been taken from [39].

Hot water energy content of hot water in Zagreb DH is 266.75 MJ/m^3, and that of Aalborg DH is 163.78 MJ/m^3. This difference is mainly due to the difference in supply and return temperatures of the DH systems. Hot water density and heat capacity temperature dependence plays a minor role.

Temperature difference between the supply and return temperatures, in the winter period, in Zagreb DH is 66 ºC, while that of Aalborg DH is 40 ºC.

It is desirable that the hot water energy content is as high as possible, so to minimize the amount of water that has to circulate through the system, which means that less electricity will be consumed by the circulation pumps, and possibly smaller pump stations could be installed.

Rising the hot water content by rising the supply temperature leads to unwanted heat losses. So, high energy content should be achieved through the decreasing of the return temperature.

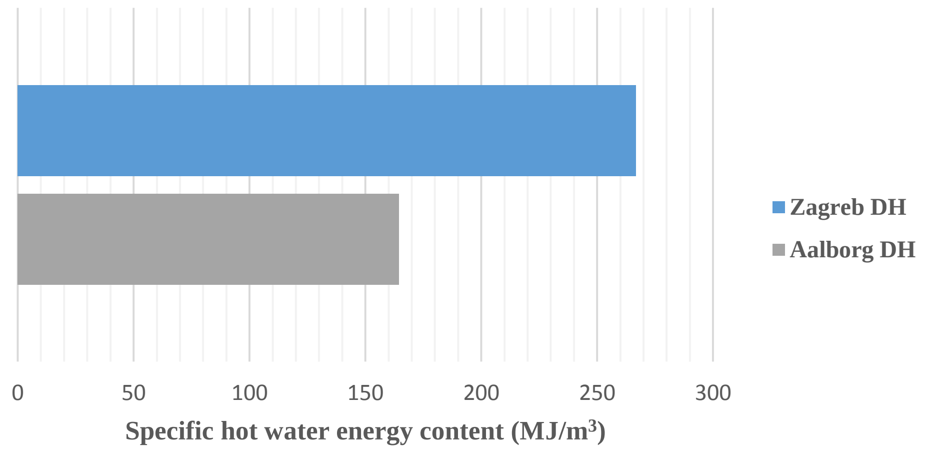


Figure 41. Hot water energy content

Specific connected area per kilometer of DH network length is shown in the Figure 42.

Specific connected area per kilometer of DH network length has been calculated (14) as a ratio of total connected area and total length of the individual system respectively.

$$A_{ca,l} = \frac{A_{ca}}{l} \tag{14}$$

Zagreb DH has much denser heat demand compared to Aalborg DH, with around 27500 m^2/km, while Aalborg DH has around 8100 m^2/km.

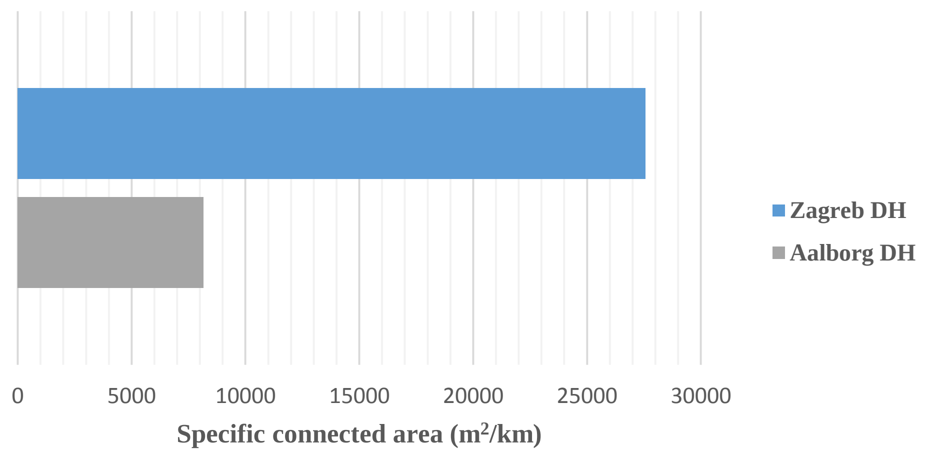


Figure 42. Specific connected area per km of DH network length

Specific water loss of both DH systems is shown in the Figure 43.

Specific water loss has been calculated (15) as the ratio of annual water loss and the total length of the hot water network of the individual systems respectively.

$$L_{w,l} = \frac{L_w}{l_{hw}} \tag{15}$$

Specific water loss in Zagreb DH is 2687 m^3/km, while that of Aalborg DH is 74 m^3/km which represent a significant difference. This difference is due to the fact that, in the Zagreb DH, many of the pipes are quite old and leaky, with an average age of 27.5 years, and the ones in Aalborg DH, are relatively new with an average age of only 17 years.

