USING HIGH GRADE WASTE HEAT FOR COOLING PURPOSES IN DISTRICT HEATING SYSTEMS

A case study by

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COLOPHON

Title
Using high grade waste heat for cooling purposes in district heating systems: A case study

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I. PREFACE

I hereby present you with my master thesis which is written as a final project for the master program Construction Management and Engineering at the Eindhoven University of Technology. This thesis is the result of research in the field of district heating networks and cost optimization. The research is performed in collaboration with KPN.

In a time of environmental instability, working on an innovation that aids in the development of energy efficient solutions to our society has been an interesting experience. Involvement and up close experience with these solutions has positively influenced my enthusiasm towards this highly innovative subject within the construction industry.

For his help in developing this thesis I'd like to thank my first supervisor from the TU/e, Wiet. Finding an angle of approach after investigating this subject has been particularly difficult for me. The frequent appointments I was able to make with you and case sensitive knowledge you possess have been a great help for me. I would like to thank Bauke, my second supervisor from the TU/e, for offering me feedback and advice on how to conduct this research and Ronald, my supervisor from KPN, for his guidance on the practical application of the research.

Additionally I would like to thank my girlfriend Lynn, my close friends, and family for their support.

Niek Olijve Eindhoven, 2015

II. ABSTRACT

It can be difficult for companies outside of the district heating sector to determine the financial viability of district heating systems. This thesis focuses on the adaptation and review of a network optimization model to be used as a financial optimization model. In the thesis, literature study is performed in order to determine the input parameters required for the model. The model is subsequently applied to a case from KPN in which a network extension is used to provide waste heat to cool a datacenter. The model is assesed on functionality, practicality, applicability, and accuracy. The results from the model simulations are compared to values retrieved from practical experience. The analysis confirms the model's efficiency in calculating complex district heating networks. It also acknowledges the need for practical experience in determining the values for the model parameters.

III. SUMMARY

Energy efficiency is becoming an increasingly important part of society. Fossil fuels are getting scarcer and more expensive. To counter these trends, global agreements have been made in order to increase energy efficiency and reduce emissions. Currently around 5% of the Dutch energy production is renewable. By 2020 the Dutch government wants this number increased to 20%. The ultimate goal of this initiative is to decrease carbon emissions and reduce global warming. In order to reach this goal not only does production need to be cleaner but consumption should be targeted as well. By increasing energy efficiency and therefore decreasing energy consumption, emissions can be greatly reduced.

District heating systems can aid in the reduction of energy consumption. A district heating system is a centralized heating and/or cooling system that is able to store and transfer heat to and from the system. District heating systems use one or more central heat suppliers to provide heat through a series of pipes to consumers. District heating systems often utilize waste heat as a power source and therefore contribute to energy efficiency measures. District heating can boost energy efficiency and reduce the operational costs of heating and cooling systems.

KPN will be placing and managing a datacenter in an industrial area in Rotterdam. Such datacenters require a large amount of cooling for the servers which are housed inside the building. In order to provide in the cooling need for the building, KPN wants to determine the financial viability of connecting the datacenter to an existing district heating network. With the aid of an absorption cooler, they would use the waste heat from the system to cool the facility. There is little information available for non-industry specific companies to determine the financial viability of district heating network extensions. This resulted in the following goal for this master thesis:

Adapt and review a network optimization model to be used as a financial optimization tool in district heating systems.

The financial optimization model is used to determine the financial viability of the district heating network extension. In order to run simulations with the model, parameters have to be determined. These are based on literature research and calculations. Since a model always has a margin of error, the effect of the parameters on the financial outcome is determined. This results in a sensitivity analyses which describes the influence of each parameter on the outcome in relation to its estimated accuracy.

The reviewed model uses vertices and edges to create a grid derived from a street map. This grid represents the possible locations for pipelines to be installed and contains the consumers and suppliers. Using cost optimization, the best option for pipe installation and service is simulated, resulting in an optimal cost estimation.

Varying scenarios have been simulated in order to identify the effect of parameters on the cost of district heating extensions. Finally an expected, best, and worst case scenario is simulated to determine the viability of the district heating extension. The expected case and best case produced positive yearly results of ~€50.000 and ~€130.000 respectively. The worst case resulted in a yearly loss of ~€45.000. In addition to the direct financial benefits, the reduction in social cost of carbon is determined as well and is calculated to be ~€35.000 annually. Quantification of these benefits can be used to obtain environmental subsidies or indicate the social benefit of a project.

Results from a cost calculation by the heat distribution company WBR are also compared. These calculations are subjective but can still be used as a benchmark for the simulations. Under the same conditions, the expected scenario of WBR had a budget deficit of € 330.000 over 15 years. Recalculation of their case, results in two cases which do result in a profit.

From these findings it can be concluded that the considered project is feasible under the right circumstances. Both the simulations and calculations from WBR do not take all factors contributing to the total cost into consideration. Therefore KPN should analyze both results and retrieve and combine the information that they think represents the case best. The results from analyzing the calculations by WBR indicate the simulations provide a realistic solution. Some of the parameters used in this thesis are very similar to the parameter value's WBR used. Other values were slightly different, this can be attributed to lack of information and subjectivity of the WBR calculations. The WBR calculations resulted in a small budget deficit which can be explained by the short project duration that was considered in these calculations. Demand insecurity is one of the major reasons for considering a short project duration. The ablation of this risk would stimulate the use of a longer project duration, which would make the project viable.

It can also be concluded that the model can be used to calculate the financial viability of any district heating system regardless of it being an extension or green field analysis. The model is optimally used in calculations for larger district heating systems, which are harder to approximate by hand. In contrary, smaller district heating systems might be better approachable by situational calculations. The reason for this are anomalies, such as specific construction site situations and irregular consumers. Additionally, local policies can be implemented better in these calculations.

IV. SAMENVATTING

Duurzaamheid en energie efficiëntie spelen een alsmaar belangrijkere rol in onze samenleving. Fossiele brandstoffen worden schaarser en daarmee kostbaarder. Om deze ontwikkelingen tegen te gaan zijn internationale overeenkomsten tot stand gekomen die energie efficiëntie moeten vergroten en emissie van broeikasgassen verminderen. Op dit moment is ongeveer 5% van de Nederlandse energie productie duurzaam. De Nederlandse overheid wil dat dit in 2020 is verhoogd naar 20%, om de uitstoot van broeikasgassen te verminderen en de opwarming van de aarde tegen te gaan. Om dit doel te kunnen bereiken moet niet alleen de productie maar ook de consumptie van energie worden aangepakt. Door de energie-efficiëntie te vergroten en daarmee energie consumptie te verminderen kan de uitstoot van broeikasgassen aanzienlijk worden verlaagd.

Warmtenetten kunnen een grote rol spelen in de afname van energieconsumptie. Warmtenetten zijn gecentraliseerde warmte- en koelingssystemen die warmte kunnen opslaan en transporteren. Daarbij maken ze gebruik van één of meerdere warmte leveranciers die warmte leveren aan consumenten door een netwerk van pijpleidingen. Warmtenetten maken vaak gebruik van restwarmte als warmtevoorziening en dragen daarom bij aan de duurzaamheidsdoelstellingen. Warmtenetten kunnen dus de energie-efficiëntie verhogen en de operationele kosten van warmte- en koelingssystemen verlagen.

KPN beheert een datacenter op een industrieterrein in Rotterdam. Datacenters hebben een grote hoeveelheid energie nodig om de bijbehorende servers te koelen. Om aan deze koelbehoefte te voldoen wil KPN het datacenter aansluiten op een bestaand nabijgelegen warmtenet. KPN wil de warmte van dit netwerk gebruiken om hun gebouw te koelen met behulp van een absorptiekoeler. Om te bepalen of dit mogelijk is, wil het bedrijf de financiële haalbaarheid van deze aansluiting berekenen. Er is momenteel echter weinig informatie beschikbaar voor bedrijven die niet direct te maken hebben met warmtenetten om de financiële haalbaarheid van warmtenetten uit te rekenen. Dit heeft tot het volgende onderzoeksdoel geleid.

Pas een bestaand netwerk optimalisatie model aan om gebruikt te worden als financieel optimalisatie instrument van warmtenetten en bepaal hoe goed deze als zodanig functioneert.

Het financiële optimalisatie model wordt gebruikt om de financiële haalbaarheid van warmtenet-uitbreidingen te bepalen. Om simulaties te kunnen doen met het model is het nodig om de waarde van de parameters van het model te bepalen. Deze waarden zijn gebaseerd op literatuuronderzoek en berekeningen. Het is daarbij nodig om de effecten van parameters op de uitkomst de bepalen, omdat simulaties altijd foutmarges behelzen. Dit is gedaan door middel van een gevoeligheidsanalyse, waarin de nauwkeurigheid en invloed van parameters op de uitkomst is bepaald.

Het onderzochte model gebruikt vertexen en lijnstukken om een raster van straten te maken. Dit raster stelt de mogelijke locaties om pijpleidingen te installeren voor en bevat tevens de locatie van de consumenten en producenten. Met behulp van een kostenoptimalisatie berekening wordt de meest voordelige locatie voor de plaatsing van leidingen bepaald. Daarnaast wordt de levering van warmte gesimuleerd en wordt de optimale kostenschatting bepaald.

Verschillende scenario's zijn gesimuleerd om de effecten van parameters op de kosten van warmtenetten te bepalen. Afsluitend zijn er drie scenario's uitgerekend: een verwacht, een minimaal en een optimaal scenario. De resultaten hiervan zijn respectievelijk een jaarlijkse winst van ~€50.000, ~-€45.000, en ~€130.000. Naast de directe financiële baten zijn er ook maatschappelijke baten gebonden aan het project in de vorm van een reductie van de koolstofuitstoot. Kwantificatie van deze baten kan gebruikt worden om subsidies aan te vragen en de maatschappelijke voordelen van het project aan te tonen.

De resultaten uit de simulaties zijn vergeleken met een kostenschatting van de warmteleverancier Warmtebedrijf. De berekeningen van Warmtebedrijf (WBR) zijn subjectief maar kunnen wel gebruikt worden om de resultaten van de simulatie te toetsen. Het verwachte scenario van WBR heeft een begrotingstekort van €330.000 over een periode van 15 jaar. Herberekening van dezelfde case met parameters uit de literatuur resulteert in twee cases die wel winst maken.

Uit deze bevindingen kan geconcludeerd worden dat het beschouwde project financieel haalbaar is onder de juiste omstandigheden. Zowel de simulaties als de berekeningen van WBR zijn niet in staat om rekening te houden met alle factoren die invloed hebben op de totale kosten. Om deze reden zou KPN beide resultaten moeten combineren en de informatie die voor hun belangrijk is moeten filteren uit het geheel.

Uit de resultaten van de analyse van de WBR berekening blijkt dat de simulaties een realistische uitkomst hebben. Sommige van de parameterwaarden die in deze thesis gebruikt zijn komen sterk overeen met de waarden die WBR heeft gebruikt. Andere waarden hadden kleine verschillen die te verklaren zijn door een verschil in beschikbare informatie en de subjectiviteit van de berekeningen van WBR. De berekeningen van WBR hebben een begrotingstekort die veroorzaakt wordt door de korte beschouwde projecttijd. Onzekerheid van afname is één van de belangrijkste risico's om een korte projecttijd in acht te nemen. Het wegnemen van dit risico kan het gebruik van een langere projecttijd stimuleren wat het project haalbaarder maakt.

Er kan verder geconcludeerd worden dat het model bruikbaar is voor zowel netwerkextensies als greenfield analyses. Het model komt het meest tot zijn recht in het berekenen van grootschalige complexe warmtenetten. Daarentegen kan het voordelig zijn kleinschalige uitbreidingen met de hand uit te rekenen. De reden hiervoor is dat het makkelijker is in te spelen op afwijkende situaties en rekening te houden met lokaal beleid.

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1. INTRODUCTION

This chapter contains the introduction for a master thesis research project which is executed in collaboration with KPN. The project concerns the implementation of high grade waste heat for cooling purposes of a data center in Rotterdam. The objective of this chapter is to introduce the topic, outline the scope of the project and determine the approach of the research.

Background information is provided on the subject and its social and scientific relevance. The research problem is defined and distilled into several research questions. A research approach and research model are established which will serve as a guideline throughout the project.

1.1. CONTEXT

Social relevance of energy efficiency

Energy efficiency is becoming an increasingly important part of society. Fossil fuels are getting scarcer and more expensive, global agreements have been made in order to increase energy efficiency and reduce emissions (Elliot, 2015). Currently around 5% of the Dutch energy production is renewable (Figure 1). By 2020 the Dutch government wants this number increased to 20% (Rijksoverheid, 2015). The ultimate goal of this program is to decrease carbon emissions. In order to reach this goal not only does production need to be cleaner but consumption should be targeted as well. By increasing energy efficiency and therefore decreasing energy consumption, emissions can be greatly reduced.

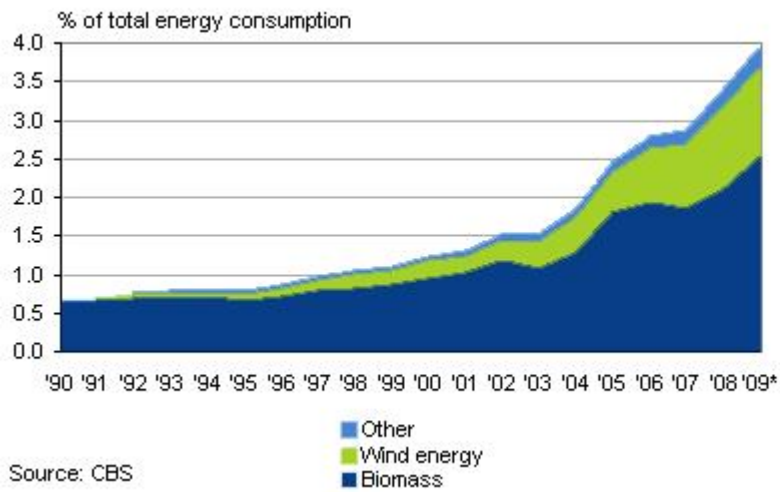

Figure 1. Percentage renewable energy of total energy consumption (CBS, 2015)

Within the energy and electricity sector a lot of resources are currently wasted (Stevens, 2012). In order to sufficiently accommodate the energy requirements of the Dutch population, electricity suppliers have to supply energy equal to the highest demand at any time and have to incorporate a buffer in order to prevent power-outages. Combined with the high difficulty of storing energy and the peak demands in the system a significant amount of the energy that is produced goes to waste (Lawrence Livermore National Laboratory, 2013). Furthermore energy consumption is expected to increase because of the growing number of electrical appliances and because of the electrification of the mobility sector (e.g. electric bikes, scooters and cars), electrification of heating systems and the increase in ICT appliances (Zhou, 2013). The growing share of renewable energy, which is inherently less predictable, will create more fluctuations in the power grid which have to be managed through a dynamic demand (DHPA, 2013).

Smart Grids

These predictions sparked the emergence of Smart Grids, a combination of new technologies and measures targeting the energy grid. The term Smart Grids describes a culmination of technologies in energy efficiency and represents a Smart 'Energy' Grid that is able to manage the supply and demand of energy. By shaving peak demands and efficiently linking production and demand, energy-efficiency can be increased significantly. Currently several case studies have been started globally testing Smart Grid technologies and proving its viability. Most of these projects are focused on the electricity grid, whilst most experts agree that the true efficiency of a Smart Grid can only be achieved by combining all energy systems into a hybrid Energy Grid (Favre-Perrod, 2005).

District heating systems

A district heating (DH) system is a centralized heating and/or cooling system that is able to store and transfer heat to and from the system. District heating systems use one or more central heat suppliers to provide heat through a series of pipes to consumers. District heating systems often utilize waste heat as a power source and therefore contribute to energy efficiency measures. District heating can boost energy efficiency and reduce the operational costs of heating and cooling systems (Bloomquist, 1999). The waste heat from a power source can be qualified as high grade or low grade waste heat. High grade waste heat is heat of temperatures above 90 degrees Celsius and has more functionality options than low grade waste heat.

In district heating systems high grade waste heat is sometimes used to cool buildings with the aid of an absorption cooler. An absorption cooler is a device that is able to use heat to produce cooling. The basic working principle of an absorption cooler is similar to that of a refrigerator. The difference is that an absorption cooler uses heat to create a pressure difference and a normal refrigerator uses a compressor.

According to the Dutch Heat Pump Association (DHPA) district heating systems can also provide a unique service in the management of the electrical grid when powered by electric heat pumps because of its high predictability rate and ability to postpone and buffer its net load. Furthermore these systems are able to store energy relatively well though they lack the option of feeding the energy back into the electricity grid.

This research focuses on a district heating system in Rotterdam which is powered by a Combined Heat and Power (CHP) plant located in the Rotterdam harbor. The plant is fueled with waste and biomass and provides electricity and heat for the surrounding area.

1.2. RESEARCH PROBLEM

Introduction to the problem

Currently district heating networks are generally constructed by dedicated heat transportation companies which purchase waste heat and transport it to private homes and businesses against a profit (Schepers & Van, 2009). These companies possess the tools to determine the profit of district heating networks, however, outside of the district heating industry this information is difficult to acquire.

Small scale communities and business collaborations can benefit from district heating as well but are less desirable for heat transport businesses (Truong & Gustavsson, 2014). In these settings district heating development needs to be powered by internal action. A lack of knowledge and calculation tools is a barrier in this matter. The availability of a calculation tool and basic calculation values can stimulate the adoption of district heating systems for these parties.

The industrial sector uses 30 percent of all energy consumed domestically, one-third of the energy consumed in industry is discharged as thermal losses. Part of the thermal losses is discharged as high grade waste heat which is immediately accessible for district heating purposes. The majority however is low grade waste heat which has been considered economically unviable to capture. Emerging technologies are beginning to make this accessible however, opening the door for these companies to develop their own small scale district heating networks (Naik-Dhungel, 2009).

Case

KPN will be placing and managing a datacenter in a brown field in Rotterdam. Such datacenters require a large amount of cooling for the servers which are housed inside the building.

Together with several other businesses KPN aspires to create a connection to Rotterdam's currently existing District Heating system which uses high grade waste-heat to service part of Rotterdam's real estate. The District Heating system is supplied with waste heat from a waste-incineration and power plant. The plant produces more heat than required for the current district heating system so additional consumers are desirable.

For KPN the high grade heat will be used to cool the building with the aid of an absorption cooler. KPN's cooling (and subsequently heat) demand will be the highest in the summer when temperatures are high. For the other companies which require the heat for heating purposes, their peak demand will be in the winter when temperatures are low. This creates a demand symbiosis which allows optimal usage of pipe capacity in both winter and summer, creating a theoretically cheaper situation.

Problem definition

KPN wants to calculate and define the financial benefits from collaboration between companies. Very little information is publicly available on the financial optimization of district heating systems and the financial viability of cooling using high grade waste heat.

No reliable calculation method exists to calculate the feasibility of district heating investments. Therefore companies are hesitant to take the risk of investing in this sustainable solution.

Research objectives and limitations

The goal of this research is to adapt a network optimization model to be used as a financial calculation tool and review its effectiveness. The model will be used to determine the financial viability of using high grade waste heat for cooling purposes in a case study. The model should be rigorous enough to be applicable to similar projects. The thesis should serve as a guideline for businesses outside of the district heating industry in determining the financial viability of district heating solutions.

In order to solve the problem definition as stated earlier, the overall objective of this thesis can be formulated as:

Adapt and review a network optimization model to be used as a financial optimization tool in district heating systems.

Research Questions:

- *Under which conditions is using high grade waste heat for cooling purposes in district heating systems viable?*
  - *What are the costs of a conventional cooling system?*
  - *How can the collective costs be divided among the players involved in the cooperation?*
- *How can the input parameters for the calculation be determined?*
- *How accurate is the model at determining the financial viability of a district heating system?*

1.3. RESEARCH APPROACH

The research approach describes the different methods that are used in this research and functions as a guideline during the research.

Methodological justification

As described in the research objective the goal of this research is to adapt and review a financial optimization model which can help stimulate the adoption of district heating systems among businesses. The study is divided into three phases, an analysis phase, a design phase, and a reflection phase. The following paragraph describes these phases and the research methods used in each phase.

