Modeling and Multi-Objective Optimization of the Helsinki District Heating System and Establishing the Basis for Modeling the Finnish Power Network

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Abstract

Due to an increasing awareness of the importance of sustainable energy use, multi-objective optimization problems for upper-level energy systems are continually being developed and improved. This paper focuses on the modeling and optimization of the Helsinki district heating system and establishing the basis for modeling the Finnish power network. The optimization of the district heating system is conducted for a twenty four hour winter demand period. Partial load behavior of the generators is included by introducing non-linear functions for costs, emissions, and the exergetic efficiency. A fuel cost sensitivity analysis is conducted on the system by considering ten combinations of fuel costs based on high, medium, and low prices for each fuel. The solution sets, called Pareto fronts, are evaluated by post-processing techniques in order to determine the best solution from the optimal set. Because units between some of objective functions are non-commensurable, objective values are normalized and weighted. The results indicate that for today's fuel prices the best solution includes a dominating usage of natural gas technologies, while if the price of natural gas is higher than other fuels, natural gas technologies are often not included in the best solution. All of the necessary costs, emissions, and operating information is provided for the the Finnish power network in order to employ a multi-objective optimization on the system.

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Chapter 1 Introduction

1.1 Overview

With an increasing awareness of the importance of energy conservation, solutions are being developed by researchers and scientists to deal with this issue. The word “solutions”, rather than “solution” is used, with the understanding that there is not just one solution to the world’s energy problems, but many. Most of the energy issues that we face today can be summed up into a single term: sustainability. Sustainability is defined by the World Commission on Environment and Development as “the way to meet the needs of the present without compromising the ability of future generations to meet their own needs” [1]. Four aspects that are considered to be pillars of sustainability are the technological, environmental, economic, and social aspects of a system [2]. With this in mind, operating at the lowest cost cannot be the only criterion for the development of a system. The system must also incorporate some, if not all of the other aspects of sustainability. The environmental aspect can be incorporated by attempting to reduce undesirable emissions such as CO_2, NO_x, SO_x and particulate matter. The technological aspect can be included by improving the inner workings of the system and, thus, increasing the efficiency. The economic aspect can be taken into account by considering all long term and short term costs such as construction and fuel costs, respectively. The social aspect can also be incorporated by including measures for the acceptability of the energy-consuming technology under consideration.

Two systems are modeled in this paper: (1) the district heating system located in Helsinki, Finland and (2) the Finnish national electricity network. The Helsinki district heating system is recognized among European countries for its efficient use of energy [3]. Although most of the production for the system comes from fossil fuel technologies, the system takes advantage of combined heating and power (CHP) plants. The district heating system also operates centralized heat pumps and uses waste heat from at least one underground computer hall. Finland’s national electricity grid consists of a variety of power producers using fossil fuel technologies, hydroelectric plants, wind farms, and solar photovoltaics. The first of these systems is analyzed here with the upper level of the Sustainability Assessment Framework (SAF) developed in [4]. The SAF is a two-level hierarchical methodology that considers energy-mix planning (upper level) and technology development (lower level) [5]. This method is used in order to thoroughly assess energy systems and systems of systems with the goal of developing optimal system configuration solutions. The upper level assessment takes the entire network into account and views individual technologies as black boxes. Therefore, the inner workings of each technology are reduced to a single efficiency or a set of efficiencies to account for partial and full load. The network of power producers includes transmission loses and is evaluated based on criteria for some if not all of the aforementioned aspects of sustainability. The lower level assessment takes the inner workings of each individual technology into account. Here, more detailed decisions are made that affect different parts of the system such as the combustion temperature or the rotational speed of a shaft. All of the changes made are in effort to improve the thermodynamic efficiency of the system.

When optimizing a system in an attempt to design and operate optimally, each criterion considered, referred to as an objective function, is either minimized or maximized. This, of course, requires an efficient and effective algorithm. When the optimization problem is one of optimizing multiple criteria simultaneously, the problem is called a multi-objective optimization. In this thesis work, the Helsinki district heating system is optimized with respect to technological, environmental, and economic criteria or objectives. The result is a set of solutions in which post-processing techniques are applied in order to determine the best solution among the optimal ones chosen by the optimization algorithm. In addition, a model of the Finnish national electricity network is proposed for future coding. Further work may also include the Finnish national electricity grid as part of a larger optimization problem that includes the Helsinki district heating system and other parts of the Northern European Electricity Market. This being said, the district heating system is the main focus of this thesis work.