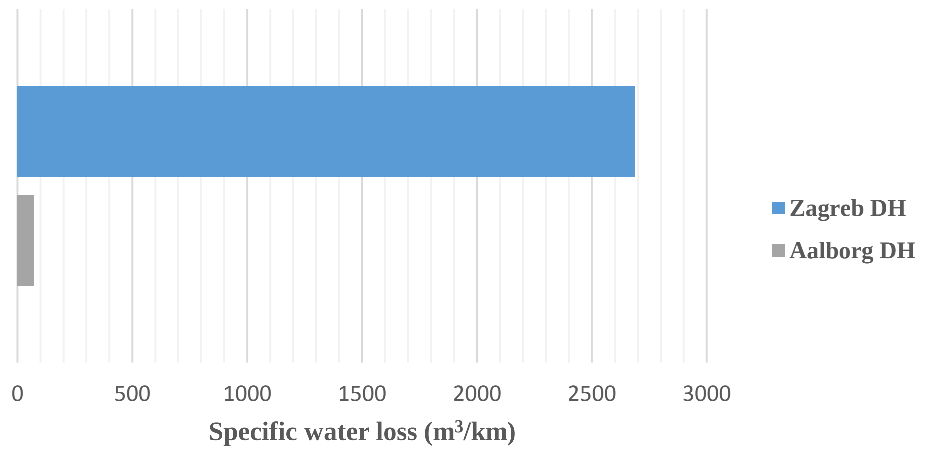


Figure 43. Specific water loss in Zagreb DH and Aalborg DH

Total specific heat losses of both DH systems are shown in the Figure 44.

Specific heat losses, due to water losses have been calculated as a product of hot water energy content calculated in (16) and the specific water loss of the individual DH systems respectively.

$$E_{w,l} = L_{w,l} \cdot E_{hwec} \tag{16}$$

It should be noted that specific heat losses, due to water losses calculated in this way are extreme, because of the fact that the supply temperature used in the calculation is a maximum one.

Specific heat losses, due to heat transfer, have been calculated as the difference between total specific heat losses, and the specific heat losses due to water loss of the individual DH systems respectively.

Total specific heat loss in Zagreb DH is 2944 GJ/km, while that of Aalborg DH is 928 GJ/km.

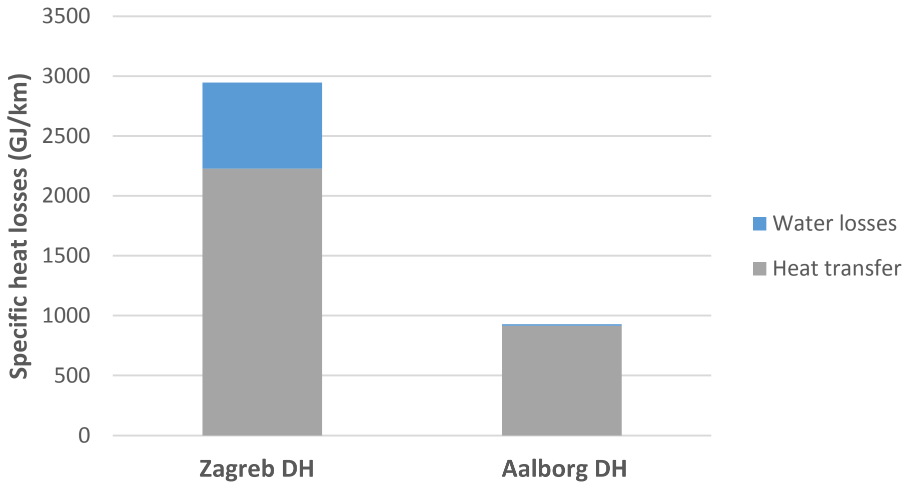


Figure 44. Total specific heat losses in Zagreb DH and Aalborg DH

This difference is, once again, caused by the average age of the pipe sections in Zagreb DH compared to the Aalborg DH. Old pipe sections in general have much lower insulation protection and have higher water losses.

It can be concluded that there are few fundamental differences between the two DH systems, one of which is the difference in the supply area.

Zagreb DH has a concentrated supply area within the city of Zagreb, while Aalborg DH, has more spread out supply system, involving several nearby towns. From this arises the vast difference between the total lengths of the network of DH systems, which has a significant impact on the other indicators.

Second fundamental difference is temperature levels of the supply and return temperatures. In Zagreb DH, during the coldest days, the supply temperature is around 130 ºC while that of Aalborg it is 90 ºC. High supply temperature is directly related to the high heat losses of the Zagreb DH system.

Third fundamental difference is the age of the pipe sections within the network, which are related to water losses and heat losses.

6. ECONOMICS

6.1. Economics Zagreb DH

Price formation in Zagreb DH depends on the tariff groups, models and elements (see Table 24). Tariff groups designate in which group a customer belongs, in households or industry, and business consumers. Tariff models designate what type of heat energy meter is installed, is it a joint meter shared by multiple customers or an individual one. Tariff elements include prices for energy and power. Energy is priced, in hot water DH system, per kWh. For tariff group household, it is 0.02793 EUR/kWh, while in industry and business consumers, it is 0.05587 EUR/kWh. Power is priced, in hot water DH system, per kW. For tariff group of households, the annual price is 22.498 EUR/kW, and for industry and business customers it is 30.543 EUR/kW.

Table 24. Heat prices in Zagreb DH[2] [12]

	Tariff groups	**Tariff models**	**Tariff elements**	
			Energy (EUR/kWh)	Power (EUR/kW a)
Water	Households	TM7, TM8	0.02793	22.498
	Industry and business consumers	TM1, TM3	0.05587	30.543
Steam			Mass (EUR/t)	Power (EUR/(t/h a))
	Industry and business consumers	TM2, TM4	47.37	1343.81

Energy is priced, for steam DH system, per tonne of steam. Its price for industry and business customers is 47.37 EUR/t. Price of power in steam DH is 1343.81 EUR/(t/h a).

Prices shown in the Table 24 were formed in December 2012 [15].