Literature Study (Analysis Phase)

During the analysis phase information needs to be gathered. This can be divided into scientific background information and case specific information. The scientific background information represents information such as similar district heating systems, cost allocation formulas, and financial models. These are investigated and mapped using a literature study at the start of the project to provide a clear idea on the possibilities and functioning of relevant systems and techniques. A general foundation on the functioning of district heating systems is required in order to determine the available options in creating a representative model.

Data Collection (Analysis Phase)

The case specific information relates to information about the system in question and the businesses that are involved in the project. Some of this information is readily available and is provided by KPN while more specific information (primarily regarding input parameters) needs to be acquired. Information regarding demand-profiles of the consumers and location are most important and should be collected prior to model simulation.

Model Design / Case Study (Design Phase)

During the design phase the financial optimization model is adapted and set up using the information and techniques acquired in the analysis phase. Similar models found during the analysis phase are integrated with a model developed by Mazairac (2015).

This model is applied to a project from KPN as a case study. Case studies are very suited for creating a deeper understanding of a complex issue and can extend experience to what is already known through previous research (Soy, 2006). The case study also serves as relevance for KPN.

During the reflection phase the model is reviewed. Sensitivity analyses are necessary to check the range of results. The satisfaction of the businesses needs to be analyzed and discrepancies in the model may warrant specific parts to be redesigned. Finally its effectiveness is scrutinized and recommendations for further research are made.

Research model (Reflection Phase)

Figure 2 represents the research model. The model shows initiation of the thesis execution starts with the project proposal. When the execution begins the literature study is initiated, parallel to the literature study, data collection can be started. These stages are depicted in parallel in the research model, though data collection is initiated in a slightly later stage. Succeeding this model the design is started. A model created by Mazairac (2015) is used as a benchmark to base the new model on. The research model shows that if reflection uncovers unsatisfactory results the unusable material is discarded and design is reinitiated. When results are found satisfactory the results are concluded in a report.

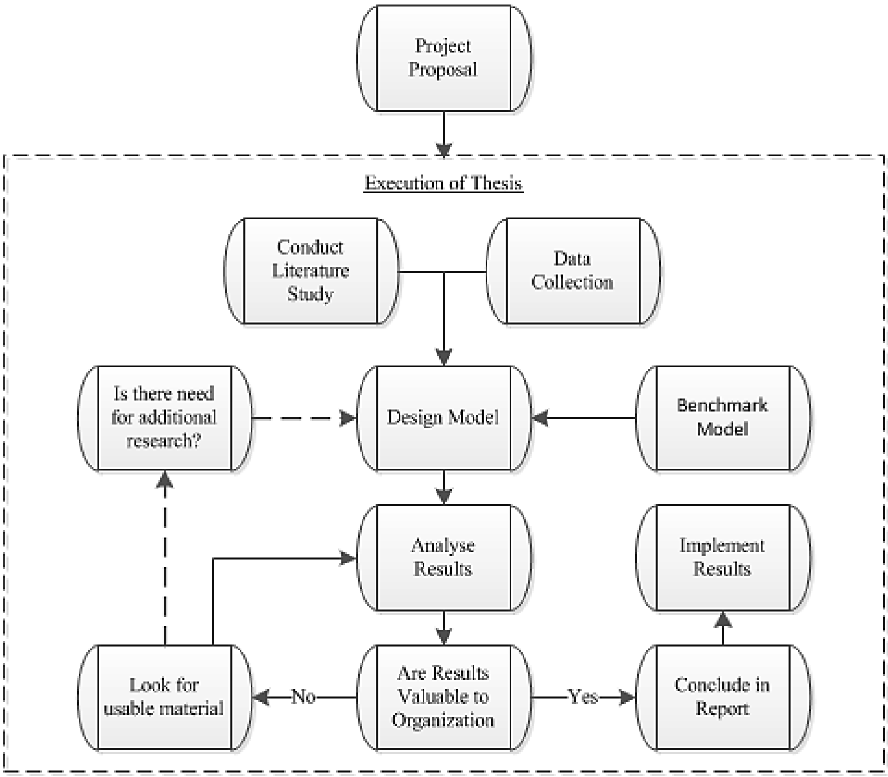

Figure 2. Research Model

1.4. EXPECTED RESULTS

Since most of the study focuses on the adaptation and utilization of a model, little speculation is possible on its final output. However, speculations can be made on the outcome of several of the other research methods.

The literature study focuses on creating insight into previously conducted studies and into the background of several methods and systems. It is expected that comparable situations have been studied. The model that is created is based on extracted formulas and techniques which are expected to be found in other articles.

2. CONTEXTUAL ORIENTATION

This chapter is in support of the financial optimization model. It functions as a starting point of the content discussed throughout this master thesis and aims to provide insight in the operational environment of district heating systems. Subsequently this chapter should manifest the role district heating systems will play in the future energy market.

In the first chapter information is provided on the current energy market, its size, growth and the amount of energy lost through transport and conversion. This provides insight in the inefficiency of the energy market which provides existential meaning for energy efficiency measures such as district heating. Subsequently the impact of carbon emissions and the rising global focus on the reduction of fossil fuels and implementation of renewable energy sources is explained. Lastly the heat market and competitiveness of district heating systems is illustrated to indicate the viability of district heating systems as a solution to the problem.

2.1. ENERGY MARKET

Over the past century our dependency on energy has increase exponentially. Every household contains a multitude of electronic devices; businesses are largely computer- and therefore electricity driven and globalization has increased the energy use from traffic (Comtois, 2015).

The world per capita energy consumption (Figure 3) has been increasing since the 1900's and has seen a significant growth spurt after the Second World War (Tverberg, 2012). This growth spurt is accompanied by an increase in use of oil and natural gas. The use of biofuel however has seen a steady decline since the 1840's.

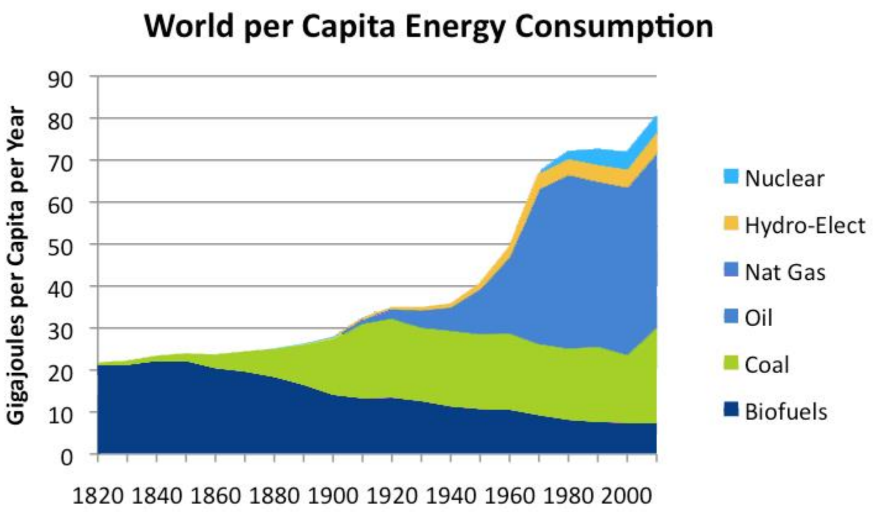

Figure 3: World per Capita Energy Consumption (Tverberg, 2012)

The energy market can be described as the culmination of all distributed energy-holding resources (Frederiksen & Werner, 2013). Energy can be transported in the form of electricity, gas, heat or fuels and subsequently different types of energy can be converted to one another. This makes resources within the energy sector very interdependent.

The energy system structure can be divided into four parts; primary energy supply, total final consumption, total end use and total efficient end use. The primary energy supply encompasses all potential energy supplied to the energy system to satisfy the total energy demand. Potential energy refers to the total calorific value of fuels and other energy sources i.e. the energy they would produce considering a 100 percent efficiency in energy conversion. This category represents the total energy delivered to the energy system. The total primary energy supply is 73,6 exajoule (EJ) in Europe and about 490 EJ globally (Stevens, 2012). Part of the potential energy is converted into usable energy for consumption such as refined fuels, electricity, and heat which makes up the total final consumption. The usable energy is transported to the end users who will either use it directly or for local conversion such as engines and boilers. This is the total end use. For the total efficient end use, inefficiency at the consumer or end-user has to be considered. A light bulb for example produces heat along with its intended purpose: light. Throughout the entire energy system all energy that is not efficiently converted or used is lost as waste heat. Figure 4 displays the world energy flow in these different stages. The light grey line which can be seen at the end of the graph represents rejected energy through waste heat.

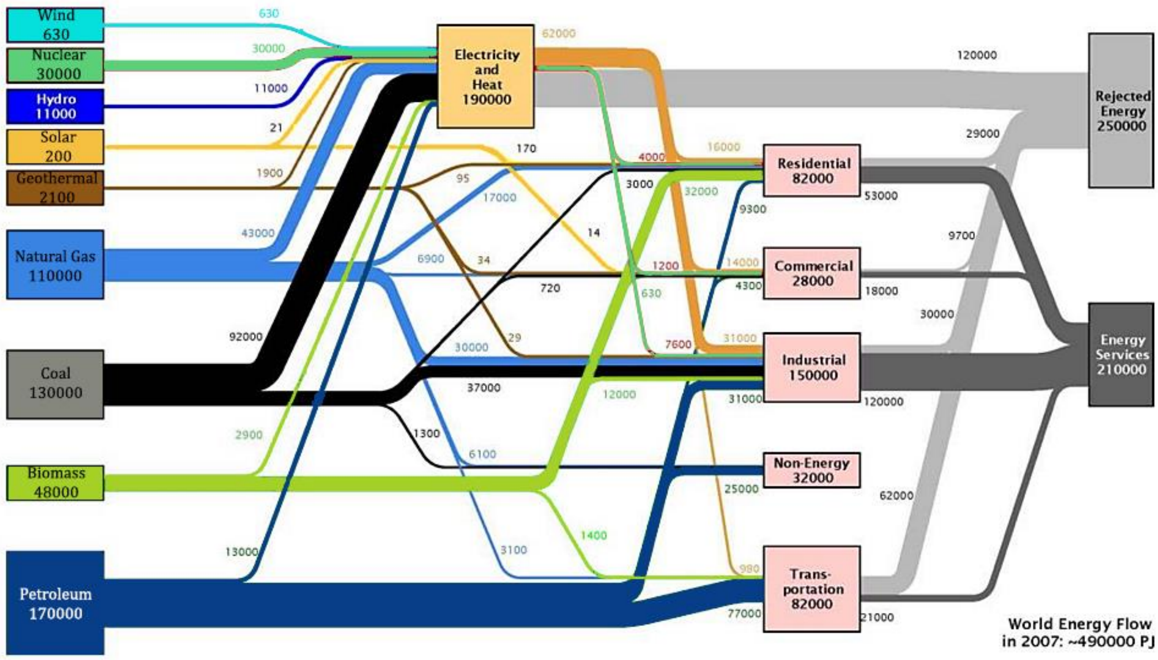

Figure 4: Stages of energy consumption in Europe in 2003 (Stevens, 2012)

Figure 5 shows the stages of energy consumption in Europe in 2003, this figure does not include the 30% end use inefficiency. The step between primary energy supply and final consumption represents the first energy transformation including power generation, oil refining and central heat recycling. In this transformation process 22.4 EJ is lost due to heat losses corresponding to ~30% of all primary energy supplies. In the local conversion process another 17.1 EJ is lost due to inefficient conversion. At the end use inefficiency stage an estimated 30% of the remaining energy is again lost as waste heat. In total more than half of the primary energy supply is lost in heat losses, either in the first transformation process or at the end-user.

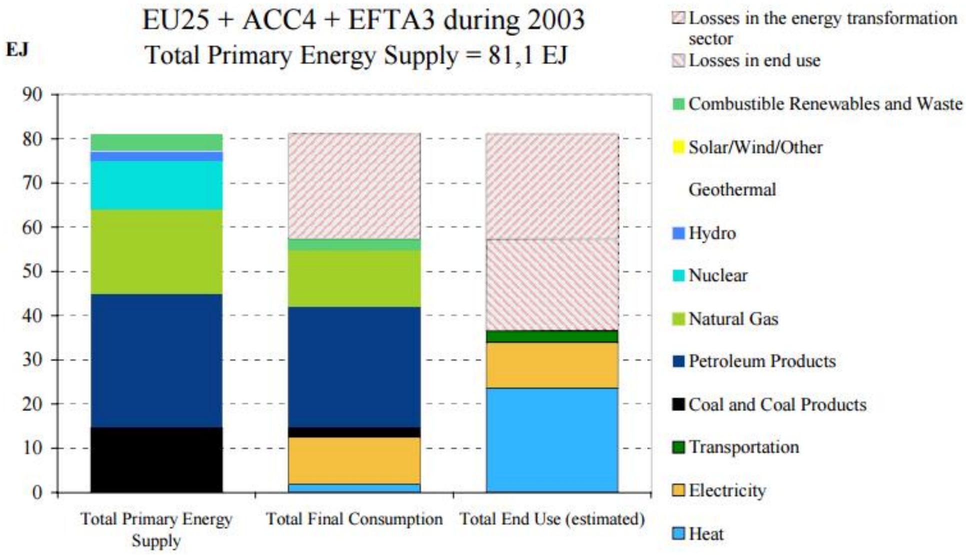

Figure 5: Energy balances in Europe during 2003 (Werner, 2007)

These losses must be reduced in order to increase overall energy efficiency and reduce carbon dioxide emissions. District heating could contribute to this goal by utilizing existing heat losses in order to satisfy heat demand.

2.2. ENVIRONMENTAL IMPACT

Rising concentrations of carbon dioxide and other greenhouse gases created by the burning of fossil fuels are steadily warming the earth's climate. The ultimate effects of these changes are still uncertain but scientist already concluded that physical and biological systems on all continents and in most oceans have been affected by recent climate changes. This includes damages to flora and fauna on a scale that could significantly affect the ecosystem (Rosenzweig et al., 2007). Furthermore, the consumption of fossil fuels has major impacts on the security of the energy market. Speculation still exists on the size and lastingness of fossil fuel reserves. Shaffee and Topal estimate the time depletion of oil and gas to be around 35 years and expect coal to last another 107 years (Shafiee & Topal, 2009).

These developments have instigated governments to further their energy efficiency measures. Improving energy efficiency is one of the most cost-effective ways of reducing CO_2 emissions and increasing security of energy supply. The European Union has set targets to be attained by 2020 for the reduction of greenhouse gas emissions by 20% and improvements in energy efficiency by 20% (European Comission, 2014). As was stated in the previous chapter section, district heating can play a significant role in achieving these goals.

There are several factors that make district heating so energy efficient; the ability to utilize waste heat, economy of scale advantages, and the ability to synergize with other energy sources.

Utilization of waste heat

First of all district heating has the ability to utilize energy that would otherwise be wasted, effectively increasing energy efficiency by the percentage of utilized waste heat. Any industry with a significant waste heat production is eligible for these efforts as long as the investment costs underweigh the benefit gained from heat recovery. The benefit gained from heat recovery can also be expressed in terms of environmental efficiency improvements.

Economy of scale

Other than the ability to recover waste heat district heating also allows heat production on a larger scale compared to local heat production efforts. Even with a dedicated heat production unit this can result in a significant decrease in energy losses. Although district heating does create the need for heat transportation, heat storage and production will become significantly more efficient.

Synergy with renewable energy sources

District heating also benefits from a high synergy with renewable energy sources. Renewable fuels like biofuels and waste-incineration work exceptionally well in CHP power plants. These power plants have become a major part of Scandinavian heat supply and are becoming increasingly popular through the desire for renewable and independent energy.

District heating also synergizes with renewable energy through its ability to store energy efficiently. Renewable energy sources such as wind energy and solar energy are considered dynamic suppliers. In order to counteract this fluctuating energy supply, demand-side management needs to be applied to the energy demand. Peak shaving is a major part of this and works by shaving demand peaks as well as being able to effectively utilize peaks in energy supply. District heating systems generally have a buffer available which allows them to play into demand and supply peaks, therefore increasing the efficiency of other renewable energy sources.

2.3. HEAT DEMAND

The current heat demand is mainly dependent on heat requirements from industrial, residential, service and agricultural sectors (Pardo, Vatopoulos, Krook-Riekkola, Moya, & Perez, 2012). Within these sectors heat is required in a variety of pursuit; from ore reduction in the steel industry to dry-cleaning and space heating. Intuitively these activities have different heating and temperature demands. This chapter focuses on the most common heat demand of temperatures below 100 ºC which is used for space heating among others.

Several factors influence the general Heat Demand in Europe. The required inside temperature plays a considerable role in the energy required for space heating. Whereas in the 1970's indoor temperatures of 13 ºC were not uncommon (Frederiksen & Werner, 2013) the average indoor temperature nowadays is 21 ºC and expected to increase to 22 ºC (Shove, 2014). Even though indoor temperature averages are increasing, improvements in insulation and energy efficiency is limiting the energy required for space heating (Kemna & Acedo, 2014).

Another influence on the average heat demand is outside temperatures. Outside temperatures have a huge influence on the discrepancy between the required temperature and actual temperature (Kemna & Acedo, 2014). This temperature difference needs to be heated and effects the amount of energy required for space heating. Day-night cycles and seasonal changes have a large effect on outside temperatures which in turn have a large effect on heat demand. Therefore the heat demand varies throughout the year.

In order to provide a better insight into the heating requirements of regions due to climate, heating degree days (HDD) have been designed. This term reflects the demand for energy needed to heat a building and is derived from measurements of outside temperature (European Environment Agency, 2012). There are several methods to calculate the HDD. The most popular method considers the average temperature on any given day and subtracts it from the required room temperature of a building. If the number is negative the day is not assigned an HDD value. In case of a positive response that number equals the days' HDD value. The average value building design, energy systems, behavioral aspects and levels of insulation al influence the amount of energy that is needed to heat a home. Therefore these factors need to be taken into account when assessing a buildings energy need with HDD. The average amount of HDD in the EU-27 was 3000 in 2008. In 1980 this was ~3400 HDD resulting in a decrease of 13% over the past 30 years due to temperature changes (Figure 6). These changes are not homogenous throughout Europe and have a bigger effect on northern countries then they have on southern countries. Due to the continuing changes in climate the decreasing number of HDD is expected to dwindle further to a projected decrease of 9% in 2050 (European Environment Agency, 2012).

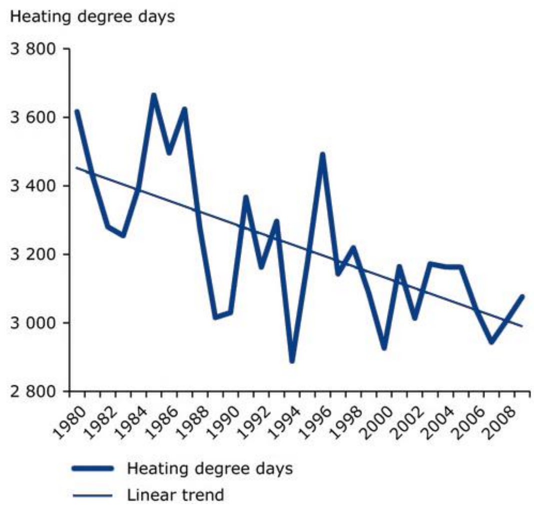

Figure 6: Heating degree days (European Environment Agency, 2012)

Historically local heat production has been the most used form of space heating. Currently gas and electric boilers are still the primary form of heating used in residences though centralized heating systems are gaining in popularity. The Scandinavian countries have been on the forefront of district heating adoption and have been steadily developing a district heating system since 1960. District heating currently supplies more than 50% of the heating demand in Finland, Denmark and Sweden (Frederiksen & Werner, 2013).

In 2010 the final energy consumption in the EU-27 (the composition of the European Union from 1 January 2007) was 48.2 EJ (Bertoldi, Hirl, & Labanca, 2012). Of this amount 26.65% was attributed to residential use, equaling 12.84 EJ. Space heating equipment is the single largest electricity end-user in the residential sector and accounts for 41.5% of the residential consumption. Another 17.7% is used for water heating adding up to 59.2% or 7.6 EJ (EIA, 2013).