Distribution model, for the cost of heat power and energy, depends on the technology installed in a particular building, and can generally be divided by age of the buildings. All new buildings have installed calorimeters into individual apartments, by which individual energy consumption can be determined. Difference between the overall heat energy consumption, measured on the central calorimeter of the building, and the sum of individual apartment measurements, is the heat energy necessary for domestic hot water preparation. That difference is distributed among

[2] Prices of the tariff elements have been calculated from HRK to EUR with the following exchange rate 7.6074 HRK/EUR [40]

the apartments on the basis of the floor area of the individual apartment. Consumption of heat energy for the individual apartment, of the old buildings that do not have installed calorimeters into individual apartments, is calculated on the basis of floor surface area of the individual apartment, and the total heat energy consumed. Consumption of heat energy, for the individual apartment of the old buildings that have installed electric calorimeters on radiators in individual apartments, is calculated on the basis of measured individual heat energy consumption and total consumption of the building on the basis of apartment floor area.

As a result of the lack of data for Zagreb DH profit and loss accounts are presented for the whole of HEP District Heating. It has been already mentioned, that Zagreb DH represents the largest share of the HEP District Heating operations (see Figure 11, Figure 12, and Figure 13) so some valuable conclusions could still be made about the overall state of economy of Zagreb DH.

Figure 45 shows income and expense accounts of HEP District Heating. Although the total income has been rising, in the period from 2006 to 2012, from nearly 67 million EUR to over 85 million EUR, total expenses have been rising more significantly in the same period. During the entire period from 2006-2012, the company has generated losses from little over 8 million EUR in 2006, to 61 million EUR in 2012, which represents an increase of 742%. This rapid increase during that period was directly connected to the increase of expenses in relation to electricity generation companies, which is well correlated with the increase of the total expenses (see Figure 45).

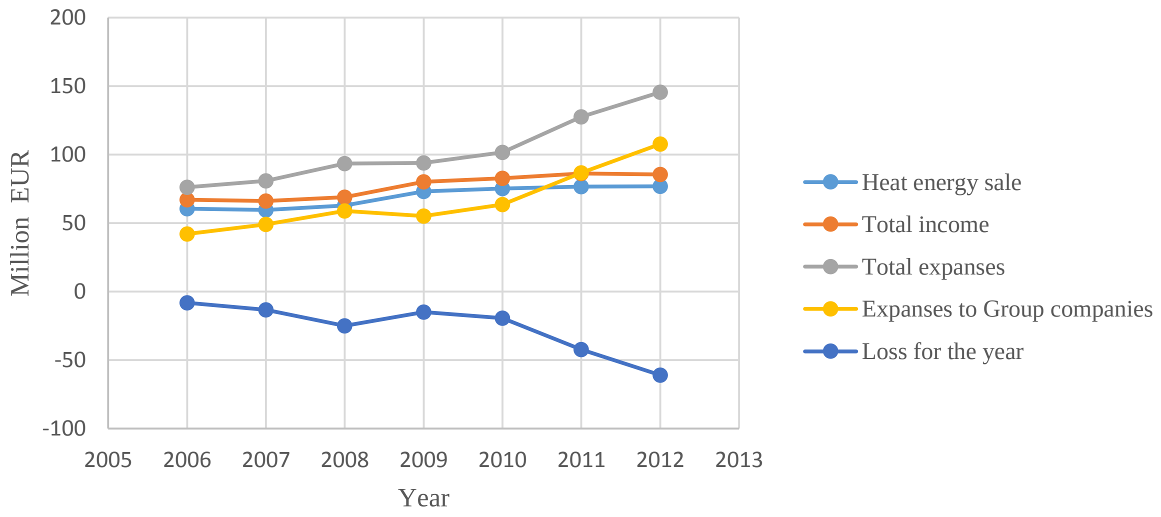


Figure 45. Profit and loss accounts of HEP District Heating

6.2. Economics Aalborg DH

Price formation in Aalborg DH is the same for both households, small businesses and business customers (see Table 25). It is composed of a yearly subscription and an energy and power pricing. Subscription fee is 167.57 EUR per year. Energy is priced per m^3, which costs 2.1369 EUR. Power is priced per m^2 of the connected area which costs 2.1369 EUR.

Table 25. Heat prices in Aalborg DH[3] [17]

	Subscription (EUR)	Energy (EUR/m^3)	Power (EUR/m^2)
Households and small businesses	167.5760	2.1369	2.1369
Business consumers	167.5760	2.1366	2.1366

Pricing the energy per m^3 helps encourage the customers to try to reduce the return temperature as much as possible. It is preferable that the return temperature would be only 30-35 ºC [17].

Table 26 shows the number of employees in the Aalborg District Heating. The number of employees increased form 83 in 2009 to 86 in 2012.

Table 26. Number of employees in Aalborg District Heating [19]

Year	**2008**	**2009**	**2010**	**2011**	**2012**
Number of employees in Aalborg District Heating	83	87	87	87	86

As a result of the lack of data for only Aalborg DH profit and loss accounts, data for the whole of Aalborg Forsyning, Varme is presented. It is important to mention that Aalborg DH represents almost the entire share of the Aalborg District Heating operations (see Figure 18 and Figure 19).

Income and expense accounts of Aalborg District Heating is presented in the Table 27. Biggest share of the income is heat sales with 85.42 million EUR, with the total income at 92.64 million EUR. The share of the heat sales to the total income is 92.2%. Costs of the purchases of heat energy from other companies is around 62.35 million EUR, representing around 66% of the total expenses. Another important part of the total expenses are expenses tied to the production of energy within Aalborg District Heating own plants. Expense of production of energy in the Aalborg DH supply area is 8.63 million EUR while the production of heat energy in

[3] All prices have been calculated from DKK to EUR with the following exchange rate 7.4593 DKK/EUR [41]

decentralized area is at 3.14 million EUR. Cost of administration is 5.13 million EUR while installation and other costs are 3.69 and 0.4 million EUR.