2.4. COMPETITIVENESS

Future Heat Market

The competitiveness of district heating is largely dependent on the heat market. The state of the current heat market has previously been discussed but in order to determine the future competitiveness of district heating systems, the future heat market and more specifically the district heating-heat market has to be considered as well. Considering trends such as global warming and increases in heat conservation technologies the national and global heat demand is likely to diminish. Since heat transport constitutes part of the supply costs of district heating, high centralized heat demand is positive for its competitiveness. The percentage of population living in cities in Europe is expected to grow from 50% in 2010 to 70% in 2050 (Statista, 2014). According to a study by Person and Werner (Persson & Werner, 2011) district heating is expected to stay competitive due to the density of city districts, even at ambitious heat reduction targets. It can be concluded that the heat market is expected to decrease whilst undergoing a shift from decentralized heat demand to centralized heat demand.

Costs

District heating's competitive qualities are based on low-cost heat generation or heat recycling from strategic heat resources. Economies of scale, waste utilization, or combined production make centralized heat generation a cheaper alternative to local generation. Though heat production is cheaper, centralized production constitutes the need for heat transport. In general this means that for district heating to be competitive, the money saved through centralized production must be equal or higher than the amount spent on transport.

The previously mentioned statement provides a basic picture of the competitiveness of district heating; however, more aspects are important considering its cost division.

District heating systems require a large initial investment compared to traditional heating systems. Therefore district heating systems should be considered as a long-term investment, so adequate time is reserved for the distribution of cost. These long term investments are also accompanied by the addition of a higher risk. Long term investments are less predictable than short term investments and this should be accounted for in the cost calculation. Furthermore district heating systems require a higher amount of maintenance and changes to the systems operational environment require a response in the systems setup.

Generally speaking district heating systems favor urban settings with a high centralized heat demand. Preferably these regions are of significant standard as to limit long term risks (Urban Persson, 2011).

2.5. CONCLUSION

The global energy consumption has been going through a steady increase which is not likely to change. In the current energy system more than half of the total gathered energy is lost as waste heat due to inefficiency at an end use state or in energy conversion.

Because of the effect of energy consumption on the environment and the depletion of fossil fuels, a global effort has taken hold to increase energy efficiency measures and bring down the emission of greenhouse gasses. District heating has proved to be an effective method of utilizing otherwise wasted heat and therefore increase energy efficiency. District heating also offers future advantages when taking into account the synergy between DH systems and irregular renewable energy sources with the ability to store energy in large tanks.

In order to be viable DH systems requires a high centralized heat demand which diminishes the percentage of transport cost in relation to the production cost. Local energy efficiency measures like improved insulation are decreasing the average amount of heat required per household. Conversely urbanization is increasing the percentage of the population living in cities. The total heat market is therefore expected to decrease while undergoing a shift from decentralized to centralized heat demand.

The district heating market is expected to grow significantly over the following years in countries with a centralized heat demand and cool environment. It is also expected to play a major part in energy efficiency measures globally and is very compatible with other energy efficiency measures.

3. DISTRICT HEATING

This chapter focuses on general aspects and characteristics of district heating and its environment. The first paragraph provides readers with a global insight in district heating systems, its functionality and history. The second paragraph describes the future competitiveness of district heating and denotes its relevance. The third paragraph focuses on heat recovery systems and the addition of waste heat energy in a district heating system.

3.1. HISTORY

District heating encapsulates heat supply systems utilizing centralized heat generation which uses a heat carrier to transport the heat between facilities. District heating systems start with the recovery of heat from either dedicated heat production or more commonly, waste heat. Depending on the heat carrier the system is powered by a pump which transports the recovered heat to a heating network through pipes. Facilities are able to extract heat from the supply pipes using a heat exchanger. The exchanger transfers the heat from the original network to the facilities network. The heat carrier is then transported back to the centralized heat generator through return pipes.

District heating was first introduced in the 1880's in the USA. These first generation systems used steam as a transportation method and took advantage of excess steam from power plants. The steam pipes were installed in concrete ducts and had condensate return pipes. The biggest problems with these systems were substantial heat losses, corrosion and safety hazards due to the high pressure. Nowadays steam is rarely used though some steam operated systems still exist. (Henrik Lund, 2014)

The second generation of systems was driven by pressurized hot water, mostly over 100 ºC. These systems emerged in the 1930s and largely replaced the first generation steam systems. It uses water at temperatures over 100 ºC as a heat carrier and used hot water pipes in a concrete duct as transportation method.

In the 1970's the third generation of systems emerged. These systems lowered the temperature of the heat carrier to below 100 ºC which increased efficiency by reducing heat loss. The system also features pre-isolated transport pipes which are buried directly into the ground. These systems are also referred to as the "Scandinavian district heating technology" since many of its manufacturers are Scandinavian (Henrik Lund, 2014).

The next generation of district heating should focus on the synergy between district heating and other energy efficiency measures. Lund (2010) concludes that the role of district heating is significant but needs to be further developed to decrease grid losses and exploit synergies. Renewable energies as well as CHP production and energy conservation is an essential factor in the climate change response in Europe as well as many other countries (H. Lund, 2010).

3.2. ENERGY SUPPLY

Introduction

The following paragraph sets out to create an outline of the changes district heating energy supply has undergone. The Swedish energy market is used as a guideline since it is most representative of the district heating market in general.

Traditional Heat Supply

In the past decades district heating fuel and energy sources have experienced a lot of changes due to the changing energy market. Prices and availability of fuel have driven the preferred fuel source for district heating as well as improvements in technology. Until the 1980's oil was the most preferred energy source. After the 1980's solid fuels gained popularity as well as electric boilers, large heat pumps and waste heat recovery. The use of solid fuels for generation created an independence from crude oil and had significant environmental advantages (Eriksson, Finnveden, Ekvall, & Björklund, 2007). Solid fuels also created problems however, especially considering boiler design. Most fuels needed a specific boiler design due to complications in for example the chemical composition of their emissions which need filtering for the corrosiveness of their combustion cycle.

Coal boilers were considered the standard from which other designs originated. Coal is globally the most used fuels source because of its relative abundance and ease of use. Despite these advantages environmental policies steered the popularity of fuels towards biomass and garbage as a fuel source instead of fossil fuels. Figure 7 displays the trends in fuel sources over the past 40 years.

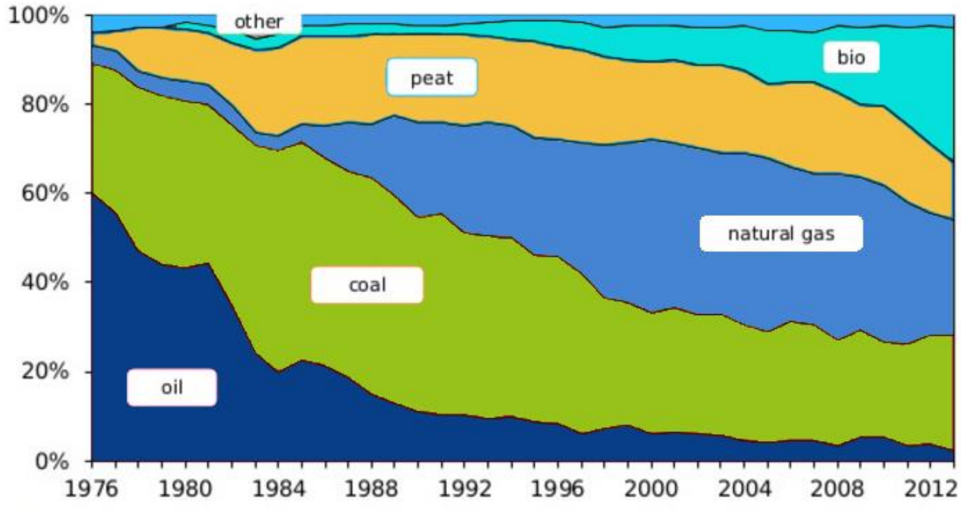

Figure 7: Fuels for district heat and cogeneration ***(Finnish Energy Industries, 2014)***

CHP plants

Combined Heat and Power (CHP) generation is one of the fundamental principles in district heating systems. The ability to recover otherwise wasted heat was the initial cornerstone for district heating systems and was the primary concept that made district heating viable. Although CHP generation does not directly influence this project it plays a major role in district heating systems and requires a basic understanding for the justification of district heating systems.

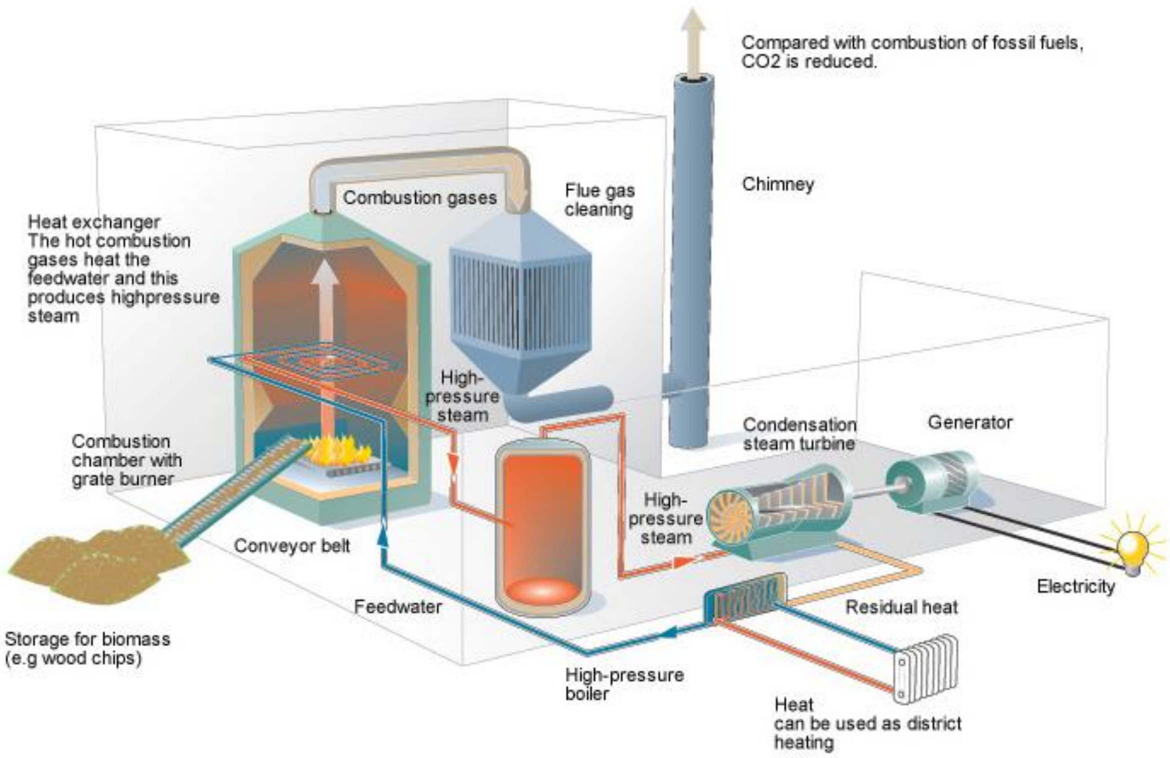

Figure 8: Schematic example of a CHP plant running on biomass fuel (Energyland, 2015)

Figure 8 shows a schematic picture of a CHP plant running on biomass fuel. Although a variety of CHP plants exist the basics are relatively similar. Fuel is burned in a combustion chamber. The hot combustion gases that are released during this process heat the feed water in a heat exchanger and produce high pressure steam. The high pressure steam is transferred to a steam turbine which powers an electricity generator. Any residual heat from the turbine is directed to another heat exchanger and recovered to be used for district heating. The feed water is then redirected to the combustion chamber. The combustion gases are cleaned and leave the system through a chimney. Sometimes these gases are condensed in order to retrieve any latent heat. Often this requires measures to prevent corrosion from resulting liquids such as sulfuric acid. According to the international energy agency, co-generation has an average conversion efficiency of 58%, considerably higher than a conventional thermal plant's 36% (Taylor, 2015).

CHP plants also play a major part in waste management. Due to many impurities in waste it cannot be burned at high temperatures as this would result in highly corrosive substances. This makes waste incineration ineffective as a fuel for dedicated energy production. CHP however enables waste to be a financially viable alternative for other fuels. In Europe 10,4 % of heat in DH systems is produced by waste incineration (Holmgren, 2006).

The ability to recover heat and the ability to use fuels that would otherwise be useless make CHP a very resource efficient technology. Considering the Kyoto protocol's efforts to reduce carbon emissions, among which the allowance to trade in emissions, CHP plants gain extra appeal. The ability to trade in emissions allows an extra financial benefit to CHP plants. The reduction in CO_2 emissions through energy efficiency can be traded and can result in financial stimulation towards CHP plants. The EU has committed to reduce emissions to 20% below 1990 levels by 2020. Holmgren (2006) claims that as long as coal based power plants are the marginal electricity producers, the combination of district heating and CHP can significantly contribute to reaching these goals. Figure 9 displays the percentage of total electricity production that is produced by CHP plants.

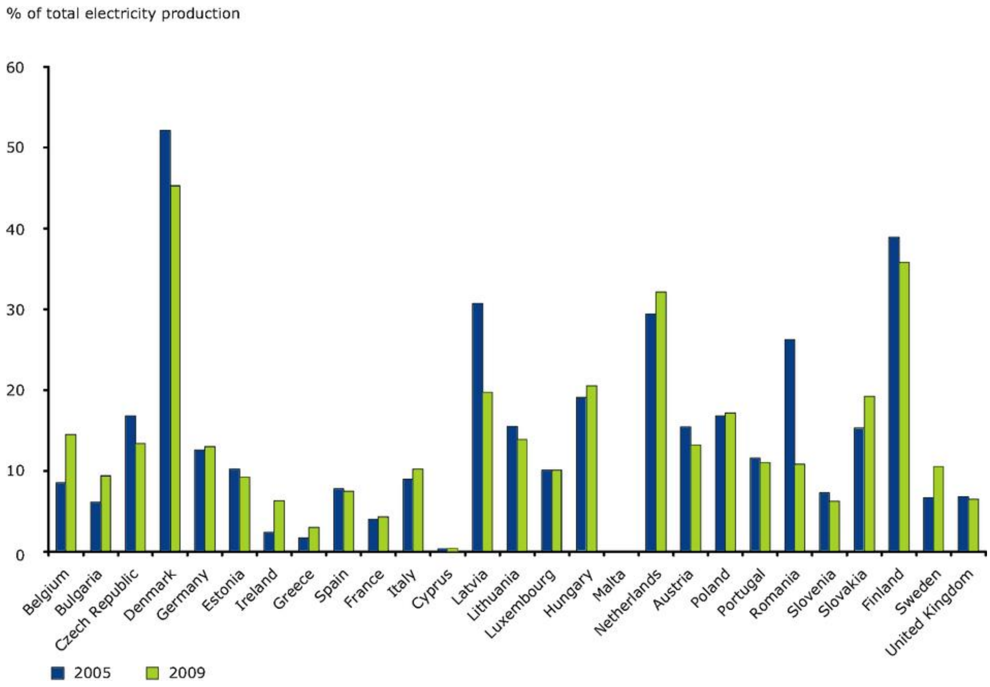

Figure 9: CHP percentage of total electricity production (Erra & Fortum, 2011)

Policies

Compared to local end-use heating systems, district heating systems are far more dependent on national and international policy. District heating systems require large investments, giving them a longer turnaround period. Their scale, both physically and financially, create long term risks. The International Energy Agency and European Union both agree on the fact that the combination of CHP and district heating systems "can be an essential part of strategies for greenhouse gas emissions mitigation and energy security" (Taylor, 2015)(Euroheat & Power, 2005) yet the market share of CHP has shrunk from 14% to 10%.

The European Union recognizes this problem and is planning a policy push via the Energy Efficiency Directive. Member states will be required to submit an assessment of CHP and district heating application potential. In the "Framework strategy for a resilient Energy Union with a forward-looking climate change policy" the EU further acknowledges the role of district heating in European environmental efforts. The European Commission Communication states "the upcoming heating strategy is expected to set out measures aimed at better exploiting the huge efficiency gains from District Heating and Cooling and facilitating investment in the heating sector" (Euroheat & Power, 2015). The EU also stimulates the adoption of national policies to further the development of district heating systems. Varying support measures are already in place which can serve as an example for other nations (Euroheat & Power, 2005).

Waste heat recovery

Waste heat recovery concerns the recovery of waste heat for utilization purposes, generally for district heating systems. The idea of waste heat recovery is in line with the fundamental principle of district heating yet hasn't gained much momentum in terms of market share. Studies like Johnson et al. (2008) show a huge part of energy is wasted in the industrial sector. Their research found 20-50% of energy in metal and non-metallic mineral manufacturing is lost as waste heat and Sogut et al (2008) found that a cement plant in Turkey wasted 51% of the process heat. These examples would lend themselves well for the use of waste heat recovery.

There has been a lot of research on the recovery and reuse of waste heat in the industry sector but these studies have mostly been limited by two factors. First of all the studies mostly focus on the recovery of heat for internal reuse or reuse within the industry sector (Cunningham & Chambers, 2002)(Drak & Adato, 2014). Secondly the waste heat considered in these studies is generally high grade (hotter than 200 degrees Celsius) since lower temperature waste heat is economically and technically more difficult to reuse (Fang, Xia, Zhu, Su, & Jiang, 2013). Energy intensive industries such as; petroleum processing, chemical and non-metallic mineral manufacturing, smelting and metal pressing are able to recover and reuse high grade waste heat but are still losing about 50% of their heat, mostly as low grade waste heat (Fang et al., 2013). Furthermore, lower energy intensive Industries produce recoverable low grade waste heat as well. Although low grade waste heat is ineffective for reuse in the industry sector it is well suited for use in district heating systems especially low return water temperature district heating systems. These district heating systems are significantly better at exploiting sustainable energies as well as capturing surplus heat than conventional systems (Fang et al., 2013).

To indicate the potential of industrial waste heat recovery and district heating systems Fang et al. (2013) created a simple formula (1) called the coefficient for potential. The coefficient is defined as the ratio between the theoretical amount of waste heat and district heating demand.

(1) $$\eta_{th} = \frac{E_{th}}{E_{dh}}$$

In this formula η_{th} indicates the potential for utilizing waste heat in the district heating system. Three stakeholders have to be considered within a waste heat recovery system for district heating. The industrial players provide the waste heat for a small fee to heat-supply enterprises; in return they receive environmental certificates or subsidies. The district heating enterprises are able to utilize the recovered heat and sell it to the public in return for a normal heating fee. The public is able to use environmentally responsible products and gives a good reputation to the industrial players. This interaction between the different players is displayed in Figure 10.

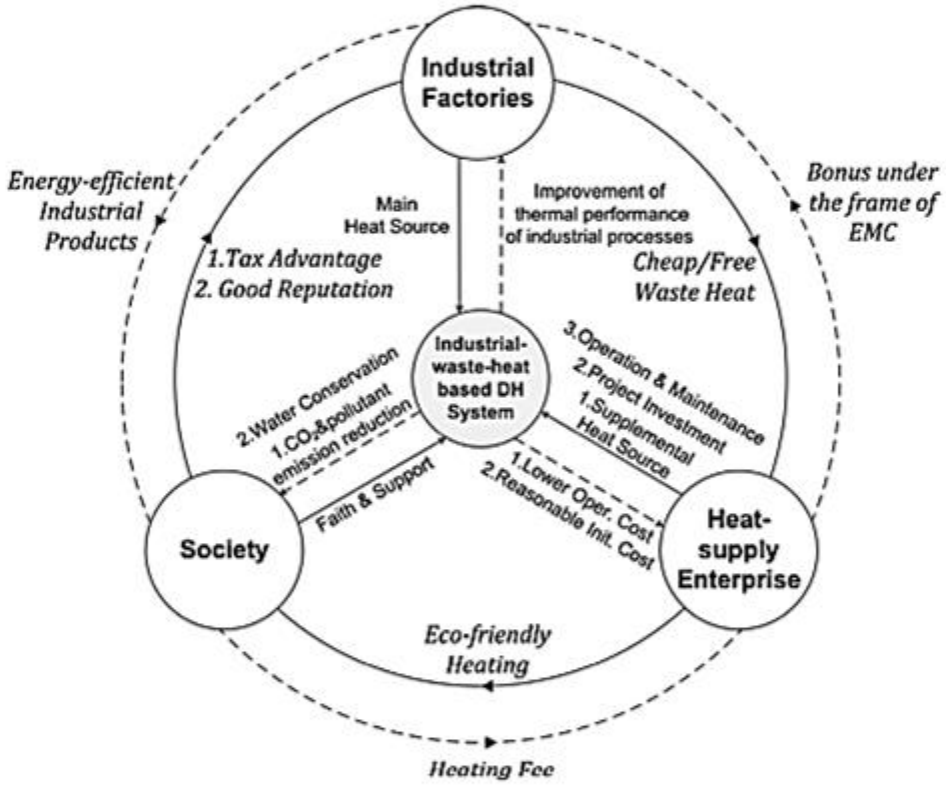

Figure 10: Relationship among participants of industrial-waste-heat based DH system (Fang et al., 2013)

Technologically the recovery of waste heat is relatively simple, especially when the waste heat temperature is within an acceptable range of the heat carrier temperature. In this case a simple heat exchanger is able to recover most heat and supply it to the district heating system. If the waste heat is of a very low temperature, an absorption heat pump (AHP) has to be installed to recover the heat. In most industries the supply of heat is a secondary activity and does not receive first priority. Therefore waste heat production is relatively unstable in that setting and vulnerable to adverse conditions, e.g. severe weather, equipment failure, stagnant market etc. (Fang et al., 2013), consequently a secondary heat production unit such as a heating boiler should be installed to cover a decrease in waste heat production or peak demands.