Aalborg District Heating had a loss of 1.13 million EUR in 2012.

Table 27. Income and expense accounts of Aalborg District Heating [42]

	Income (Million EUR)	Expense (Million EUR)	Total (Million EUR)
Heat sales	85.42	0.00	85.42
Purchase of heat	0.00	62.35	-62.35
Production - central	0.00	8.63	-8.63
Production - decentralized	2.69	3.14	-0.44
Distribution	4.13	10.42	-6.29
Administration	0.21	5.13	-4.92
Installations	0.00	3.69	-3.69
Other	0.17	0.40	-0.23
Total	92.64	93.76	-1.13

6.3. Economics comparison

Considering the fact, that the price formation is different in Zagreb DH, and Aalborg DH, it cannot be compare directly.

There is no subscription fee in Zagreb DH (except the one for contracted heat power), while there is a subscription fee in Aalborg DH. Energy in Zagreb DH is priced per kWh, while in Aalborg DH it is priced per m^3. Power subscription in Zagreb DH is priced per kW, while in Aalborg DH is in m^2 of the connected area.

As a result of those differences, comparison is made between the total annual cost of heat service, for a detached house, and a kindergarten, for both DH systems. Assumed parameters of the detached house, and the kindergarten relevant for the calculation are presented in the Table 28.

Table 28. Assumed parameters used for comparison

	Detached house	Kindergarten
Area (m^2)	162	2555
Power (kW)	21	225
Annual heat consumption (kWh/a)	27512	449000
Annual heat consumption (m^3/a)	602	9828

Annual cost of heat service, in Zagreb DH and Aalborg DH, for a detached house are shown in the Figure 46. Annual cost of heat service for a detached house in Zagreb DH has been calculated as the sum of the energy and power cost in a single year using the data from the Table 24 and Table 28.

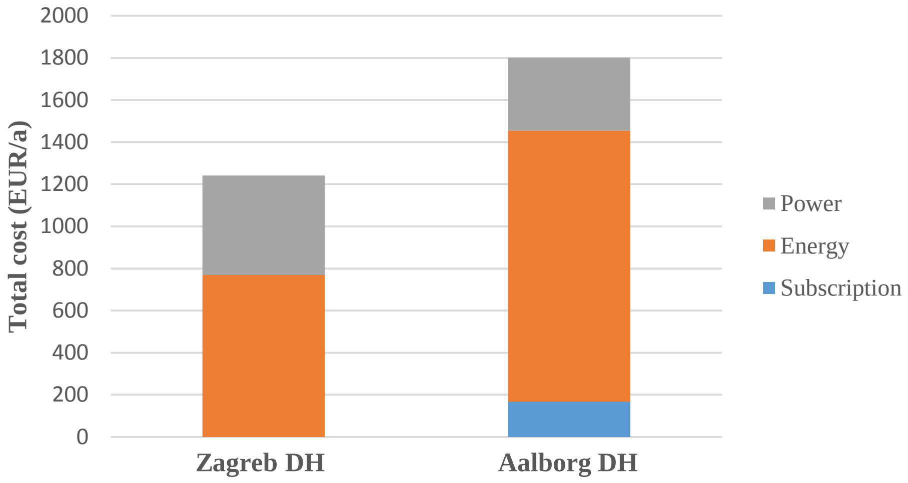


Figure 46. Annual cost of heat service in Zagreb DH and Aalborg DH for a detached house

Annual cost of heat service for a detached house in Aalborg DH has been calculated as the sum of the subscription fee, energy and power costs in a single year from the data in the Table 25 and Table 28.

Annual heat service cost in Zagreb DH is around 1240 EUR while, in Aalborg DH, it is around 1800 EUR, which is about 45% more. This difference is due to the fact that there is no subscription cost in Zagreb DH, and the energy costs in Aalborg DH are higher. Total power costs are lower in Aalborg DH than in Zagreb DH.

Annual cost of heat service, in Zagreb DH and Aalborg DH, for a kindergarten are shown in the Figure 47.

Annual cost of heat service for a kindergarten, in Zagreb DH, has been calculated as the sum of the energy and power costs in a single year using the data from the Table 24 and Table 28. Annual cost of heat service for a kindergarten, in Aalborg DH, has been calculated as the sum of the subscription fee, energy and power costs in a single year using the data from the Table 25 and Table 28.

Annual heat service cost in Zagreb DH is around 31956 EUR while, in Aalborg DH, it is around 26624 EUR, which is 20% less. This difference is due to the fact that energy costs more in

Zagreb DH, in the case of the industry and business consumer tariff group, than in Aalborg DH. Cost of power is also lower in Aalborg DH, and subscription fee is negligible compared to the overall cost.