3.3. DISTRIBUTION

Heat is distributed in district heating systems through a system of pipes and nodes. Currently the most widely used pipes are flexible pre-insulated pipes which are generally installed underground beneath existing road structures. Multiple heat carriers are feasible for use within district heating but by far the most commonly used is softened or demineralized water. The purification of water is meant to increase conductivity and decrease oxidation (Frederiksen & Werner, 2013).

Within district heating systems substations are placed to control the flow and temperature to users. These substations are largely comparable to transformers in electric power engineering. Heat exchangers, mixing equipment and control valves control the output of temperature and pressure in the substations creating a manageable and consistent output.

In district heating systems hydraulics are generally separated. This means water flowing through the main line system will never enter buildings for heating. Heat is transferred from one system to the other through heat exchangers in the substations. Many layouts of separation are possible depending on cost, performance and temperature differences. Concerning the transport of heat, four major factors have to be considered; carrier temperature, heat loss, carrier size and flow velocity (Frederiksen & Werner, 2013).

Carrier temperature and heat loss
The temperature of the heat carrier is generally determined by the available energy supply. Some facilities are able to produce high temperatures while other facilities are only able to service low temperature heat carriers. Nevertheless heat carrier temperature has a big influence on the functioning of district heating systems. Systems functioning on extremely high temperatures (steam) endure problems with corrosion. The temperature of the heat carrier also determines the amount of power a system can produce given a set pipe diameter and flow velocity. High temperature heat has more functionality than low temperature heat and can for example be used for cooling purposes. Furthermore high temperature DH systems suffer relatively higher heat losses than lower temperature DH systems.

Heat loss is one of the major limiting factors to the size of district heating networks. A significant loss of heat will result in the dissipation of energy and will reduce the efficiency of the system. In comparison to local heat production the heat lost in transport should always be less than the production efficiency advantage from economy of scale in order for district heating to be more energy efficient. Therefore it is important to reduce the energy loss through distribution as much as possible.

The temperature decrease in distribution between two points can be calculated with the following formula:

$$\Delta t_s = -4 \cdot K \cdot L \cdot d_0 \cdot (t_s - t_a) / \left(v \cdot {d_i}^2 \cdot \rho \cdot c\right)$$

With the following parameters:

Δt_s = temperature drop in the supply flow between two intersection [°C]
K = heat transmission coefficient, with reference to the outer pipe surface [W/m^2K]
L = pipe length between the intersections [m]
t_s = supply temperature [°C]
t_a = ambient temperature [°C]
v = water velocity [m/s]
d_i = inner pipe diameter [m]
d_o = outer pipe diameter [m]
ρ = water density [kg/m^3]
c = specific heat capacity for water [J/kgK]

Some important factors that can be derived from the formula are the following. The amount of heat lost is dependent on the temperature difference between the heat carrier and its surroundings. Therefore a higher heat carrier temperature will result in a higher temperature difference and more heat loss. Moreover the diameter of the pipes influences the heat loss; a smaller pipe diameter will have a relatively greater surface area in contact with the environment in relation to its volume. In order to counter this effect smaller pipes need relatively more insulation in relation to their capacity and are therefore more expensive per capacity unit (Urban Persson, 2011).

Flow velocity and carrier pipe sizing.

As was mentioned in the previous paragraph the carrier temperature, flow velocity and carrier pipe sizing determine the power capacity of the distribution system. Determining the right choice of carrier pipe diameter and flow velocity is a complex issue (Frederiksen & Werner, 2013). The flow velocity describes the speed at which the carrier liquid travels through the piping. Fluid dynamics dictates that the resistance of the pipe on the water flow creates a pressure drop between two points. A higher flow velocity results in a larger pressure drop. However, higher flow velocity increases the power capacity of the network and may therefore be required to meet a specific power demand. Determining the balance between these factors requires extensive calculations and is too complex to accurately determine in this research. Consequently the flow velocity shall be determined using the graph in Figure 11 which displays the recommended design flow velocity in accordance with the inner pipe diameter.

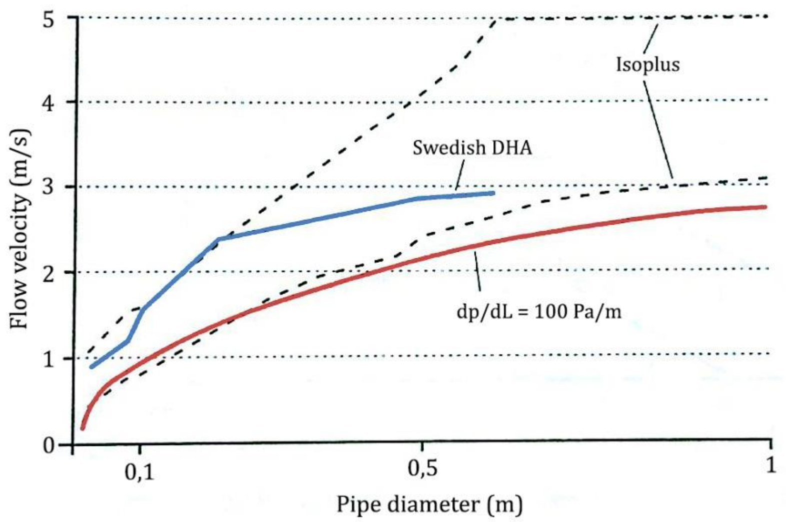

Figure 11: Design flow velocity in accordance with various recommendations (Frederiksen & Werner, 2013)

3.4. ECONOMICS AND COST

'The business concept of DH systems is derived from the advantages gained by economics of scale and heat recycling. Centralized heat production from strategic sources should decrease production costs enough to cover cost of distribution and customer benefit; this is displayed in Figure 12.

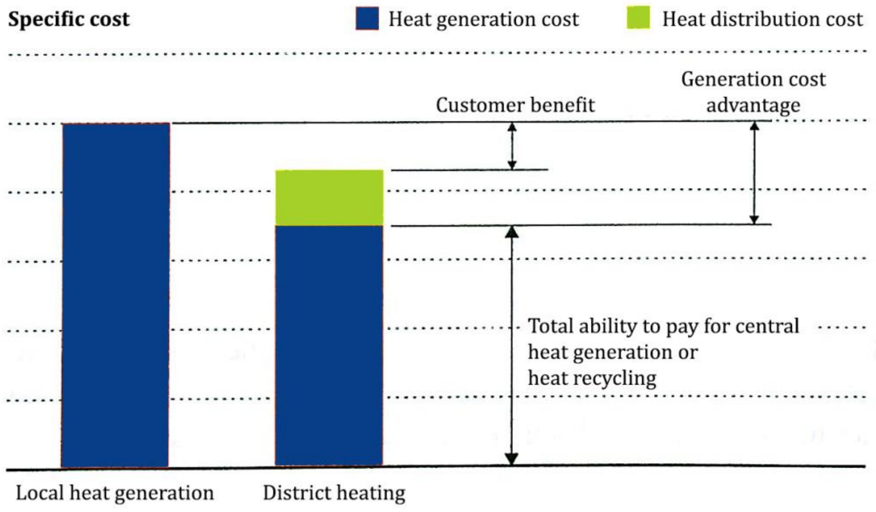

Figure 12: The general cost situation for district heating compared to that for local heat generation (Frederiksen & Werner, 2013)

There are several essential economic issues that come into play when dealing with DH systems compared to traditional heating methods.

Firstly DH systems require high initial investment cost and require less operating costs than traditional systems. Therefore taking into account the duration of the project becomes a bigger factor in the financial situation. There is also more risk involved from uncertainties that can develop during this time, which can be translated into a higher cost of capital (Pirouti, Bagdanavicius, Ekanayake, Wu, & Jenkins, 2013). In order to properly evaluate the costs of these long term investments it is important to consider the investment in terms of net present value.

Secondly DH systems require expenses to be made for the transportation of heat. The costs associated with distribution can be divided into four categories of annual cost; the distribution capital cost, distribution heat loss cost, distribution pressure loss cost and the distribution maintenance cost (Frederiksen & Werner, 2013). The distribution capital cost represents the annual repayments of investment capital for the construction of the district heating network. The heat loss cost is determined by the amount of power that has to be produced in order to make up for the loss of heat. The distribution pressure loss cost is associated with the operating costs of the DH system and the distribution maintenance concerns maintenance on the constructed network.

Thirdly the contribution of DH systems to energy efficiency measures may warrant the allocation of subsidies. The availability and size of the subsidies differs per country and even per project. Furthermore subsidies might be available on different fronts, such as innovation within energy efficiency measures.

Finally DH systems require collaboration between the heat supplier and heat distributor which are often not the same company. In the effort of co-generation and waste heat utilization the allocation of benefits is often a difficult subject. For example, different taxes may apply to the use of fuel for electricity production and heat production. In a combined generation effort the allocation of costs or benefits from these tax differences plays a large role in the collaboration between the parties (Sjödin & Henning, 2004).

3.5. COOLING

The same technology used for district heating networks can be applied to district cooling networks. These networks function in a similar fashion to DH networks but with a cooled down heat carrier. These networks are the warm weather equivalent of DH networks and can generally be found in cities with a high average temperature such as Jeddah in Saudi Arabia.

Furthermore high grade waste heat from DH networks can be used for cooling with the aid of an absorption heat pump. Absorption heat pumps use a heat source to provide the energy that is required to drive the cooling process as opposed to electricity in a normal heat pump. In order to understand the absorption cooling process a basic comprehension of the principles in a heat pump is required. All heat pumps take advantage of the Charles' law, which states: "For a fixed mass of gas, at a constant pressure, the volume is directly proportional to the absolute temperature". Heat pumps use this principle to cool and heat a refrigerant at specific places in the cooling cycle. A regular heat pump uses an expansion valve to decrease the pressure of the refrigerant which also lowers its temperature. Heat is than absorbed from the desired location with the cooled refrigerant and directed to a compressor. The compressor increases the pressure of the refrigerant which also increases its temperature. The refrigerant which is now at a high temperature and high pressure is directed to second location where it can release some of its heat. Afterwards the refrigerant passes through the expansion valve and the cycle is repeated.

Comparable to a compression heat pump absorption coolers use the principle of pressure difference to power the cycle. Absorption coolers use two working fluids; an absorbant and a refrigerant. The refrigerant is a highly hydrophilic substance with a low boiling point, such as ammonia and lithium bromide. The absorbant is water.

The absorption heat pump is based on the fact that one specific pressure and temperature corresponds to one solubility value of a solution. The system runs through 4 steps as demonstrated in Figure 13. In the generator the solution of absorbant and refrigerant is run through the heat supply, which in the case of district heating systems is the high grade waste heat, causing the refrigerant to evaporate out. The refrigerant flows to the condenser and the absorbant is transported to the absorber. In the condenser cooling water is used to absorb heat from the refrigerant and transfer it to a cooling tower. The refrigerant condenses from the loss of heat and is transported to the evaporator through a pressure valve. The refrigerant is released in the evaporator, which is under low pressure, causing the refrigerant to vaporize and cool the chilled water. Finally the evaporated refrigerant flows to the absorber where it is brought back in connection with the absorbant. The refrigerant is absorbed into the absorbant and transported back into the generator completing the cycle (Shecco, 2012)(Bhatia, 2012). The principle of the absorption heat pump is the same as a normal heat pump. Both use condensation and evaporation of a refrigerant to absorb and dispense heat.

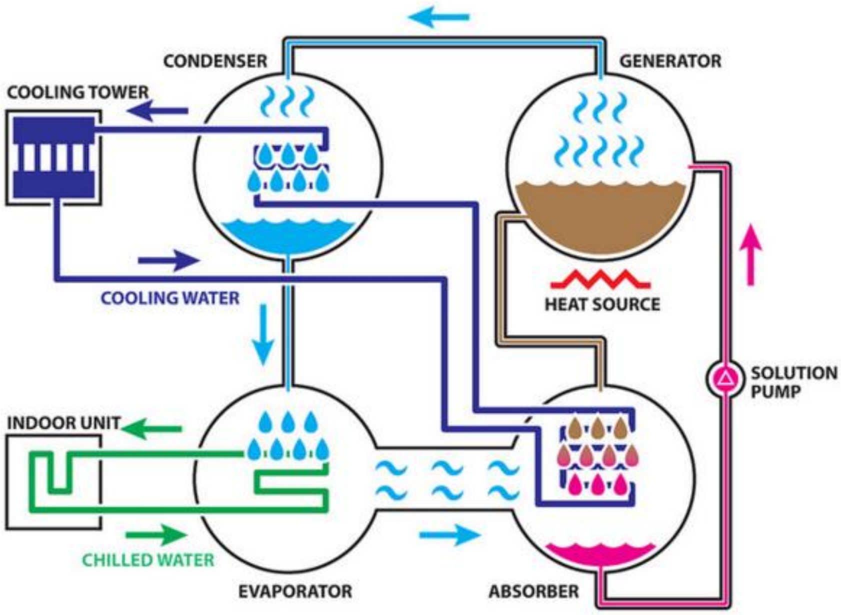

Figure 13. Schematic absorption cycle (Shecco, 2012)

3.6. FUTURE CHALLENGES

Despite the existence of district heating networks for over a century and its many valuable merits district heating is still a niche technology. There are few consultants available regarding these systems and the availability of information to consumers is limited (Frederiksen & Werner, 2013). Furthermore a lack of awareness diminishes the pull consumers have on the market and limit the utilization of opportunities suited for district heating networks.

Legislation from the government aiding in the development of district heating networks will also help in the growth of district heating networks. Measures that reduce the risk of these long term investments and subsidies stimulating development will aid in the realization of networks.

Technologically district heating networks has room to grow as well. Presently the energy industries are still largely regarded as separate sectors. In the future sustainable developments in the energy sector will bring various energy industries closer together. Patrick Favre-Perrod speaks of a future energy network which should replace the current electricity network (Favre-Perrod, 2005). This network would allow synergy between different types of energy, such as electricity, heat and readily producible fuels such as hydrogen. Within such a network, district heating networks can function as mitigation of the electricity grid, using electricity to power the system when demand is low and storing energy as heat within the network (Lund, Möller, Mathiesen, & Dyrelund, 2010). District heating networks can also integrate energy exchange systems in which a difference in temperature requirement of buildings can be used to exchange energy instead of using an outside source.

3.7. CONCLUSION

District heating systems have existed for over a century and encapsulate installations which transport heat from central heat production facilities to consumers. District heating systems gain their competitive advantage from economies of scale and the ability to capture heat that would otherwise be lost. Modern implementation of district heating systems is still limited outside of the Scandinavian countries but technologies are increasing rapidly and more countries are beginning to see the environmental benefits of district heating systems. Combined heat and power generations has allowed the energy efficiency in power production facilities to improve significantly and has created the option for fuel sources that would be unviable under conventional power production. One of the disadvantages of district heating systems is the uncertainty involved with long time investments. Because of the relatively high investment cost district heating systems are inflexible in reactions to market conditions. District heating systems combine well with future technologies such as smart grids giving them more functions in the future.

4. CASE STUDY

4.1. INTRODUCTION

This chapter describes the further implementation of the research. In order to reach the goal stated in chapter 1 further development of the case study is required. This chapter describes the actions performed during the case study and substantiates the choices made. An elaboration is made on the studied case and the decision for the base model used for the calculations. Furthermore insight is given in how conclusions can be drawn from the use of the model.

4.2. ROTTERDAM HEAT NETWORK

This research focuses on an existing district heating network in Rotterdam owned and operated by a public-private partnership called Warmtebedrijf. Work on this network started in the spring of 2012 and finished in 2013 (VolkerWessels, 2012). The network utilizes residual heat from industrial processes in the Rotterdam Port to transport it to households and other consumers across Rotterdam. The network is about 26 kilometers long and has a closed circuit system with supply and return pipes running along the full length of the transport line. The pipes have an inner diameter of 400 mm and an outer diameter of 500mm which allows them to transport heat at a capacity of 105 MWth (thermal Watt) of relatively high temperature heat. The supply temperature is around 98 degrees coming into the transport system with return temperatures between 50 and 70 degrees. Altogether the network can supply heat to about 50,000 households (Warmtebedrijf Rotterdam, 2015).

Heat in the network is provided by Europe's largest waste and power plant, AVR Rozenburg, which processes waste and converts it into usable forms of energy such as heat, electricity and steam (AVR, 2015). The energy released in this process is captured through heat exchangers and purchased by Warmtebedrijf as heated water. This particular project has reached a sustainable energy ratio of 50% resulting in a reduced CO_2 emission of 80 kilotons annually.

KPN owns a datacenter located about 1 km from the central heat distribution pipe. This is a small distance for district heating systems which makes the area eligible for connection to the network. The datacenter has a significant yearly cooling demand which is transformed into a heating demand with an absorption cooling system. Two other consumers with a significant heat demand are located nearby with an expected consumption high enough to warrant collaboration. More information on these consumers is provided in chapter 7.

A financial calculation of the network extension is required to determine the viability of the project. Warmtebedrijf also performs a calculation since they are the developing company. The calculation for KPN is required to improve their position in negotiations by giving them a second opinion on the costs. Comparison with the calculations from Warmtebedrijf is used to determine the viability of using this calculation method for future endeavors. The calculations are performed from the perspective of Warmtebedrijf. Therefore KPN and other businesses are referred to as consumers and purchasing costs from these consumers are denoted as revenue.

4.3. BASE MODEL

Literature study has shown the complexity of district heating systems and subsequently the complexity of the financial calculation of these systems. Traditionally determining the financial viability of a district heating project is accomplished with individual calculations and estimations. There are a few problems with this method. Firstly it is a slow process, and an increment in details determines the precision of the calculations. Secondly this method requires extensive knowledge of the project details and can't be performed by secondary parties. Finally this method does not necessarily provide insight in the relation between certain parameters and their effect on the overall outcome.

In order to determine the financial viability of the case as described above a financial optimization model is used. This model is based on a model created by Johannes Dorfner and Thomas Hamacher in their research "Large-Scale District Heating Network Optimization". The model created by Hamacher and Dorfner (2014) uses cost optimization to determine the structure and size of a district heating network in a specific area (Dorfner & Hamacher, 2014). Whereas the base model uses cost optimization to determine which areas to service, this research uses cost optimization to determine under what circumstances network extension can be profitable. A detailed explanation of the models functioning is provided in the next chapter.

4.4. SIMULATIONS

The financial optimization model as described in the previous paragraph is used to determine the financial viability of the network extension. In order to run simulations with the model, parameters have to be determined. These are based on literature research and calculations. Since a model always has a margin of error, the effect of the parameters on the financial outcome is determined. This results in a sensitivity analyses which describes the influence of each parameter on the outcome in relation to its estimated accuracy.

5. MODEL BASIS

5.1. INTRODUCTION

This chapter explains the functionality of the model used for the simulations. The general idea behind the model is explained followed by the major equations and restrictions.

The model that is described in this chapter is based on a network optimization model from Dorfner and Hamacher (2014), which is further developed by Mazairac (2015). The model uses vertices and edges to create a grid derived from a street map. This grid represents the possible locations for pipelines to be installed and contains the consumers and suppliers. Using cost optimization, the best option for pipe installation and service is simulated.

5.2. VERTICES AND EDGES

Vertex graph theory is used to model the pipeline structure of the district heating system. The nodes or corners in the district heating layout are modeled as vertices. As explained in the previous chapters the most logical location for pipelines is beneath a road structure. Therefore the network of vertices and edges that are viable options for the pipelines should be derived from the road structure of the considered area. In case of existing pipes outside the road structure these should be considered as well.

Vertices and edges are used in mathematics to define two-dimensional figures. Vertices can be considered corners or nodes and is a place in the figure where two or more lines or edges meet. The edges are the lines between two vertices. By inputting the length of the edges and which vertices they connect a mathematical figure is constructed that can be used for calculations.

The vertices are indexed as υ_i, corresponding to the intersections and endpoints in the road and pipeline structure. The set of vertices is denoted as V. The lines or edges connecting the vertices are denoted as $e_{ij} = (\upsilon_i, \upsilon_j)$ with $i \neq j$. The set of edges is denoted as E in which each edge represents the supply and return pipes, therefore two lines are modeled in each edge *e;* e_{ij} and e_{ji}.

5.3. ALLOCATION OF POWER DEMAND AND SUPPLY

The vertices can represent power sources within the grid. All vertices are given a maximum thermal output capacity Q_i^{max} in Watt. For most vertices this value is set to zero to denote that no production capacity is available. For the power sources vertices however this number should be equal to the maximum production capacity of the power supply. The set of *source-vertices* is defined by V_0 so V_0 is a subset of V.

Power demand is represented within the nodes by the parameter $p_{d_i}^{demand}(t_n)$. The parameter returns a specific demand per time, the demand can therefore vary over time and a demand profile can be used. The demand parameter in turn has influence on other variables such as required pipe size. Power demand is always denoted as heating demand. Cooling demands are therefore converted to heating demands.

5.4. PARAMETERS

Pipeline

As mentioned in the previous chapter section power demand is denoted by parameter $p_{d_i}^{demand}(t_n)$. The length of the edges is given by parameter $l_{e_{ij}}$. The existence of pipelines in edges has to be considered as well and is denoted by parameter $\epsilon_{e_{ij}}$ with a value of 1 for existing pipelines and a value of zero when no pipelines exist. The maximum thermal power capacity, which is dependent on the pipe diameter, is denoted by $p_{e_{ij}}^{lim}$ (W) with a maximum thermal output capacity $p_{so_i^c}^{out,lim}$ for vertices.

Economics

All variables denoted as c (including subscript) represent economic variables. The investment costs required for building the pipeline network are represented by c_e^{fix} for the fixed costs per meter and c_e^{var} for the variable cost per Watt meter (Wm). The operating and maintenance costs are determined by c_e^{om} as cost per meter per year. Heat generation cost and revenue are denoted by $c_{so_i^c}^{en}(t_n)$ and $r_{d_i}^{en}(t_n)$ as cost/revenue per Watthour (Wh).

Technical

Other parameters that have to be considered regard technical aspects of the pipeline system such as thermal losses and load hours. The thermal losses are divided in fixed losses $\theta_{e_{ij}}^{fix}$ and variable losses $\theta_{e_{ij}}^{var}$. The parameters α and τ are dimensionless and quantify the time effects on the simulation. Since all calculations are denoted as costs per year the simulations which simulate a single day need to take this into account when determining the costs. Parameter α considers the annual cost of long term investments and is influenced by the considered term and discount factor. The parameter τ influences the annuity of the daily activities such as revenue and production cost, the value of τ is influenced by the simulated duration. In the case of a 1 day simulation τ equals 365.

5.5. VARIABLES

The binary decision variable $x_{e_{ij}}$ determines the placement of a pipe on edge $\epsilon_{e_{ij}}$. If $x_{e_{ij}}$ is given a value of one a pipe must be built and there has to be a power flow $P_{e_{ij}}^{in}(t_n)$ in the direction i → j into the pipe. The demand and thermal losses along the edge determine the total loss of power in that edge which is subtracted from $P_{e_{ij}}^{in}(t_n)$ to determine the power flow going out $P_{e_{ij}}^{out}(t_n)$. The variable $p_{so_i^c}^{out}(t_n)$ represents the power production in power source *i*.

5.6. EQUATIONS

The cost function is made up of the total investment cost per year, the cost for operation and maintenance, cost of heat generation minus the revenue for delivered heat for the period of one year.

Following derived parameters are used for this equation in order to shorten its length: k_{SO^c}, k_E, $k_{SO^c}^{en}$, $u_{D^{nc}}^{en}$. These parameters are further exemplified below.

The general function for the model is defined by formula (1) in which z is the yearly cost of the district heating network:

$$(1) \qquad z = k_{SO^c} + k_E + k_{SO^c}^{en} - u_{D^{nc}}^{en}$$

The costs of the source k_{SO^c} are defined in formula (2.1). Formula (2.2) determines the annual fixed costs $k_{so_i^c}^{fix}$ of a production unit. The fixed cost $c_{so^c}^{fix}$ is annualized with the annuity factor α and multiplied with the source existence parameter. The operation and management costs are then added to make up the annual fixed costs. It should be noted that when the production unit already exists, the pipe existence parameter $\epsilon_{so_i^c}$ has a value of one and therefore no fixed costs are ascribed to that production unit whilst still ascribing operation and management cost to that unit if used. The decision for use is determined in formula (2.1) with the multiplication of the decision variable $x_{so_i^c}$. The annual variable costs $k_{so_i^c}^{var}$ are determined in a similar fashion, shown in formula (2.3). The variable costs are dependent on the maximum power capacity $p_{so_i^c}^{max}$ of the production unit for the final source cost. The sum of costs for all production units combined makes up variable k_{SO^c}.

$$(2.1) \qquad k_{SO^c} = \sum_{so_i^c \in SO^c} \left[k_{so_i^c}^{fix} * x_{so_i^c} + k_{so_i^c}^{var} * p_{so_i^c}^{max} \right]$$

$$(2.2) \qquad \forall so_i^c \in SO^c: k_{so_i^c}^{fix} = c_{so^c}^{fix} * \alpha * \left(1 - \epsilon_{so_i^c}\right) + c_{so^c}^{om}$$

$$(2.3) \qquad \forall so_i^c \in SO^c: k_{so_i^c}^{var} = c_{so^c}^{var} * \alpha * \left(1 - \epsilon_{so_i^c}\right)$$

k_E denotes the cumulative edge costs per year (€/a) and is defined in formula (3.1, 3.2 and 3.3). The edge cost consists of the variable and fixed edge cost. Formula (3.2) represents the annual fixed costs in and edge and is found by multiplying the length of that edge with the fixed cost per meter and annualizing it using the annuity factor. The pipe existence parameter functions identical to formula (3.2), lastly the fixed costs for operation and maintenance are taken into account by multiplying the per meter cost with the length of the edge. The variable investment cost $k_{e_{ij}}^{var}$ is defined in formula (3.3) and is calculated using the same principle. The variable cost per meter is multiplied by edge length, annualized and multiplied by zero in the event of a pre-existing pipe. Finally the total edge costs are determined by multiplying the variable cost with the maximum pipe capacity and multiplying the fixed edge cost with the decision variable $x_{e_{ij}}$. Note that $x_{e_{ij}}$ is a decision variable determining the use of the edge whereas $\epsilon_{e_{ij}}$ denotes the previous existence of the pipe.

$$(3.1) \qquad k_E = \sum_{e_{ij} \in E} \left[k_{e_{ij}}^{fix} * x_{e_{ij}} + k_{e_{ij}}^{var} * p_{e_{ij}}^{max} \right]$$

(3.2) $\forall e_{ij} \in E: k_{e_{ij}}^{fix} = c_e^{fix} * l_{e_{ij}} * \alpha * \left(1 - \epsilon_{e_{ij}}\right) + c_e^{om} * l_{ij}$

(3.3) $\forall e_{ij} \in E: k_{e_{ij}}^{var} = c_e^{var} * l_{e_{ij}} * \alpha * \left(1 - \epsilon_{e_{ij}}\right)$

Heat generation costs $k_{SO^c}^{en}$ are determined by the following formula (4). This formula says that for all source nodes so_i^c and all time units t_n the annual heat generation costs $k_{so_i^c}^{en}$ at time (t_n) is determined by multiplying the heat generation costs per W $c_{so_i^c}^{en}$ with annuity factor τ and length of time units Δt to determine the generation costs of the annual thermal energy output.

(4) $\forall so_i^c \in SO^c: \forall t_n \in T: k_{so_i^c}^{en}(t_n) = c_{so_i^c}^{en}(t_n) * \tau * \Delta t$

The revenue from consumers $u_{D^{nc}}^{en}$ is determined in formula (5). This formula is constructed similarly to formula (3). The revenue from consumer d_i at time t_n is equal to the revenue $r_{d_i}^{en}$ multiplied by the annuity factor τ and length of time units Δt.

(5) $\forall d_i \in D: \forall t_n \in T: u_{d_i}^{en}(t_n) = r_{d_i}^{en}(t_n) * \tau * \Delta t$

5.7. CONSTRAINTS

Vertex equation

In accordance with the first law of thermal dynamics all energy in the system must be accounted for. In each vertex the sum of all outgoing power to neighbor vertices $p_{e_{im}}^{in}$ at time (t_n) plus the consumption of node i $p_{d_i}^{in}$ at time (t_n) must be met with an equal amount of incoming power $p_{e_{mi}}^{out}(t_n)$ minus the power created in node i $p_{so_i^c}^{out}(t_n)$. Neighboring vertices are defined as $m \in N_i$ with m representing each adjoining vertex of vertex i. Formula (6) displays this constraint. The formula is slightly counterintuitive in that the incoming power of node i is denoted as the outgoing power from the edge *im*.

(6) $\forall v_i \in V: \sum_{m \in N_i}\left[p_{e_{im}}^{in}(t_n)\right] + p_{d_i}^{in}(t_n) - \sum_{m \in N_i}\left[p_{e_{mi}}^{out}(t_n)\right] - p_{so_i^c}^{out}(t_n) \leq 0$

Edge equation

For each edge a formula (7.1) is installed to determine the heat losses in that edge. The formula denotes that the power input of an edge $P_{e_{ij}}^{in}(t_n)$ is equal to the power output of an edge $P_{e_{ij}}^{out}(t_n)$ plus the fixed $\delta_{e_{ij}}$ and variable heat losses $\eta_{e_{ij}}$. The formula includes a binary decision variable x_{ij} which combined with formulas (12.1 and 12.2) effectively reduces the power flow to 0 if the pipe is not used. Formula (7.2) indicates the variable heat losses in the pipe. Note that $\eta_{e_{ij}}$ does not represent the actual variable heat loss but rather subtracts the variable power losses that occur in edge e_{ij} from P_{ij}^{in} when multiplied with $P_{e_{ij}}^{in}(t_n)$. Here variable heat loss in W per Wm is multiplied with the edge length for power loss per W. In order to subtract the variable power loss from P_{ij}^{in} this value is subtracted from 1 and multiplied with the incoming power value. The fixed heat losses $\delta_{e_{ij}}$ are calculated in formula (7.3) by multiplying the fixed heat losses in Watt pet meter $\theta_{e_{ij}}^{fix}$ with the edge length $l_{e_{ij}}$.

(7.1) $\forall e_{ij} \in E: \eta_{e_{ij}} * P_{e_{ij}}^{in}(t_n) - P_{e_{ij}}^{out}(t_n) = \delta_{e_{ij}} * x_{e_{ij}}$

(7.2) $\eta_{e_{ij}} = 1 - l_{e_{ij}} * \theta_{e_{ij}}^{var}$

(7.3) $\delta_{e_{ij}} = l_{e_{ij}} * \theta_{e_{ij}}^{fix}$

(7.4) $\forall e_{ij} \in E: \eta_{e_{ij}} * P_{e_{ij}}^{in}(t_n) - P_{e_{ij}}^{out}(t_n) - \delta_{e_{ij}} * x_{e_{ij}} = 0$

Formulas (7.1, 7.2, 7.3 and 7.4) ensure that the model always considers a two-way flow. So if a supply pipe is built a return pipe is also built. In these formulas x represents a decision variable and can therefore only have a value of 0 or 1.

(8.1) $\forall e_{ij} \in E: x_{e_{ij}} = x_{e_{ji}}$

(8.2) $\forall e_{ij} \in E: x_{e_{ij}} - x_{e_{ji}} = 0$

Pipe and source capacity

The model has to take into consideration the capacity of the power source and pipes. These limits are modeled using the following constraints. Formulas (8.1 and 8.2) determine the maximum power source output $p_{so_i^c}^{out,max}$, which is set to the highest value of $p_{so_i^c}^{out}(t_n)$. Even though the formula indicates $p_{so_i^c}^{out,max}$ can have any value greater than $p_{so_i^c}^{out}(t_n)$ the effect a higher power output has on cost in combination with the cost optimization ensures the value is as low as possible. Formulas (9.1 and 9.2) indicate the maximum power output $p_{so_i^c}^{out}(t_n)$ has to be smaller than the source capacity $p_{so_i^c}^{out,lim}$. This formula also contains a decision variable indicating that if the source is not used no power will originate from it.

(9.1) $\forall so_i^c \in SO^c: \forall t_n \in T: p_{so_i^c}^{out}(t_n) \leq p_{so_i^c}^{out,max}$

(9.2) $\forall so_i^c \in SO^c: \forall t_n \in T: p_{so_i^c}^{out}(t_n) - p_{so_i^c}^{out,max} \leq 0$

(10.1) $\forall so_i^c \in SO^c: p_{so_i^c}^{out,max} \leq p_{so_i^c}^{out,lim} * x_{so_i^c}$

(10.2) $\forall so_i^c \in SO^c: p_{so_i^c}^{out,max} - p_{so_i^c}^{out,lim} * x_{so_i^c} \leq 0$

The edge capacity equations are constructed in a similar fashion to the source capacity equations. Formulas (11.1 and 11.2) indicate the max power flow $p_{e_{ij}}^{max}$ in the edge is set to the highest value of the incoming power flow $p_{e_{ij}}^{in}$. Formulas (12.1 and 12.2) ensure the max power flow does not exceed the pipe capacity $p_{e_{ij}}^{lim}$ and contains the decision variable $x_{e_{ij}}$ to stop power flow in case the pipe is not used in the model. The pipe capacity is determined by the diameter of the pipe.

(11.1) $\forall e_{ij} \in E: \forall t_n \in T: p_{e_{ij}}^{in}(t_n) \leq p_{e_{ij}}^{max}$

(11.2) $\forall e_{ij} \in E: \forall t_n \in T: p_{e_{ij}}^{in}(t_n) - p_{e_{ij}}^{max} \leq 0$

(12.1) $\forall e_{ij} \in E: p_{e_{ij}}^{max} \leq p_{e_{ij}}^{lim} * x_{e_{ij}}$

(12.2) $\forall e_{ij} \in E: p_{e_{ij}}^{max} - p_{e_{ij}}^{lim} * x_{e_{ij}} \leq 0$

Taking the formula's and constraints into account the model uses an iterative optimization program called Cplex which optimizes the cost z as described in formula (1). The result is the maximum obtainable revenue given the input values of the parameters under certain variable output values. For the model simulations the parameter values and subsequent variable values per simulation are provided in the report.

6. PARAMETER DETERMINATION

In order to effectively use the model basis as described in the previous chapter, parameter values need to be determined for the simulations. This chapter describes the parameters that are used for the simulation and the reasoning behind their valuation.

6.1. EDGE COST

Fixed and variable edge cost

Edge cost can be divided in the fixed edge cost c_e^{fix}, variable edge cost c_e^{var} and operation and management cost c_e^{om}. Pipe cost is dependent on the pipe diameter which in turn depends on the maximum power required in the pipe. Figure 14 displays a graph showing the cost for pipeline construction per nominal diameter (DN). The nominal diameter of a pipe denotes the inner diameter of a pipe. Four costs are displayed in the graph depending on the area of construction. This is because the cost of closing down roads and performing roadwork is higher in densely populated areas like the inner city. The area considered in this paper is a brown field area which is similar to an outer city area. The directionality constraint in the model ensures a two-way pipe system is built. Therefore the installation costs should be less than the costs displayed in the graph since road work only has to be performed once. As a result a slightly lower fixed edge cost should be considered. The equation describing the linear trendline shown in Figure 14 can be found trough interpolation of two data points in the graph. The outer city area equation is described in formula (1). Extracting the fixed cost from the formula results in formula (2) describing the variable cost with a fixed investment cost of €243,21.

(1) $c_e = 0{,}107(18{,}18 \cdot d_i + 2273).$

(2) $c_e^{var} = 1{,}94 \cdot d_i$

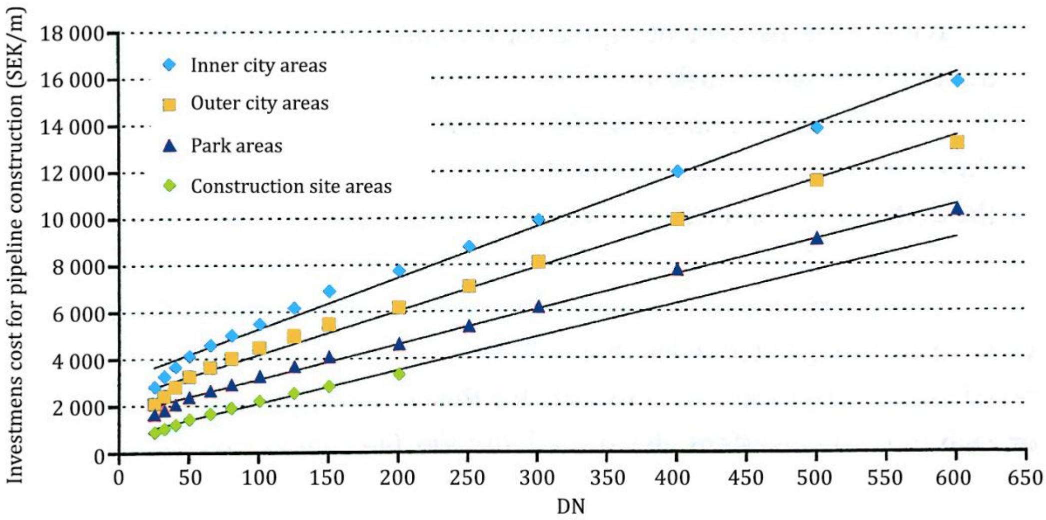

Figure 14: Typical construction investment costs for district heating pipes per route length (Fjärrvärme, 2007)

With d_i being the inner pipe diameter in mm and c_e being the conversion combined fixed and variable cost of an edge. The cost is transposed to Euro using the SEK to Euro rating in 2007 (XE, 2015). The required inner pipe diameter can be determined using an equation determining the power capacity of a pipe (3).

(3) $$P = K \cdot (t_s - t_r) \cdot v \cdot \pi \cdot {d_i}^2 \cdot \rho \cdot c$$

P = Pipe power capacity [W]
K = heat transmission coefficient, with reference to the outer pipe surface [W/m^2K]
t_s = supply temperature [°C]
t_r = return temperature [°C]
v = water velocity [m/s]
d_i = inner pipe diameter [m]
ρ = water density [kg/m^3]
c = specific heat capacity for water [J/kgK]

In order to determine the inner diameter given a max power flow, the water velocity and, supply and return temperatures need to be known. The flow velocity can be determined using the graph in Figure 15. A linear trendline is required to describe the relation between the water velocity and pipe diameter. The trendline is also called a regression line and is the line that best approximates the data in a certain range. All trendlines in this thesis are determined using the least square method. Although the graph is slightly irregular, limiting the range to values between 0,1 and 0,5m pipe diameter will provide a more accurate linear trendline. Formula (4) describes the trendline equation.