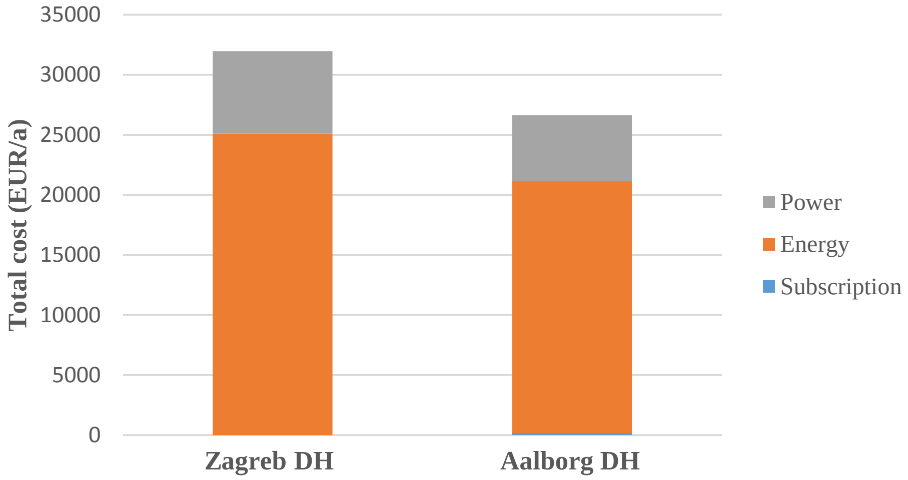


Figure 47. Annual cost of heat service in Zagreb DH and Aalborg DH for a kindergarten

Customers in Aalborg DH are charged according to the number of cubic meters of hot water used, and not according on the amount of energy used, so there is an incentive for the individual customer to extract as much heat from the district heating water as possible before it is sent back to the heat producers. In this way, individual customers are working on lowering the return temperatures.

Total income of HEP District Heating is 85 million EUR, while that of Aalborg District Heating is 92 million EUR. This difference is due to the fact that, although, HEP District Heating sold 34% more heat energy, during the 2012, heat energy prices for the category of households are about 45% more expensive in Denmark.

Other income, which is composed of mostly electricity sales and special heat sales, is 9.9% in Zagreb District heating, compared to 7.8% in Aalborg District Heating.

Total expenses in Zagreb District Heating are 145 million EUR, while, in Aalborg District Heating, it is 93.8 million EUR which is 35% less.

Figure 48 shows heat sales, other income and total expenses of HEP District Heating and Aalborg District Heating.

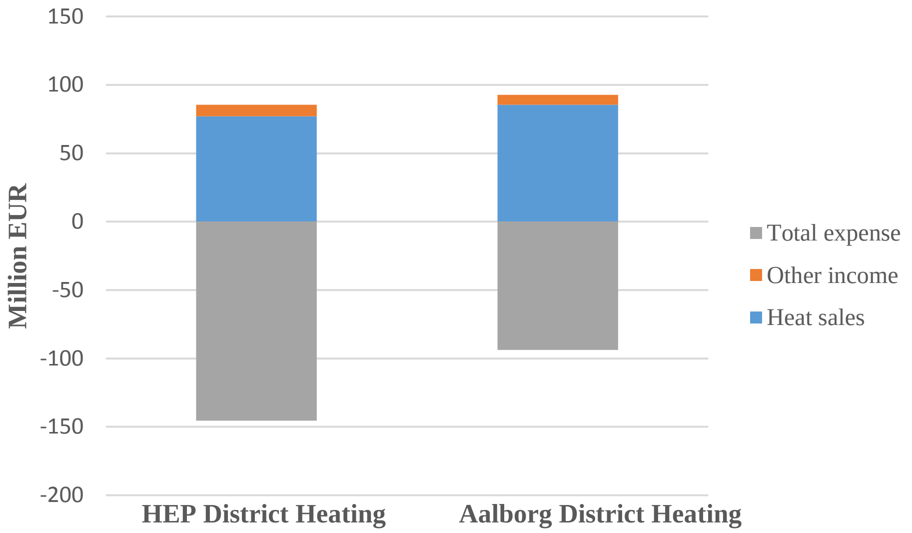


Figure 48. Heat sales, other income and total expenses comparison of the two companies

Specific production cost of TJ of heat energy, costs 15807 EUR in Zagreb District Heating, while in Aalborg District Heating, a TJ of heat energy was produced for 13646 EUR.

Specific sale cost was 9281 EUR/TJ in Zagreb District Heating while, in Aalborg District Heating, it was 13482 EUR/TJ. These specific values have been calculated from the gross production of heat energy, of both companies, divided by the total expense of production in the case of specific production cost, or divided by total income (including other income) in the case of specific sale cost.

It is important to note, that HEP District Heating is insolvent, due to the fact, that its stated loss exceeds the level of capital, and that short term liabilities exceed short term assets [15]. This is mainly due to high production cost and inadequate pricing of heat energy.

7. DISCUSSION

As the comparative analysis has shown Aalborg DH system is more advanced than Zagreb DH system in the supply, demand, distribution and economic spheres.

Due to this far more improvement could be stated for Zagreb DH than Aalborg DH.

Heat supply in Zagreb DH is composed of CHP units and heat only boilers, fired by oil and natural gas. There is no: surplus heat from the industry, waste to energy plants, renewable energy sources like solar thermal, geothermal or biomass plants

Ratio of heat power and electricity capacity and the ratio of heat energy generation to electricity generation (only CHP) are both lower in Aalborg DH, indicating higher utilization of CHP units in the overall heat power and energy generation. This is desirable because CHP units have better fuel utilization than conventional condensation thermal power plants.

All of the generating units in Zagreb DH are on average older than that of Aalborg DH, which translates to higher efficiency and better fuel utilization. Distribution of power and heat energy is much higher in Aalborg DH; heat generation is performed with 16 units at 14 locations, and in Zagreb DH with 14 units at 2 locations.