(4) $$v = 3{,}25 \cdot d_i + 1{,}175$$

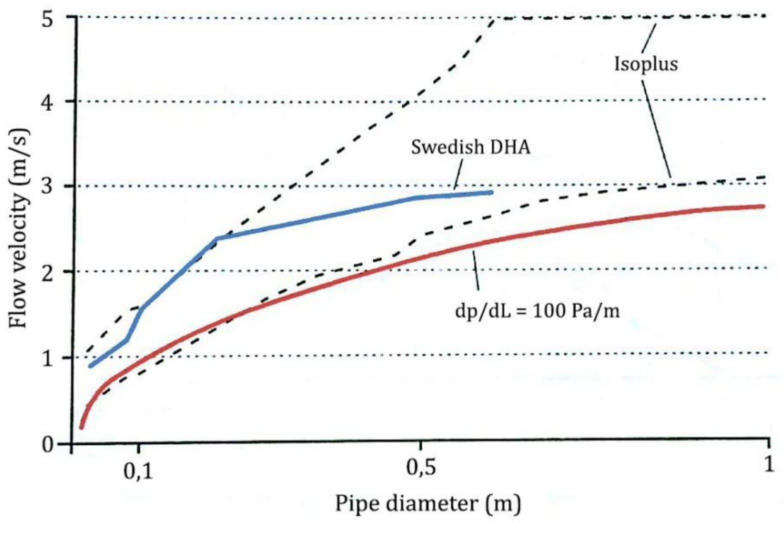

Figure 15: Flow velocity relation to pipe diameter

Using formula (3) and (4) a formula can be created displaying the pipe diameter required to sustain a certain power capacity. Figure 16 shows this graph for a temperature difference Δt of both 4 and 40 degrees Celsius. The heat carrier liquid transfers heat to the destination and loses temperature itself. A 40 degree temperature difference in carrier liquid is normal for a standard district heating network and is used for the normal consumers in this case study. The datacenter has a lower temperature difference of 4 degrees because of the absorption cooler which can only absorb heat above a certain temperature.

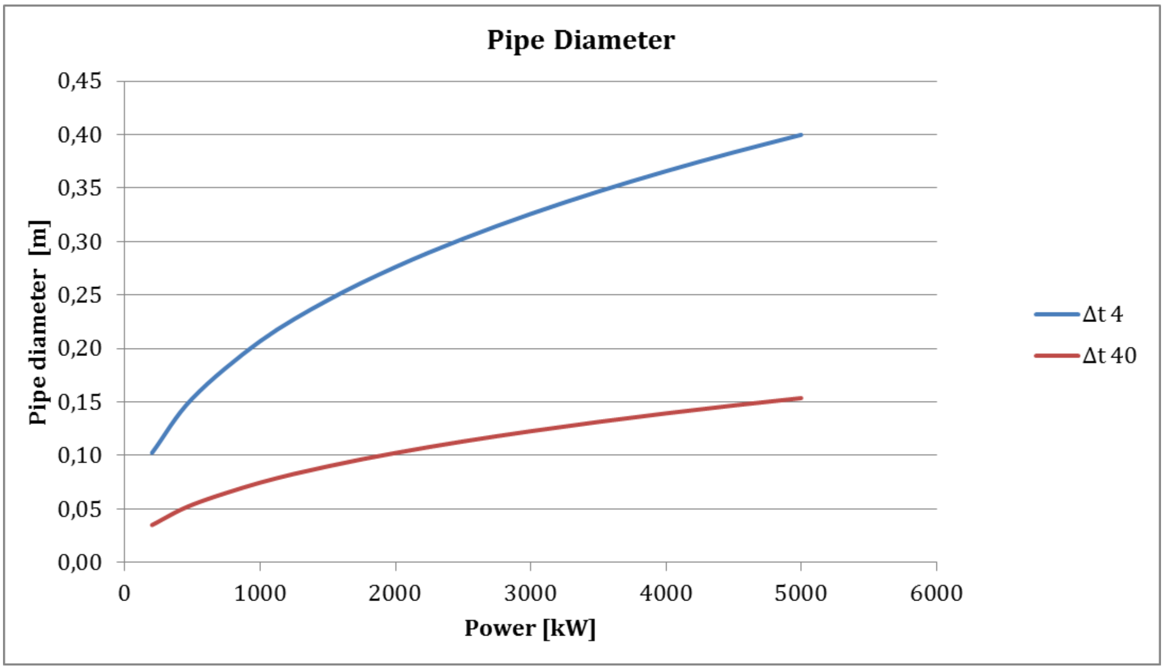

Figure 16: Pipe diameter per kW

Using formula (1) the variable cost capacity is displayed in relation to the power capacity in Figure 17.

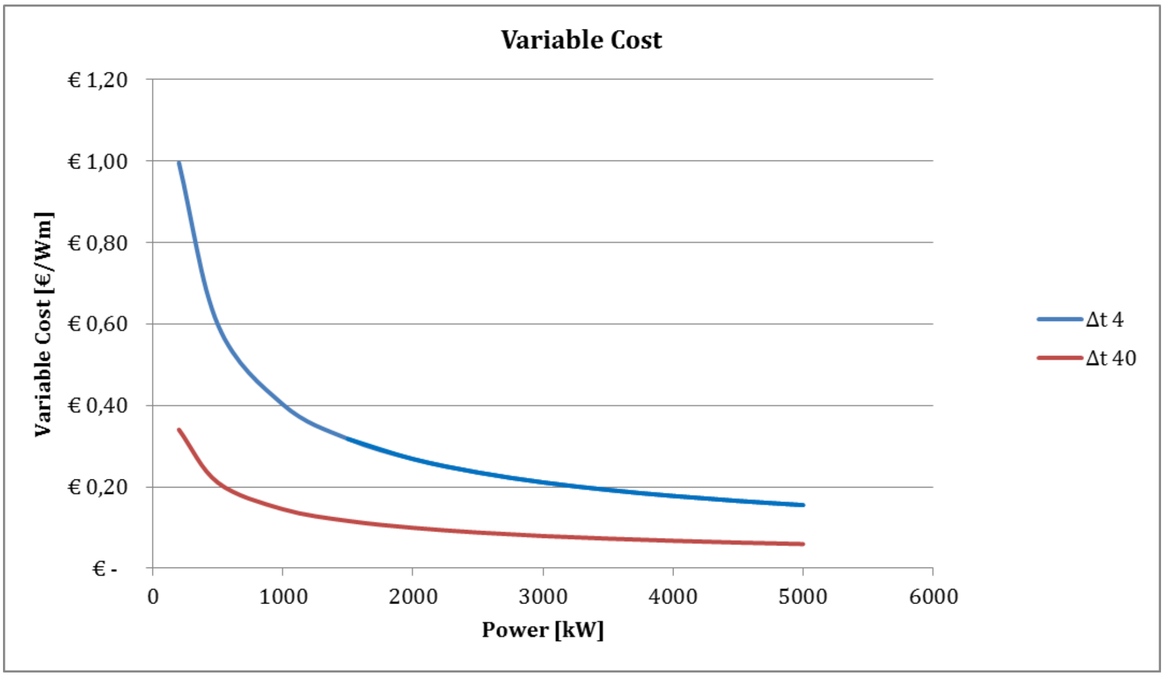

Figure 17: Variable Cost per kW

Combining the variable cost capacity per kW with the previously mentioned fixed investment cost results in the total pipe cost per meter kW displayed in Figure 18. Trendlines are created for both temperature differences resulting in the following values for c_e^{var} and c_e^{fix}. For a temperature difference of 4 degrees c_e^{var} equals 0,0847 [€/kWm] and c_e^{fix} equals 611,4 [€/m]. For a temperature difference of 40 degrees c_e^{var} equals 0,0452 [€/kWm] and c_e^{fix} equals 335,13 [€/m].

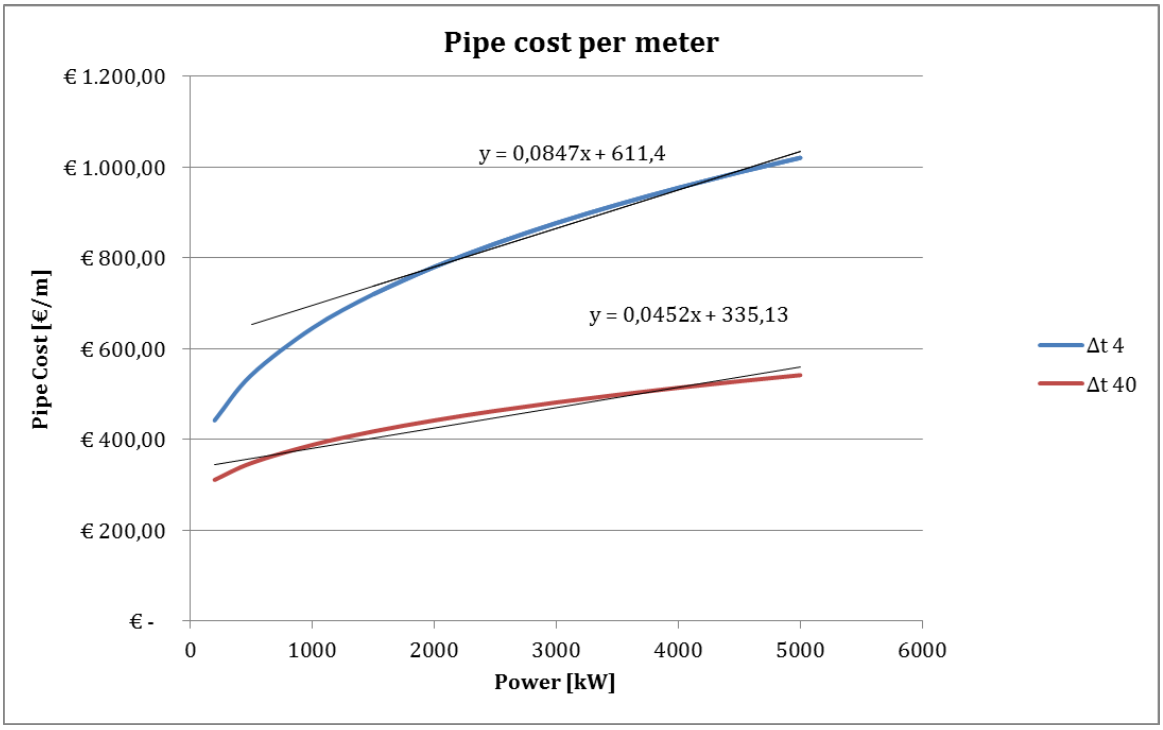

Figure 18: Pipe cost per meter kW

Operating & Maintenance Cost Edge

The operating and maintenance cost c_e^{om} of the pipes describe the costs associated with repairs and pumping costs. The amount of pumping power required depends on the amount of water that needs to be displaced and can therefore be directly linked to the investment cost. According to Werner & Frederiksen field experience has indicated distribution maintenance cost to annually be around 1% of the investment cost of underground distribution pipes (Frederiksen & Werner, 2013). This number concurs with the value provided by Dorfner & Hamacher in their article (Dorfner & Hamacher, 2014).

6.2. HEAT COST AND REVENUE

Heat cost

The cost of heat generation is largely dependent on the type of facility and type of fuel that is used to generate the heat. Generally heat is purchased from a facility by the district heating company but in some cases the heat facility is owned and operated in part by the district heating company.

Concerning the case study of KPN, heat is generated by a large Waste-to-Energy (WTE) plant located in the Rotterdam harbor. The plant imports waste from various neighboring countries and uses it as fuel to generate electricity and heat. In 2014 the plant owned by AVR used about 1,8 million tons of waste from the Netherlands and imported 0,4 million tons of waste from other countries. The expected production in 2015 is 300+388 GWh of electricity and 1250 GWh of heat.

According to a study conducted by Erra and Fortum (2011), in which values for district heating systems are benchmarked, the cost of heat production for a large solid fuel company is around 35 EUR/MWh (Erra & Fortum, 2011). This value is the same as the value for heat production used in the case study of Dorfner & Hamacher and can therefore be considered a reasonable benchmark. These numbers are however based on fuel consumption of Coal and Biomass. According to (Erra & Fortum, 2011) fuel costs account for 10 to 15 EUR/MWh of the total production cost. In waste management however gate fees are paid for the disposal of waste. These fees differ for the type of waste management facilities and amount to 102 euro per ton for waste to energy facilities in 2015 (Waste Management World, 2015). Though the fuel cost of waste incineration plants is less than that of other power generation plants, its cost efficiency is also lower. Waste incineration plants have relatively high capital costs which in combination with the cheap fuel make their marginal production cost very low. Furthermore waste incineration plants have a primary function of waste management; accordingly their activities are not determined by heat demand but rather by waste production. In summertime when general heat demand is low waste incineration plants therefore have a surplus of waste heat, reducing the value of the heat. Because of these factors the cost of heat from waste incineration facilities may vary between 5 and 25 EUR/MWh.

Heat Revenue

The average heat price for consumers according to Erra & Fortum is 63 EUR/MWh averaged over 5 countries not including the Netherlands. Figure 19 shows the average heat price in the Netherlands was 13 EUR/GJ or 46 EUR/MWh in 2004 and 2005. The Nuon prices for private consumption are 22,46 EUR/GJ or 80 EUR/MWh (NUON, 2015). These prices are meant for small consumers but give a reasonable idea of the price levels for district heating. These prices are generally based on the regular cost of heat production. A law passed in 2014 limits the maximum asking price for heat in district heating systems to the equivalent cost of traditional heating methods (Overheid, 26). For this case study the heat revenue $r_{d_i}^{en}$ from normal heat consumption, i.e. Δt of 40 degrees, is set to 60 EUR/MWh. The heat revenue from KPN's heat consumption for cooling purposes (with a Δt of 4) is determined using a benchmark analysis. It should be noted that the cost of heat for consumers is modeled as revenue since the calculation determines the viability of the network extension.

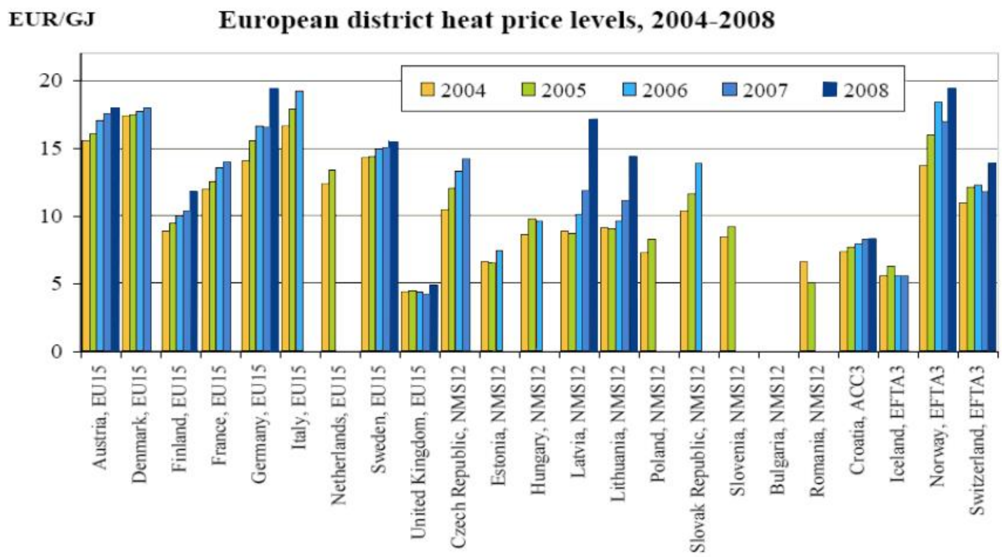

Figure 19: European District Heat Price Levels, 2004 – 2008 (Andrews et al., 2012)

6.3. THERMAL LOSSES

In order to determine the heat losses in the district heating system formula 5 from chapter 3 is used. Some of the value's in the formula are a constant while other values depend on the operating parameters of the district heating system.

(5) $$\Delta t_s = -4 \cdot K \cdot L \cdot d_0 \cdot (t_s - t_a) / \left(v \cdot {d_i}^2 \cdot \rho \cdot c\right)$$

Δt_s = temperature drop in the supply flow between two intersection [°C]
K = heat transmission coefficient, with reference to the outer pipe surface [W/m^{2}K]
L = pipe length between the intersections [m]
t_s = supply temperature [°C]
t_a = ambient temperature [°C]
v = water velocity [m/s]
d_i = inner pipe diameter [m]
d_o = outer pipe diameter [m]
ρ = water density [kg/m^3]
c = specific heat capacity for water [J/kgK]

The values for ρ and c depend on the heat carrier liquid used in the district heating system. This is almost always water, as it is in this case study. The heat transmission coefficient is also a constant for the thermal conductivity of the pipes used in the system. In this case a value of 0,5 is used which is an average value for newly built pipes (Frederiksen & Werner, 2013). The water velocity and inner pipe diameter are related to each other using formula (4). District heating pipes are installed underground. The average ambient temperature t_a is therefore set to the average temperature at a depth of 1 meter under the surface of about 10 degrees Celsius in the Netherlands (KNMI, 2006). Lastly the supply temperature of the district heating system in Rotterdam is 90 degrees Celsius. The length of pipe can be disregarded since the obtainable value is that of heat loss in W/m. The temperature difference Δt_s can be translated into a power loss using formula (3). Figure 20 shows the power loss per meter for a supply temperature of 90 degrees with a return temperature of 86 degrees.

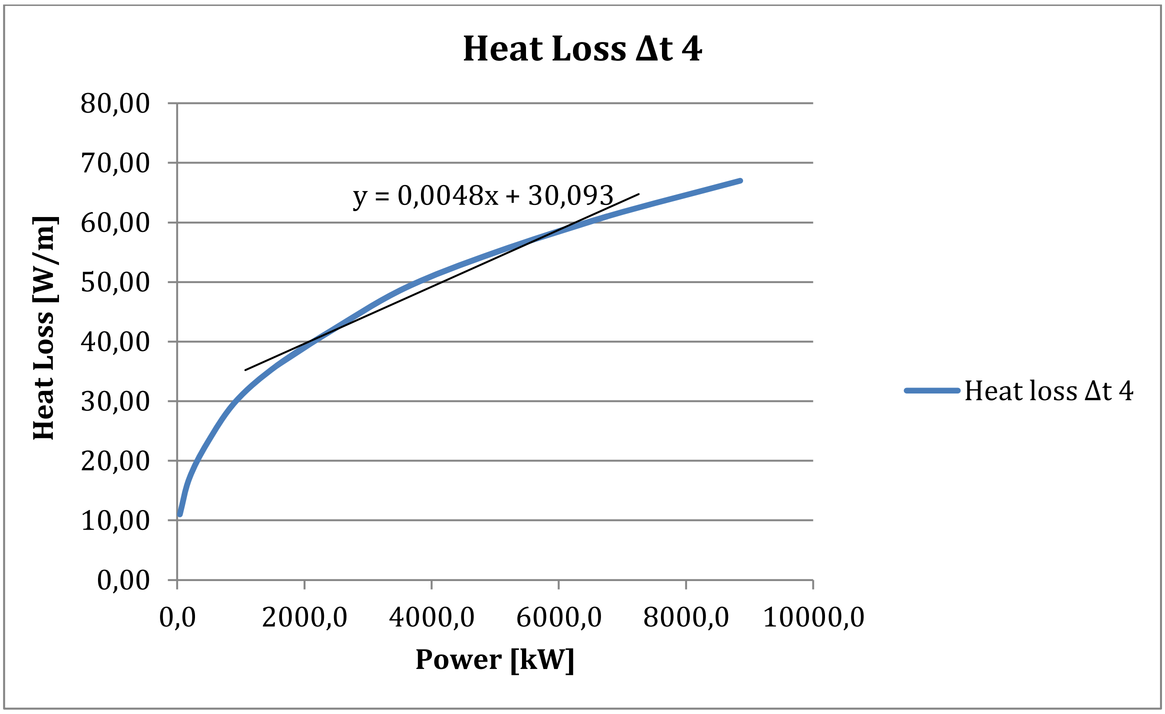

Figure 20: Heat Loss per meter

6.4. ANNUITY FACTORS

The annuity factor is used to account for the long term investment associated with realizing a district heating system. For the annuity factor a discount factor of 3.5% over a period of 40 years is used in accordance with a report on District Heating investments from the European Commission (Andrews et al., 2012).

The formula for annuity is derived from the formula provided by Dorfner & Hamacher (2014) and is constructed as follows:

$$\alpha = \frac{(1+q)^n \cdot q}{(1+q)^n - 1}$$

Where q is the discount factor and n the depreciation period. Using the previously described values this results in an annuity factor α of 0.047. If a period of 20 years is considered the value for α is 0.07.

The value for τ depends on the length of the period that is simulated. For these simulations either a full year simulation or seasonal simulations are performed. For full year τ equals 365 and for seasonal simulations τ is 91. It is also possible to do full year simulations with a lower value for τ if the period of service is less than a full year. The demand for KPN for instance is only valid during the summer. When simulating their yearly demand over a period of 40 days during the summer, a τ of 40 results in a full year analysis since the operation doesn't run during the rest of the year. Since the annuity factor converts single investments to a yearly cost, this should be taken into consideration when performing simulations of less than a year. When performing seasonal simulations the annuity of investments should be divided by the yearly percentage the simulation covers.

6.5. EDGE LENGTH / LOCATION

Warmtebedrijf gets its heat from a waste incineration/power plant located in Rotterdam Harbor which is denoted as [1] in Figure 21. Heat distribution pipes lead from the plant alongside the A15 highway to the Botlek Area. These pipes run underneath the 'Oude Maas' towards the boosterstation Hoogvliet [2]. This node serves as the first distribution point as well as containing a pressure pump to revitalize the internal pressure needed for transportation. Subsequently pipelines run to a similar node [3] after which distribution pipes are split into two separate sections. The first runs to Maasstad Ziekenhuis [5] passing several distribution points. The second section ends at the Brielselaan [4] which also houses a storage buffer of 5000 m3 and booster pumps to regulate the systems pressure (WBR, 2015).

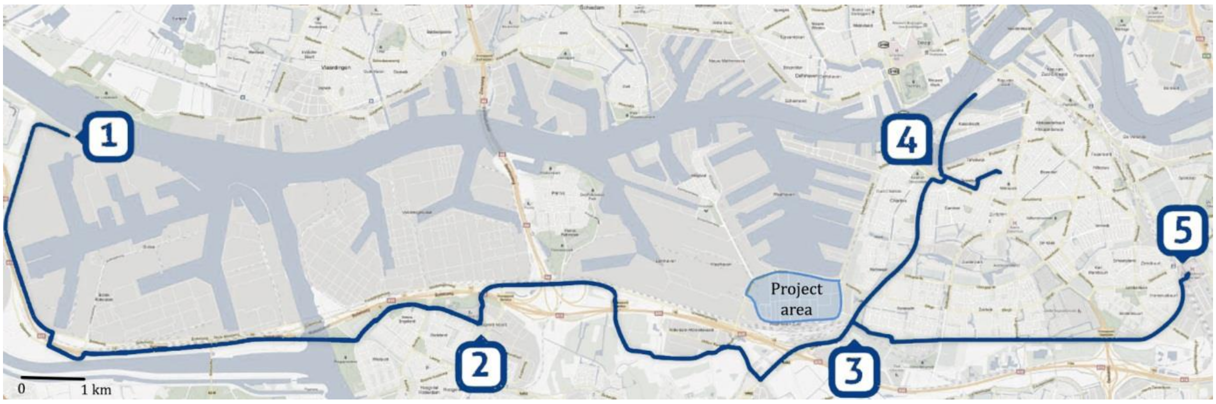

Figure 21: Main pipeline map

KPN's datacenter is located on the Anthony Fokkerweg 40. Approximately 1 km of pipeline has to be added to connect the datacenter to the current main pipeline. The first part of the pipeline is 250 meters and serves as a general connection for the brown field. The second part of 400 meters runs in a southbound direction and turns right onto the Anthony Fokkerweg for another 200 meters. The middle section which in reality runs in a curve is modeled as straight line.

7. CONSUMERS

7.1. BENCHMARK

The demand profile for the datacenter is estimated by KPN. The demand profile is determined with the average price per kWh KPN is willing to pay for the provision of heat. The price of cooling using high grade waste heat needs to be competitive to the price of cooling using a conventional cooling system. In order to determine the price KPN can afford to pay for their heat a benchmark calculation is performed. Specifications on the datacenter and cooling solutions are provided after which the calculation is performed based on yearly costs and initial investment.

Datacenter Specifications

The datacenter houses a large number of servers which require around 1800 kW of thermal cooling. When the outside temperature is low, free cooling is used to cool the servers. Free cooling uses low external temperatures to cool down water which is either stored or used immediately. Free cooling is relatively inexpensive in operation and only uses power for the transport of heat inside the building. The KPN Datacenter will use free cooling when the temperature is below 16-18 degrees depending on the efficiency of free cooling. The average amount of hours ambient temperatures drop below a certain value can be acquired from meteorological institutions and is used to determine the amount of active cooling required per year for each temperature threshold. At temperatures above the threshold the facility will have to rely on active cooling installations. For KPN this will either be a mechanical cooler or an absorption cooler. The mechanical cooler is the conventional method and is powered by electricity. The absorption cooler is mainly powered by high grade waste heat.

Mechanical Cooler

The mechanical coolers are chillers which remove heat from a liquid via vapor compression. The chilled liquid can be used to cool air when circulated through a heat exchanger. The chillers which KPN would use for the datacenter have an estimated coefficient of performance (COP) of 6 which means that for every kWe the machine uses, it produces 6 kWth of thermal cooling. These systems cost around 570.000 euro which results in a cost of capital of 41.106 euro using the annuity factor from the previous chapter. With a standby usage of 2,5 kW when not operating and a cost of 0,07 euro per kWhe for electricity in the Netherlands (Eurostat, 2015) this results in the cost displayed in Table 1 for datacenter cooling for a year.

Table 1: Yearly Cooling Cost Chillers

Cooling cost Chillers	**< 18 graden**	**< 17 graden**	**< 16 graden**
Standbycost	€ 1.362	€ 1.303	€ 1.236
Chillers consumption cost	€ 20.601	€ 27.762	€ 35.784
Cost of capital	€ 40.106	€ 40.106	€ 40.106
Total	**€ 62.069**	**€ 69.171**	**€ 77.126**

Absorption Cooler

KPN uses a 5G4MC model absorption cooler for this project which costs € 627.000. The cooler has a COP of 0,79 and therefore requires ~2275 kWth to function. The absorption cooler also requires ~85 kW of electricity to drive the pumps inside the cooler. This results in a capital cost of € 44.116 per year using the annuity factor described in the previous chapter. In order to determine the price KPN can pay for the waste heat, the expected case of 17 degrees is set to the same total cost as the mechanical cooler 17 degree case. The results of these calculations can be found in Table 2.

Table 2: Yearly Cooling Cost Absorption cooler

Cooling cost Absorptioncooler	**< 18 graden**		**< 17 graden**		**< 16 graden**	
Electrical consumption cost	€	6.455	€	8.699	€	11.212
Heat consumption cost	€	12.137	€	16.356	€	21.082
Cost of capital	€	44.116	€	44.116	€	44.116
Total	**€**	**62.708**	**€**	**69.171**	**€**	**76.411**

From these findings it can be concluded KPN can pay €0,009 per kWhth to reach a similar cost as a conventional cooling method would require. This is a very low price for heat and would not be viable under normal circumstances.

7.2. DEMAND

KPN

The yearly consumption for KPN is ~3000 MWhth per year for cooling at temperatures higher than 17 degrees. In order to create a higher demand KPN will also use the DH system to power the central heating system of the offices connected to the Datacenter. Over the past two years KPN had an average heat load of 1434 MWhth.

SOR

SOR is a housing association focused on senior citizens. They own a complex located near the main supply pipe of Warmtebedrijf containing around 250 residences. The building has a total floor surface of 19458 m^2 (Kadaster, 2015). The average heat load for nursery homes is 150 kWh per m^2 per year (Kemna & Acedo, 2014). Multiplication of these factors results in a total heat load of ~3000 MWhth.

STC

Located across the street from KPN is a building owned by the STC-group, a school focused on maritime studies. This location houses the trade school containing several educational programs for VMBO and MBO students. The building has a floor surface of 9298 m^2 (Kadaster, 2015) with an average heat load of 105 kWh for trade schools (Kemna & Acedo, 2014). This results in an average heat load of ~1000 MWh per year.

7.3. DEMAND PROFILES

In order to get a better simulation of the required district heating system demand profiles need to be established. Combinations of these profiles simulate the daily demand of the projected consumers and determine the hourly loads of the system. Since not every single day of the year can be simulated the projected demand profiles need to be averaged over the period of time they represent.

The demand profiles are approximated using an estimated yearly demand and general demand profiles for the available functions. First base numbers are used to acquire the average yearly consumption per m^2 of the considered facility. The floor area of the facilities can be acquired from the cadaster (Kadaster, 2015) . The resulting yearly heat demand can be translated into a seasonal average using heating degree days. Heating degree days determine the variation of the daily average temperature to a benchmark value, considering a linear relation between heat load and temperature deviance this information can be used to define an average heat load of that period in relation to the yearly heat load. It has to be noted that in reality the heat demand of a building is not linear to the temperature deviation so the acquired values are an approximation for the division of the heat load.

Demand profile for cooling

The cooling demand has to be considered outside of the heat demands since most of its characteristics differ from the heat load. A larger pipe size is required for the same power capacity because of the low temperature difference and the revenue from this heat supply is lower than that of the power considered with heating. The demand profile for KPN for cooling is a linear profile. KPN starts actively cooling when a threshold value for the outside temperature is reached. Since the heat demand for KPN doesn't depend on the deviation of the outdoor temperature in relation to the threshold, the heat demand over a period of time can be determined using the amount of hours the temperature is above the threshold for that period of time disregarding the amount of deviation.

Demand profile for heating

The seasonal averages need to be translated into a daily demand profile. In order to do this the heat load is set to the demand profiles of the corresponding functions. Figure 22 displays a graph, illustrating demand profiles per function. The daily average heat load for a season is set equal to the graph surface area resulting in a heat load profile for the consumers.

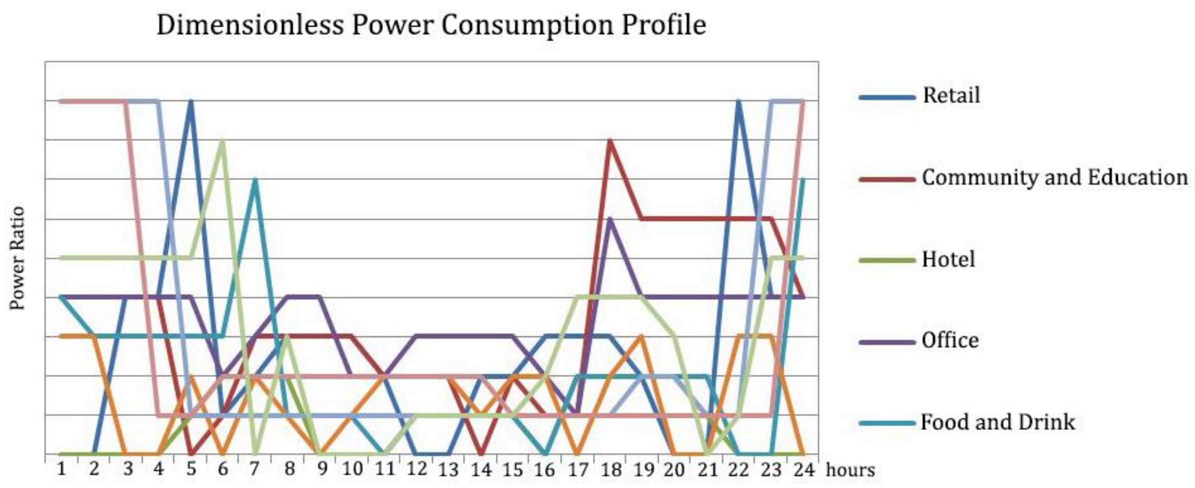

Figure 22: Heat load profiles per function (Huang et al., 1999)

8. SIMULATIONS

8.1. INTRODUCTION

This chapter provides the simulations of the KPN case study. Several scenarios are treated with slightly varying parameter values in order to create insight in the effect of the parameters on the financial viability. The first scenarios are simulations with one consumer and cover the full year in one simulation. These simulations are easier to carry out and suffice in showing cost-parameter relations. Subsequently multi-user scenarios are simulated which represent the closest approximation of the realistic scenario. Finally a quantification of the social benefits is covered.

8.2. NORMAL SCENARIO'S

Scenario 1, standard scenario

The first scenario to be considered consists of the standard parameters found in chapter 5 and the standard setting. KPN is the only consumer considered for the extension and the maximum revenue that can be obtained is set equal to the benchmark payments KPN can afford. Energy cost is set to the lowest estimated energy cost of € 0,0045 per kWh. The scenario assumes active cooling is required at temperatures above 17 degrees Celsius which is simulated as a constant daily load of 2275 kW with a value for τ of 55.

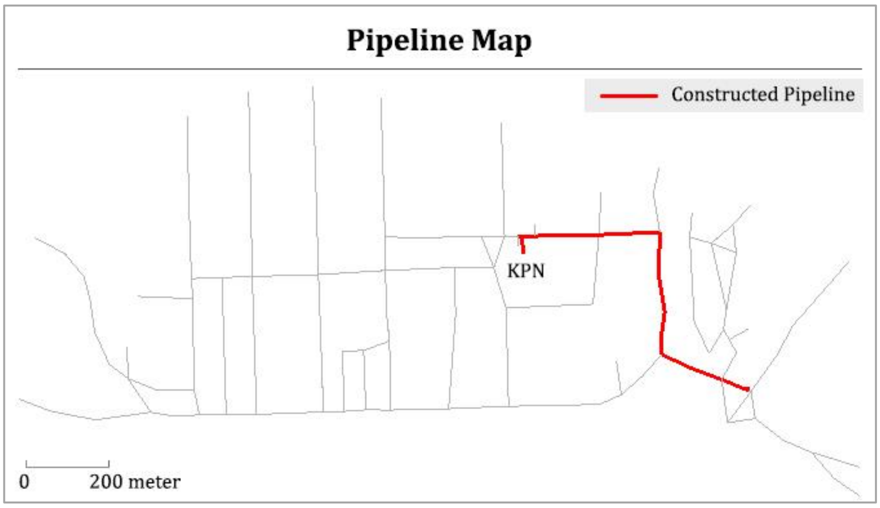

Figure 23: Pipeline map standard scenario

The results of the simulation show this scenario is unfeasible, see Table 3. The combined costs greatly outweigh any gains from revenue and a net loss of €56.933 euro per year is estimated. The costs concerned with the placement of pipes, consisting of the fixed and variable edge costs, add up to ~ 75.000 euro and are responsible for the majority of the costs. Figure 23 shows the pipe locations which amount to a total length of 1810,3 meter.

Table 3: Yearly extension costs scenario 1

Extension Costs		
Fixed Edge Cost	€	62.417
Variable edge cost	€	8.247
Energy Cost	€	13.731
Cost due to heat loss	€	380
Energy Rev.	€	-27.462
Total	**€**	**56.933**

Scenario 2, increased consumption by duration

This scenario looks into the effect of an increased yearly cooling load on the result. It has to be noted that only the amount of hours has increased the load remains at 2275 kW but is now simulated over the course of 71 days which concurs with a cooling load at temperatures above 16 degrees Celsius.

As Table 4 shows there is hardly any improvement in cost. This can be explained by the small difference between energy cost and revenue. In cases of a larger disparity the effect of an increased load is more significant.

Table 4: Yearly extension costs scenario 2

Extension Costs		
Fixed Edge Cost	€	62.417
Variable edge cost	€	8.247
Energy Cost	€	17.725
Cost due to heat loss	€	490
Energy Rev.	€	-35.451
Total	**€**	**53.429**

Scenario 3, increased consumption by load

In this scenario (Table 5) the effect of a higher consumption is also considered except now the load is doubled to 4550 kW with a constant consumption over the course of 55 days.

Again the effect on the total cost is very small. It should be noted that the variable edge cost have increased significantly due the requirement for larger pipes. The change is not completely linear due to a difference in heat losses. It should also be noted that the costs are approximated linearly within a range of 1500 – 6000 kW. If the pipe capacity would exceed this range different parameters should be considered for the edge cost.

Table 5: Yearly extension costs scenario 3

Extension Costs		
Fixed Edge Cost	€	62.417
Variable edge cost	€	16.377
Energy Cost	€	27.462
Cost due to heat loss	€	438
Energy Rev.	€	-54.924
Total	**€**	**51.770**

Scenario 4, larger Δt

The low temperature realizable temperature difference concerned with the use of an absorption cooler has a large impact on the financial viability of the district heating system. In this scenario the consumption of KPN is considered with a conventional temperature difference of 40 degrees.

Table 6: Yearly extension costs scenario 4

Extension Costs		
Edge Cost	€	34.568
Variable edge cost	€	4.342
Energy Cost	€	13.684
Cost due to heat loss	€	171
Energy Rev.	€	-27.462
Total	**€**	**25.132**

Table 6 shows this change has a major effect on the edge cost which is almost halved. The heat losses have also decreased significantly. Though the effect of the heat losses in these scenarios are low, heat losses can play a major part in larger extensions. A higher production cost would also increase the significance of heat loss.

Scenario 5, higher annuity factor

In scenario 5 the impact of the annuity factor on the cost is considered. The annuity factor used in the previous scenarios considered a project duration of 40 years. This is brought down to 20 years or a value for α of 0.07.

Table 7: Yearly extension costs scenario 5

Extension Costs		
Fixed Edge Cost	€	87.603
Variable edge cost	€	12.283
Energy Cost	€	13.731
Cost due to heat loss	€	380
Energy Rev.	€	-27.462
Total	**€**	**86.155**

The effect of a decrease in project duration depends on the size of the investment costs. In this case a halving of the project duration results in a total cost increase of ~50 percent. The investment costs increase with ~67 percent (Table 7).

8.3. MULTIPLE USERS SCENARIO

Three scenarios are considered in calculating the financial viability of the KPN case study. These are a worst case, best case, and expected scenario. All simulations are divided in a summer, winter, and spring/fall analyses resulting in a full year simulation. In all scenarios four consumers are modeled. KPN is simulated as two consumers, one using heat for cooling purposes with a small temperature difference and one using heat for heating purposes with a high temperature difference.

Expected Scenario

This scenario represents the expected outcome. The cost of heat is divided in cost during summer when the average demand is low, and a cost for the other seasons. The cost during summer is estimated at € 0,007 per kWh, the cost during the other seasons is estimated at € 0,025 per kWh in accordance with the literature found in chapter 6. The project duration is estimated at 30 years with a discount factor of 3,5%. The scenario's concerns both a cooling load and heating load which have different temperature losses. Because only one parameter value can be uses in one simulation the highest value for temperature losses are chosen. Figure 24 displays the location of the pipelines and Figure 25, Figure 26, and Figure 27 display the load profiles in the edges and consumers for all simulated seasons.

The figures show that the highest heat load is achieved in the spring and fall during a short interval. KPN has a flat demand at this peak which coincides with a high demand for the other consumers. It should be noted that the demand could be higher when both peaks occur at the same time. Since the simulation is an approximation and based on averages incidental coinciding peak demands are not taken into account which might provide a blurred image of reality. For this study pipeline capacity is set to the maximum demand of KPN since the other consumers can still use the output temperatures of KPN.