Zagreb area has a shortage of electricity production of about 1.4 TWh, which could be lowered by installation of new Combine cycle CHP plant that could also produce heat energy for DH system, which could then be extended further than it is now [28]. Environmental impact of such block would be positive as it would replace older block that are in operation today. In summer when space heating is not necessary, heat generated by the CHP blocks could be used in absorption heat pumps to produce chilled water which could be distributed within some future district cooling network or used onsite where large cooling demand exists.

Nordjylland Power Station, the largest energy producer of the energy within the Aalborg DH, has a heat storage of 25000 m^3 of hot water that it uses to optimize its operation. In Zagreb DH there is no heat storage which could be useful in EL-TO Zagreb considering its lack of cooling capacity and therefore having electricity generation tied with the heat demand which is not desirable.

There is also a possibility of the construction of waste to energy plant which could partly solve the current municipal solid waste disposal practices, that in Aalborg DH provides 20% of overall heat energy in DH system.

Geothermal heating is currently used in Zagreb, though not within the DH system, but at the Mladost public pools that have a direct geothermal power of about 6.3 MW [43]. Another location will be in operation in the southwest of Zagreb at Balto and it will be used for heat demand of a hospital, planned direct geothermal power should be 7 MW [43]. Both well-depths are around 1300 m which provide hot water at around 80ºC [43]. Further research is needed to examine the potential for expanding the geothermal heating especially with the use of adsorption heat pumps and within the DH system.

Aalborg DH energy supply primarily consist from heat energy produced in coal fired Nordjylland Power Station, Reno-Nord waste to energy plant and excess heat from Aalborg Portland. Further increase in heat recovered from Aalborg Portland is possible in the production of grey cement which could increase existing excess heat energy by about 30% [25].

Although Aalborg DH has a relatively environmentally friendly heat generation it is far from the total phase out of fossil fuels which needs to be achieved by 2035 in order to meet government commitments.

Very few renewable energy sources within the system exist (some plants use bio oil and biogas) so a lot has to be done in this field. There are several projects that are tackling that problem. The preliminary project by Vattenfall for establishing a 40% biomass co-firing in the Nordjylland Power Station was carried out but the project was put on hold [26]. Vattenfall has also done feasibility studies the extraction and storage of CO_2 form the Nordjylland Power Station Unit 3 [26].

Collaboration with Alfa Laval began in 2012 about the possibility of utilization of waste heat from a new test center for the purification of exhaust gas from ship engines. The plant is expected to commence operation in 2014 and is expected to deliver approximately 3.6 TJ of heat to the DH system [26].

Due to decoupling of heat production and distribution which is robust and flexible it is hoped that further advances in technology and market forces will see to it that new technologies in generation, distribution and storage are constructed and expanded like the waste incineration plants, geothermal plants, biomass CHP, solar thermal, seasonal heat storage and heat pumps run as much as possible by the electricity from wind turbines.

Integration of renewable energy sources and near zero energy houses in DH systems are examined below.

Considering the effort of Denmark as a whole, and Aalborg Municipality as its part, to achieve a 100% renewable energy supply until 2050, it is clear that more improvements and advances have to be made to make that possible.

Through analysis it has been demonstrated that energy savings can be created by district heating and the use of renewable energy sources like locally available biomass, wind power and low temperature geothermal sources [18].

Energy savings are essential to achieving the 100% renewable energy scenario, one of the main areas for energy savings is in buildings (household, public and private offices, shops and other building) which consume almost 40% of the final energy demand in the EU [2]. In the household nearly 2/3 of this energy is consumed for space heating [2].

Therefore energy efficient measures in buildings and the percentage of net zero energy buildings is expected to increase considerably.

Excess heat production in net zero energy buildings and their influence on different DH systems has been investigated in [44]. Main findings are that heat produced within net zero energy buildings causes a beneficial reduction of nonrenewable combustible fuels use. Higher shares of renewable energy sources within the zero net energy buildings requires a seasonal heat storage. However, there are still many aspects that need to be answered, like the economic factors and the potential completion of large solar thermal vs. solar thermal mounted on the net zero energy buildings.

Some authors conclude that the best option is gradual expansion of district heating systems and individual heat pumps for the remaining houses not connected to the DH systems, such a development is best option in present system and in the future 100% renewable system [45].

The analysis showed that CO_2 emissions, fuel demands and costs can be reduced by connecting buildings that use individual boilers based on oil, natural gas or biomass to district heating [45].

It has been demonstrated, using an hourly EnergyPLAN model, how boilers, CHP units and waste incineration plants are effected by an increase in heat pumps or absorption heat pumps [18]. Boiler production is reduced more by the application of heat pumps than the application of absorption heat pumps, but exports are also lowered because of the increase in electricity demand [18]. DH systems also help with the integration of the following renewable energy sources: geothermal heating, biogas production and solid biomass such as straw [45].

Geothermal heating prospects in Denmark are relatively low due to geologically stable region, but some parts located at the top of the country have different geological formations. At well-depth of around 2000 m a temperature of 58 ºC can be obtained, but this is still too low temperature for direct heating purpose [46].

In Thisted, 200 m^3/h of warm water is pumped form a well-depth of 1243 m and used as a low temperate source in two absorption heat pumps (5 MW and 2.7 MW) in combination with a high-temperature input from a boiler 10 MW [47]. Also in Thisted there is an 11.5 MW boiler fueled by straw [47].

Implementing renewable energy systems within DH involves detail, strategic energy planning at the level of individual DH companies, municipalities and local utilities which is rarely done, and it especially does not incorporate all aspects of 100% RES [48].

In [45] it has been concluded that an optimal expansion in the case 100% RES would be around 63-70% of the total Danish net heat demand from the current 46%.