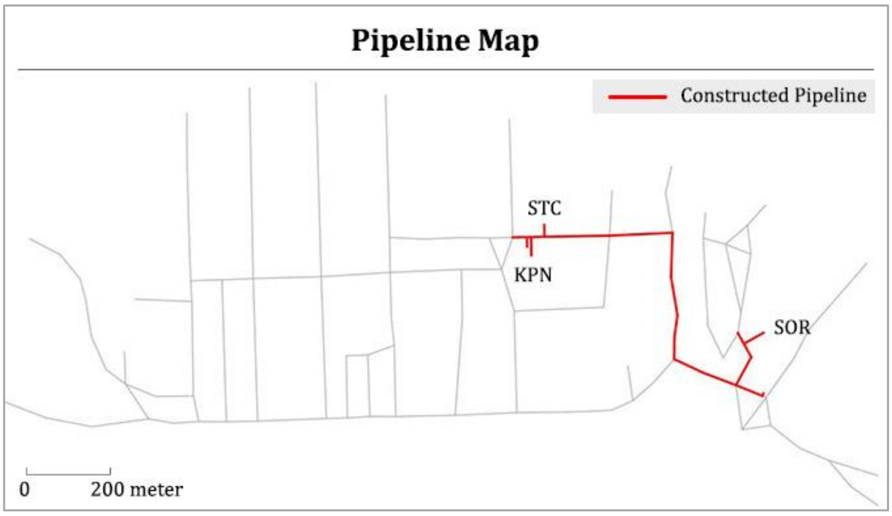

Figure 24: Pipeline Map expected scenario

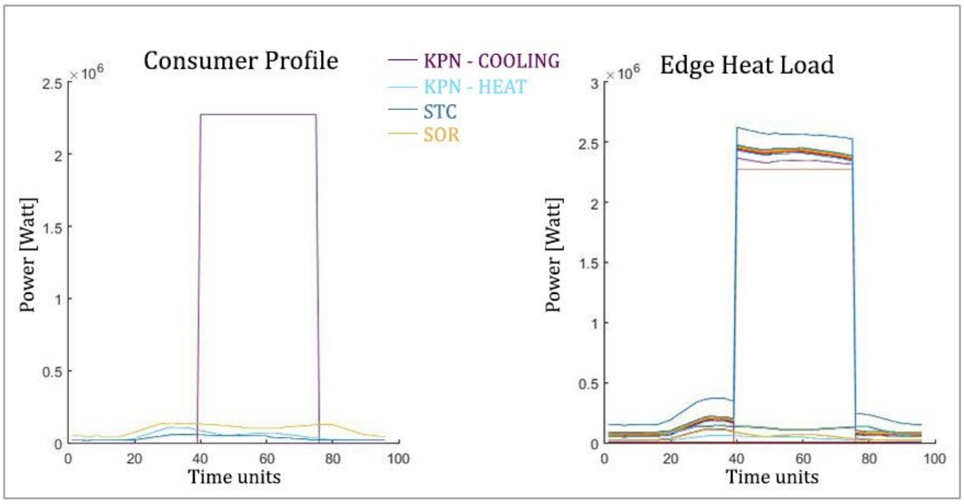

Figure 25: Heat Load Summer

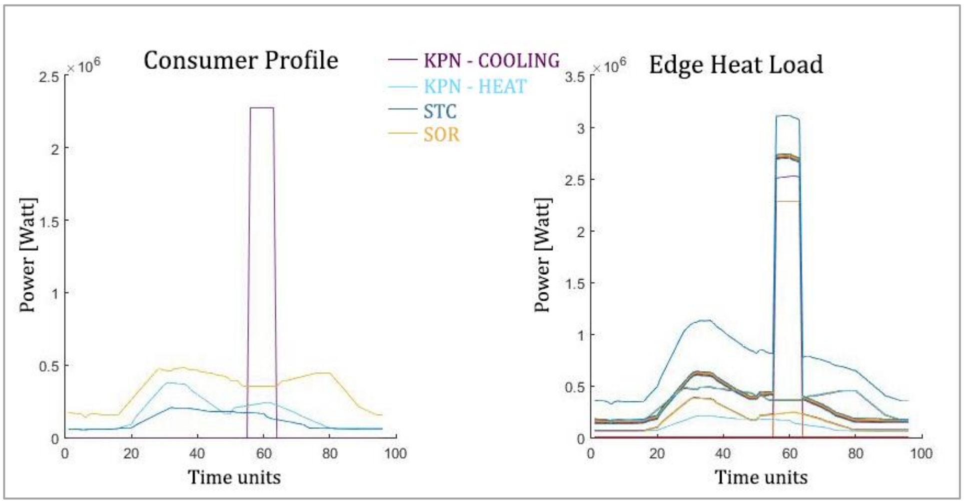

Figure 26: Heat Load Spring and Fall

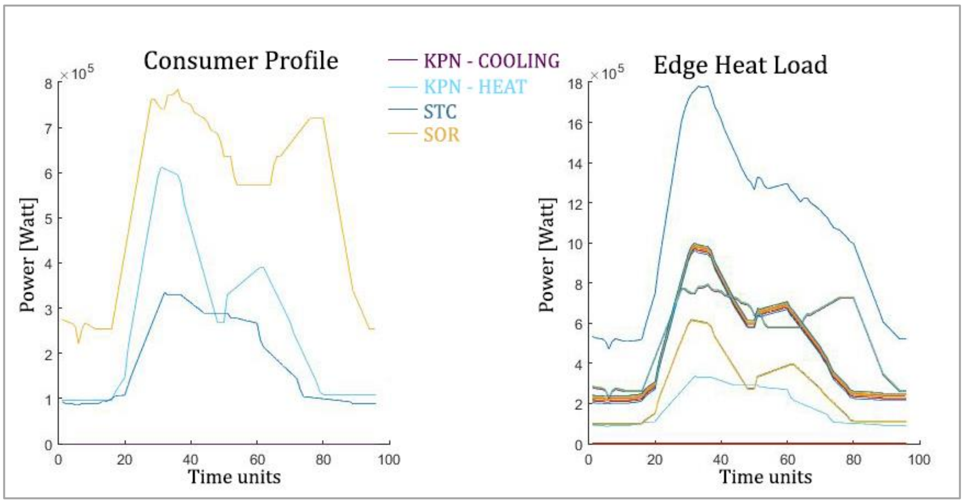

Figure 27: Heat Load Winter

The results of the expected scenario are displayed in Table 8. The edge costs are slightly higher than the previous simulations; however because of a higher demand per length of pipe percentage of edge cost in relation to the total costs has decreased significantly. The energy revenue and energy cost has also increased significantly. This can be attributed to both a higher demand and higher cost/revenue value's from seasonal and Δt changes.

Table 8: Yearly extension costs expected scenario

Extension Costs		
Fixed Edge Cost	€	89.992
Variable edge cost	€	10.279
Energy Cost	€	171.281
Cost due to heat loss	€	12.202
Energy Rev.	€	-317.575
Total	**€**	**-46.024**

Best Case Scenario

In the best case scenario the project duration is increased to 40 years. The production costs have been lowered to € 0,0045 per kWh during summer and € 0,02 during the other seasons. The demand profiles have also been increased with 10%. The result is displayed in Table 9.

Table 9: Yearly extension costs best case scenario

Extension Costs		
Fixed Edge Cost	€	74.483
Variable edge cost	€	9.359
Energy Cost	€	134.369
Cost due to heat loss	€	10.717
Energy Rev.	€	-349.333
Total	**€**	**-131.122**

Worst Case Scenario

For this scenario the project duration has been decreased to 20 years. Production costs have been increased to € 0,008 during summer and € 0,03 during the other seasons. Additionally, the demand profiles have been decreased with 10%. This leads to a net loss of ~€ 43,000 per year (Table 10).

Table 10: Yearly extension costs worst case scenario

Extension Costs		
Fixed Edge Cost	€	115.862
Variable edge cost	€	12.031
Energy Cost	€	204.571
Cost due to heat loss	€	13.305
Energy Rev.	€	-288.705
Total	**€**	**43.760**

8.4. SOCIAL BENEFIT

In addition to the direct financial benefits, the installation of a district heating systems had environmental benefits as well. These benefits are harder to quantify but can be expressed in financial benefits to the society. In order to quantify the effects of carbon emissions the term: 'social cost of carbon' has been introduced. The social cost of carbon is the present value of marginal damage to the economic output caused by carbon emissions (van den Bergh & Botzen, 2015).

The social cost of carbon (SCC) is difficult to determine because of its complexity. Estimations regarding the effect of climate change effects vary and consideration of the full scope of consequences is nearly impossible. Because of this the estimated SCC differs from 34 to 202 euro per emitted ton CO^2 (van den Bergh & Botzen, 2015)(Cai, Judd, & Lontzek, 2015) (Than, 2015). Noticeably the lowest estimations came from government initiated researches. Independent university researches indicate an SCC estimation of less than €100 per ton is unrealistic and omits important economic effects of climate change (van den Bergh & Botzen, 2015).

In order to determine the social benefit of the network extension the reduction in CO^2 needs to be determined. Determining the allocation of benefits in cogeneration is open to interpretation and can result in many different allocation methods. Normally, a pragmatic, market-based allocation method is chosen depending on the situation (Svend Fredriksen, 2013). For this calculation synergy benefits are distributed equally between electricity and heat production. Dividing the total reduction in CO^2 emission of the AVR power plant with the total production of energy units (both thermal kWh and electrical kWh) results in a reduction of 0,04 CO^2 per kWh. Multiplying the total reduction of CO^2 with an SSC of €100 per ton results in a social benefit of €35.000 per year. Additionally the incineration of waste is considered environmentally friendly because methane releases from landfills are avoided. The effect of methane on the environment is 200 times greater than that of CO^2 therefore this effect is significant as well.

8.5. CONCLUSION

To determine the financial viability of the KPN case several scenarios have been simulated both to illustrate the impact of parameter changes and to provide a range of the expected results. The simulations are a representation of the reality and concern several assumptions. District heating systems contain many exponential economy-of-scale advantages, which have been simulated using trendlines within a certain range. This limits the functionality for the model and results in a small margin of error in the assumptions. Another disadvantage of this simulation model is the inability to distinguish in types of consumption which provides problems for both the calculations for heat loss and revenue.

Financially the KPN case is more likely to result in a profit than a loss. The precision of the parameters plays a major role in this and should be improved if a smaller range is to be reached. Expectation is that the parameter for energy cost has the highest risk of uncertainty due to a lack of literature on the subject. In addition to the direct financial benefits the reduction in social cost of carbon is significant as well. Quantification of these costs can be used to obtain environmental subsidies or indicate the social benefit of a project.

9. RESULT COMPARISON

9.1. INTRODUCTION

Parallel to this research performed in this thesis the heat carrier company in Rotterdam 'Warmtebedrijf' (WBR) performed a viability study on the case as well. In this chapter similarities and dissimilarities between both studies are compared and reviewed. The comparison provides a benchmark to review the accuracy of the model and the precision of the model parameters. It should be noted that the data acquired from WBR originated from business collaboration meetings and could be distorted for negotiation advantages. Furthermore the information is limited since WBR does not want to divulge too much sensitive information regarding their operation.

9.2. EXTENSION PLANS

WBR proposed a district heating network extension which uses a single supply and return pipe for KPN and STC. Because the outgoing heat from KPN is still of sufficiently high temperature the heat can be re-injected into the supply pipe. This option was considered regarding the pipe capacity in the simulation but was not considered for the pipe length due to the setup of the model. The proposed plans used a different starting point of the extension pipeline which does not make a large difference in terms of pipeline length. A pipeline with a diameter of 0,150 m is used in the plans with a flow velocity of 3,39 m/s. This is a noticeable difference with the flow velocity used in this report which was set to 1,7 m/s at a diameter of 0,150 m. This would make a difference of ~€200 per meter pipeline. In their calculations, WBR did take into account digging works under a weir which separates the consumers from the main pipeline. These diggings are an irregular event and require considerably higher piping cost. WBR also took into account the cost for the placement of a distribution hub € 400.000 and a delivery hub € 200.000. WBR considered a project duration of 15 years for this extension.

9.3. PARAMETERS AND COST

The consumption profiles used for the calculations were remarkably similar. In this thesis SOR, KPN heating and STC demands were estimated at 10507, 5163, and 3515 GJ respectively. WBR estimated these demands at 10000, 5200 and 3500 GJ respectively. Additionally WBR estimated STC to have a heat demand for cooling purposes of 4000 GJ. The estimated piping cost is set to €1.905.000 compared to a total cost of € 1.856.870 for the expected case simulation. Since the piping cost is expected to be lower in the WBR case due to smaller pipes, the difference can be explained by the weir digging costs which would approximate € 300.000 to make up the € 200 per meter difference. WBR estimates an income of € 1.750.000 over the project duration which would result in a budget deficit of 0 - €750.000 for the KPN network extension. A recalculation of the estimated income of WBR is performed, the results of these calculations can be found in Table 11.

Table 11. WBR income recalculations

Case 1 - WBR calculation		Case 2 - Expected		Case 3 - Break-even	
Parameters		**Parameters**		**Parameters**	
Heating demand cost	*€ 30 /MWh*	*Heating demand cost*	*€ 25 /MWh*	*Heating demand cost*	*€ 25 /MWh*
Heating demand rev	*€ 60 /MWh*	*Heating demand rev*	*€ 60 /MWh*	*Heating demand rev*	*€ 60 /MWh*
Cooling demand cost	*€ 9 /MWh*	*Cooling demand cost*	*€ 6 /MWh*	*Cooling demand cost*	*€ 6 /MWh*
Cooling demand rev	*€ 9 /MWh*	*Cooling demand rev*	*€ 9 /MWh*	*Cooling demand rev*	*€ 9 /MWh*
Alpha	*0,087*	*Alpha*	*0,070*	*Alpha*	*0,091*
Project Duration	*15 year*	*Project Duration*	*20 year*	*Project Duration*	*15 year*
Discount rate	*3,5%*	*Discount rate*	*3,5%*	*Discount rate*	*4,2%*
Results		**Results**		**Results**	
Revenue/year:	**€ 155.833**	**Revenue/year:**	**€ 194.306**	**Revenue/year:**	**€ 194.306**
Project Revenue NPV	**€ 1.794.797**	**Project Revenue NPV**	**€ 2.761.549**	**Project Revenue NPV**	**€ 2.125.000**
Budget Deficit	**€ 330.203**	**Budget Deficit**	**€ -636.549**	**Budget Deficit**	**€ 0**

Three cases have been considered, the first case represents the calculations with an estimation of the parameters used by WBR. The budget deficit for an income of € 1.750.000 is set to the average of the estimated deficit by WBR which is € 375.000. Case 2 is calculated with the estimated parameters from the previous chapters in this thesis and a project duration of 20 years. This case covers the budget deficit and has a projected profit of € 636.549 on top of the discount rate. Case 3 exemplifies a case which exactly covers the budget deficit.

9.4. CONCLUSION

The comparison between both project estimates provides a lot of insight in the accuracy of the suggested parameters values. The estimated flow velocity is shown to be inaccurate compared to the values from WBR. One of the reasons for this could be a different material used in the pipes compared to the literature. A smoother pipe surface can reduce the pressure drop in pipes and therefore support higher flow velocities. The estimated project duration is also considerably different. The estimated shelf life of district heating systems is higher than the considered duration by WBR. A lower duration is most likely considered to account for the risk of uncertain consumption. A project duration of 15 years does match the conventional project duration for mechanical installations. Other cost estimations are quite similar; especially the estimated heat loads which in some cases deviate less than 1%. WBR does take into account the construction of distribution and delivery hubs which should be taken into account in future improvements of the model. Irregularities such as excavation works in weirs are unfortunately hard to take into account in general calculation tools such as the model considered in this thesis.

10. CONCLUSION AND RECOMMENDATIONS

This chapter presents the final results and findings of this research. The conclusion is presented as an answer to the main research questions. The outcomes of the model are reviewed as well as the usefulness and practicality of the model. Conceivable model improvements are discussed and finally recommendations for future research are made.

10.1. CONCLUSION

The main research questions that need to be answered are the following:

Under which conditions is using high grade waste heat for cooling purposes viable?

How can the input parameters for the calculation be determined?

How accurate is the model at determining the financial viability of a district heating system?

In order to answer these questions the model's functionality is assessed. First the features and characteristics of the model are described followed by the applicability of the model. The results of the simulations and the determination of the model parameters are discussed. Finally the accuracy of the model is described.

The model used in this research is based on an adapted network optimization model. The model uses a set of equations and restrictions to model the power flow through a series of edges and nodes. The network optimization is based on minimal cost and can be translated into a cost optimization model. The model uses linear programming for its calculations and uses linear relations for its parameters. Because of this the parameters which are often a linear trendline of exponential functions might need revision for different case sizes. For this thesis Matlab was used as a simulation tool.

The results of the simulations indicate using high grade waste heat for cooling purposes can be viable under the right circumstances. The minimal difference in heat cost and revenue for heat used in cooling purposes makes these district heating systems unviable without the inclusion of additional consumers. The viability for the inclusion of these cooling loads is largely dependent on the heat purchasing price of the heat transport business. These businesses are largely driven by waste heat of which there is a lack of demand in summertime. Combined with a very low to non-existent marginal cost this should ensure minimal purchasing prices.

The parameters used in the model simulations have been determined using literature study and calculations. Comparisons and base values were used when available in reliable reports. Some parameters required the use of basic formulas for determination. Both of these methods are reliable when using adequate formulas and base material.

The model can be used to calculate the financial viability of any district heating system regardless of it being an extension or green field analysis. The model is optimally used in the calculation of larger district heating systems which are harder to approximate by hand. In contrary, smaller district heating systems might be better approachable by situational calculations. The reasons for this are anomalies like specific construction site situations and irregular consumers, local policies can also be better implemented in these calculations. It is also possible to consider more unconventional and creative solutions for the network design.

To answer the research question the model used in this thesis is very well suited to calculate district heating networks. However due to the restrictions in creative solutions and setup time, it might be beneficial to calculate smaller district heating extensions with ulterior methods.

10.2. RECOMMENDATIONS

Based on the research, several recommendations can be made for KPN. The results from the simulations and result comparison indicate the considered project is feasible under the right circumstances. Both the simulations and the calculations from WBR do not take all factors contributing to the total cost under consideration. Therefore KPN should analyze both results and retrieve and combine the information that they think represents the case best. The results from analyzing the calculations by WBR indicate enough room for negotiation. A solution to stimulate the construction of the pipeline by WBR could be to guarantee a 20 year demand. Demand security seems to be the major reason for a short project duration and the ablation of this risk would stimulate the consideration of a longer project duration which would make the project viable.

Environmental benefits are not quantified in the results but it should be noted that these benefits are a huge driving factor for such projects. Brand improvement, environmental awareness and the social cost of carbon emissions should be considered when evaluating the environmental aspects of these projects. The environmental benefits associated with these projects can ensure projects are passed with a similar cost as alternative methods or even a small loss.

10.3. MODEL IMPROVEMENTS

As it stands alterations have to be made to the model to easier simulate varying circumstances. In order to create a simulation with multiple revenues, heat losses and time periods it is currently necessary to perform multiple simulations. Additions could be made to the model to encapsulate all these functions in one simulation. It would also be beneficial if exponential functions in the model could be simulated as such. This would improve accuracy and remove the need for different value estimations for different ranges. Part of this could be achieved by using carrier temperature as the driving parameter instead of power. In the current situation the power capacity of a production facility can have different meanings depending on the temperature difference used. A power capacity of 2000 kW can represent a large amount of water transported at a small temperature difference or a small amount of water at a high temperature difference. When using carrier temperature as a driving parameter the temperature difference created by a consumer results in the power capacity. This would ensure varying temperature differences for multiple consumers can be used simultaneously.

Additional details to the model would also increase accuracy. The required installment of distribution nodes and pumping stations for larger distribution networks can account for a 10-20% cost difference, considering the values from WBR. Other details could include the addition of ranges for specific pipes. Not every diameter of pipe is available, therefore pipes should be considered in ranges. Such an addition could include a specific price per pipe range further increasing the accuracy of the cost estimation.

The parameter values are also an area of improvement. District heating is a relatively new technology and not much information is available on its functioning. Therefore limited literature is available to base the parameters on. More extensive research into the proper values for parameters is needed in order to improve their precision.

10.4. FUTURE RESEARCH

This research focuses on the financial calculation for district heating systems for dedicated heat suppliers and secondary parties. Though finances are the primary reason for the implication or non-implication of district heating systems there is still a large barrier for the adoption among consumers. Research concerning the reasoning behind support or hesitation towards district heating system can be interesting in order to stimulate future district heating networks.

Energy exchange networks are also a rising technology which could benefit from a financial calculation model. The model used in this thesis can be modified to suit this technique since the same technology is used based on a different principle.

The model improvements as mentioned above could also justify a research in the improvement of the provided model. Specifically the incorporation of exponential functions is a difficult subject since the model is based on linear programming.

Finally a research into the base values used in district heating system calculations would be greatly beneficial to parties trying to adopt the technology. Currently information is scarce and dispersed. Concentrating existing knowledge in an easily accessible handbook for basic calculations would aid non industrial businesses in simple district heating assessments.

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