In Aalborg DH the coverage is over 98.6% and it is still rising. The supply area covers, besides the city of Aalborg, several town nearby. Supply area of Zagreb DH covers around 86358 households, of the total 304681, which represents little over 28%. So, further expansion is clearly possible.

In Aalborg DH there is in total 11305000 m^2 of connected area, while in Zagreb DH there is 7165356 m^2 or 36.6% less, which again indicates that expansion is possible, especially when one considers that the city of Zagreb has a population of 792875, while the total number of people in Aalborg Municipality is 203475. Further expansion of the supply area is possible in both systems, especially the one in Zagreb DH where only 28% of households are covered and there is a lack of electricity which could be produced within DH system with new CHP unit. Further expansion of Aalborg DH is also planned.

Specific heat power and specific electricity capacity per connected area of both DH systems are shown in the Figure 31. In Zagreb DH specific heat power per connected area is 198 W/m^2, while that of Aalborg DH is 94 W/m^2. Specific electricity capacity per connected area is equal to 74 W/m^2 in Zagreb DH, while in Aalborg DH it is 39 W/m^2. One reason for this is that the overall capacity factor of CHP plants is much higher in Aalborg DH than in Zagreb DH, with 75% and 50% respectively. Heat generation units (including CHP) capacity factor is also lower in Zagreb DH than in Aalborg DH, with 16% and 20% respectively. Second reason for the difference is due to that Zagreb DH has more generating power (both heat power and electricity capacity), while Aalborg DH has more connected area. Increasing the capacity factor of CHP plant in Zagreb DH is need, through the new CHP unit, and expansion of DH system by which there would be an increase in heat demand which is tied with electricity generation especial in EL-TO Zagreb.

Zagreb DH has a network of only 216 km, compared to the one of Aalborg DH which is almost 6.5 times longer, with its 1386 km of network pipes. Such a vast difference in the total length of the individual systems, that are relatively similar in installed thermal power and the overall annual heat energy generation, is due to the fact that Zagreb DH supply area encompasses only parts of the city itself, while the Aalborg DH supply area covers several nearby towns and the city of Aalborg. Furthermore, both thermal power plants that generate heat energy in Zagreb DH are located within the city, and some of the generating units of Aalborg DH are located outside of the city, like the Nordjylland Power Station which is about 5 km from the city outskirts and the hot water pipes pass beneath the Limfjord.

Both specific heat power and specific heat generation per kilometer of network length is higher in Zagreb DH with 5.46 MW/km and 27 TJ/km than in Aalborg with 0.77 MW/km and 4.9 TJ/km. This indicates that average pipe size is bigger in Zagreb DH and should also indicate smaller heat losses because larger pipes have smaller specific heat losses [6] but this is not the case.

Hot water energy content of hot water in Zagreb DH is 266.75 MJ/m^3 and that of Aalborg DH is 163.78 MJ/m^3. This difference is mainly due to the difference in supply and return temperatures of the DH systems. In Zagreb DH, during the winter period, hot water supply temperature reaches 130 ºC during the coldest days, and return temperature is around 64 ºC, while in Aalborg DH supply temperatures is 90 ºC, and after cooling the temperature returned to the plants is at around 50 ºC.

Therefore the temperature difference between the supply and return temperatures in the winter period in Zagreb DH is 66 ºC while that of Aalborg DH is 40 ºC. Although it is desirable that the hot water energy content is as high as possible, to minimize the amount of water that has to circulate through the system, high supply temperature is correlated with heat losses. So, high energy content should be achieved through the reduction of the return temperature. It is preferable that the return temperature would be only 30-35 ºC [17].

Specific connected area per kilometer of DH network length, points to the fact that Zagreb DH has much denser heat demand, compared to Aalborg DH, with on average over 27500 m^2/km of network length, while Aalborg DH has slightly over 8100 m^2/km. This again indicates possibility of further expansion of Zagreb DH and the presence of shorter network with larger pipes, which should translate into smaller heat losses, but the reality is that Aalborg DH has 68% smaller specific heat loss per km with 928 GJ/km compared to 2944 GJ/km in Zagreb DH. Specific water loss in Zagreb DH is 2687 m^3/km, while that of Aalborg DH is 74 m^3/km, which represent a huge difference that is due to the fact that in Zagreb DH many of the pipes are quite old and leaky, with an average age of 27.5 years, and the ones in Aalborg DH are relatively new with an average age of only 17 years, and have been systematically refurbished. Zagreb DH system has higher pressure levels than Aalborg DH which also accounts for greater water losses.

In Aalborg DH a lot has been done already to cut the heat losses (see Figure 37) from around 30% in 1982 to 20% in 2012. This has been achieved by systematic replacements and refurbishments of the pipe sections, starting with the oldest and leakiest pipes first and the introduction of low temperature DH. From 1983 to 2012, there has been replaced around 700 km of main and laterals, which has had a positive impact on net loss and water loss [26]. Newer pipe section also meant much lower water losses in the network. From 2010 new twin pipes have been installed which have much lower heat losses compared to a conventional DH pipes, these pipes have around 20% lower heat losses than conventional pipes [6]. Although significant improvements have been made, more progress is need in cutting heat losses to achieve more efficient heat supply system.

Considering heat losses in Zagreb DH, it should follow the example of Alborg DH and extensively replace and refurbish its network with new pipe sections to cut the heat losses and accompanied water losses, and increase the security of the heat energy supply.

Although the Aalborg DH already has a much lower supply temperatures than Zagreb DH further improvements are possible as accomplished by Marstal district heating system in Denmark which had an average annual supply temperature of only 74ºC and a return temperature of 34ºC [6]. Zagreb DH, with its supply temperatures that reach 130ºC in the winter time, can do a lot on the field of lowering temperature even well below 100 ºC.

By lowering the return temperature, energy content of hot water can be increased and low temperature energy sources can be better utilized, lowering the return temperature also allows further lowering of the supply temperature.

Steam DH systems that are used for space heating and hot water preparation are going to be phased out in the future due to their higher losses per same amount of heat delivered, compared to hot water system and especially to low DH systems. This is due to the higher supply temperature that are correlated with heat losses, and a lot bigger distribution losses in the form of pressure drop [6].

Price formation is different in Zagreb DH than in Aalborg DH and it cannot be compare directly. Aalborg DH has a subscription fee while Zagreb DH doesn’t. Energy in Zagreb DH is priced per kWh while in Aalborg DH it is priced per m^3. Power subscription in Zagreb DH is priced per kW while in Aalborg DH is in m^2 of connected area.

Through a comparison of annual heat service cost of detached house and a kindergarten the following was concluded: cost of heating a detached house in Aalborg DH cost 45% more than in Zagreb while the price of heating a kindergarten costs 17% less in Aalborg DH.

In the case of a detached house the difference is mainly a result of the fact that there is no subscription cost in Zagreb DH and the energy costs in Aalborg DH are higher. Total power costs are lower in Aalborg DH than in Zagreb DH. It is interesting that in the case of a kindergarten total cost are lower in Aalborg DH, this is due to the fact that energy costs more in Zagreb DH in the case of industry and business consumer tariff group than in Aalborg DH. Cost of power is also lower in Aalborg DH, and subscription fee is negligible compared to overall cost.

Energy prices in Zagreb DH for the group households are 100% lower than those in industry and business group while in Aalborg DH those two are the same. Low energy prices are not stimulating for households to improve on their thermal insulation which could greatly benefit the operation of the DH system by being able to reduce the supply temperature.

Customers in Aalborg DH are charged according to the number of cubic meters of hot water used, and not according on how much energy they use. The incentive is therefore to extract as much heat from the district heating water as and in this way individual customers are working on lowering the return temperatures.

The same should be applied to Zagreb DH. The lower the temperature of the return water, the lower the losses of heat during transport back to the heat generation unit. Good cooling of the district heating water at consumers end results in huge energy and environmental benefits [33].

Average production cost of TJ of heat energy in Zagreb District Heating in 2012 was 70.3% more than the revenue extracted from it, resulting in financial loss of 60.9 million EUR for that year. It is important to note that this year was no exception in the financial terms (see Figure 45) and that the company is insolvent due to the fact that it's stated loss exceeds the level of capital and that short term liabilities exceed short term [15].

This has to be changed, primarily by lowering the production costs and increasing the prices. Average production cost of TJ of heat energy in Aalborg District Heating in 2012 was 1.2% more than the revenue extracted from it resulting in financial loss of 1.1 million EUR.

8. CONCLUSION

Comparative analysis has shown that Aalborg DH system is more advanced than Zagreb DH system in supply, demand, distribution and economic spheres. As a result of these advantages in Aalborg DH, more improvement could be stated for Zagreb DH than Aalborg DH.

In Zagreb DH heat energy is generated by CHP units and heat only boilers, fired by oil and natural gas. Supply area of Zagreb DH covers little over 28% of the households, of the total 304681, so further expansion is possible.

Zagreb area has a shortage of electricity production. This shortage could be lowered by installation of new CHP plant which could facilitate further extension of the DH. This would also increase the capacity factor of current CHP plants, which are currently low, due to tied generation of heat energy and electricity and low heat demand. Environmental impact of such block would be positive as it would replace older blocks that are in operation today, and many heat only boilers used for heating in the individual households.

Lowering specific heat and water losses, which are 68%, and 36 times lower in Aalborg DH should be a priority in Zagreb DH. Systematic replacements and refurbishments of the old network pipes are key to this. Aalborg DH has far lower supply temperatures that translate into lower energy losses, but improvements are possible in both systems as the average annual supply temperature can be as low as 74ºC. Lowering the return temperature is also important, as it enables better renewable energy sources integration.

Customers in Aalborg DH are charged according to the number of cubic meters of hot water used, and not according on how much energy they use. The incentive is, therefore, to extract as much heat from the district heating water as possible, and in this way individual customers are working on lowering the return temperatures. This principle should also be applied in Zagreb DH.

Heating a household in Zagreb DH is cheaper than in Aalborg DH, while heating a business is more expensive. HEP District Heating operated with a loss of 60.9 million EUR in 2012. In the same year, its specific energy generation cost was 70% more than the revenue extracted. Changes are necessary and can be achieved by cutting the generation cost and revising the pricing of energy. Aalborg DH specific generation cost is 14% less than the one in Zagreb DH. Aalborg District Heating operated with a loss of 1.1 million EUR in 2012.

In both systems, there is almost no renewable energy sources. This has to change if low carbon economies are to be achieved. Although an effort is made, much of the work encompasses only feasibility studies.

Further advances in technology and market forces are hope to bring new technologies in generation, distribution and storage for DH systems, like the modern waste incineration plants, geothermal plants, biomass CHP, solar thermal, seasonal heat storage and heat pumps run by the electricity from wind turbines.

The integration of renewable energy sources in DH systems is the most important goal that still needs to be achieved.

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