1.2 Energy and Exergy Considerations

Energy is a concept that emerges from the 1st Law of Thermodynamics. While it underlies our understanding of many physical phenomena, it is stated in ways that are not laws but theorems (e.g., that of conservation of energy) which are provable and, thus, not laws. The most general statement of the 1st law which avoids this pitfall is that by Gyftopoulos and Beretta who define this as follows [6]:

> *"Any two states of a system may always be the end states of a weight process, that is, the initial and final states of a change of state that involves no net effects external to the system except the change in elevation between z_1 and z_2 of a weight. Moreover, for a given weight, the value of the quantity $Mg(z_1 - z_2)$ is fixed by the end states of the system, and independent of the details of the weight process, where M is the mass of the weight and g the gravitational acceleration."*

Using only the same primitive variables of physics, i.e., mass and elevation, and the gravitational constant, the 1st Law of Thermodynamics implies the existence of a quantity or property called the "energy" via simply the change in elevation of a weight. This change is a mechanical effect equivalent to any other mechanical effect or combination of mechanical effects. This concept is illustrated in Figure 1.1. The illustration shows that the perfectly insulated system experiences

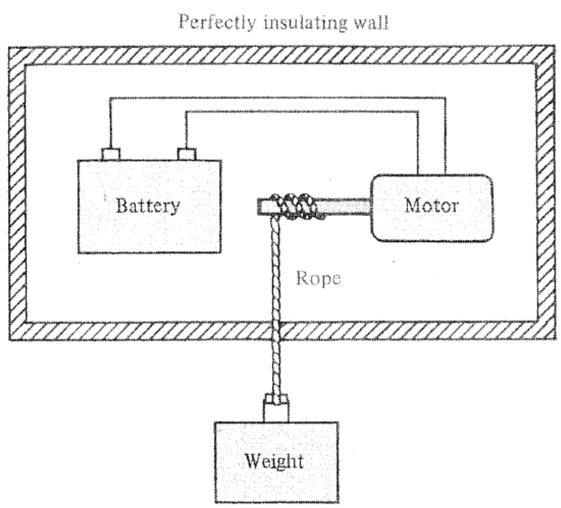

Figure 1.1 Example of a system that can experience a weight process only [6].

solely rope crossing the system boundary. The length of the rope crossing the system boundary from state 1 to state 2 is consistent with the change in elevation of the weight from state 1 to state 2. To reiterate, regardless of the number of processes in the system or the intricacies of these processes, the net effect is simply the raising or lowering of the weight. Furthermore, although the statement of the 1st Law does not extend to systems in which relativistic effects are important, it can be generated to include these. The reader is referred to [6].

An important consequence of the 1st Law is that every system in any state must have a property that we call energy. The weight process describes the change in this energy. It is important to note that energy in any state is relative to another state. For example, in the case of a weight process, the energy at elevation z_1 or z_2 is not independently given. It is the process or change in state that describes the amount of energy converted or used. The elevations z_1 and z_2 could be given energy values, but these values would still have to be relative to another or reference elevation. For example, the latter could be the ground over which the weight hovers. This concept applies to all forms of energy, e.g., thermal, mechanical, chemical, etc. Figure 1.2 is an illustration of a simple system with an energy input and energy output. The system is the red

Figure 1.2 A system with a boundary, an input and an output.

box. It is surrounded by a system boundary (black dashed line) and has an energy input and output. Energy converting systems always have losses. Thus, the energetic efficiency of a system is an important parameter and can be given by

$$\eta \equiv \frac{Energy\ Rate\ Ouput}{Energy\ Rate\ Input} \tag{1.1}$$

By definition, an efficiency is between 0 and 1. The energy rate output in this case is the desired energy rate output. This means that it is the energy needed from the system for a certain process.

Exergy, which is a special case of the generalized available energy as defined in [6], is another important concept. To put it simply, exergy is a measure of the quality of the energy.

While it has the same units as energy, an exergy analysis combines both the 1st and 2nd Laws of Thermodynamics when assessing a system. The most general statement of the 2nd Law of Thermodynamics originally stated by Hatsopoulos and Keenan [7] and later used by Gyftopoulos and Beretta is [6]:

> *"Among all the states of a system that have a given value of energy, and a given value of the amounts of constituents and the parameters, there exists one and only one equilibrium state. Moreover, starting from any state of a system it is always possible to reach a stable equilibrium state with arbitrarily specified values of the amounts of constituents and parameters by mean of a reversible weight process."*

From the statement of the 2nd Law, we can conclude that there exist many states that a system can go through while still containing the same energy value, number of constituents, and number of parameters. These different states have different levels of available energy or exergy. Utilizing this concept of the exergy, all forms of energy (namely mechanical, thermal, chemical, etc.) can be viewed on the same basis. This designation of the energy as mechanical, thermal, chemical, etc. is one of convenience only since energy is simply energy and the designation a way of referring to the energy contained in a fuel or in a hot ingot or in a moving fly wheel. Furthermore, different forms of energy transport (e.g. work, heat, and mass interactions) which involve the conversion of one form of energy into another come with varying degrees of loss in the quality of the energy. Thus, the transport of 100 J of energy in a work interaction is equivalent to 100 J of exergy transport, i.e., there is no loss in the quality, while 100 J of energy in a heat interaction is not equivalent to (in fact, is less than) 100 J of exergy transport unless the temperature at which the transport takes place approaches infinity. Thus, the amount of exergy transported by a heat interaction depends on the temperature and can be expressed by

$$E_{qk} = \left(1 - \frac{T_o}{T_k}\right) Q_k \tag{1.2}$$

where E_{qk} is the exergy transported due to the heat interaction, T_o is the dead state temperature, T_k is the temperature at which the heat interaction occurs and Q_k is the amount of energy transported. As can be seen, E_{qk} is only equal to Q_k as T_k approaches infinity. Since this is far from the case for the energy conversion systems considered in this thesis work, energy transport in the form of a heat interaction will necessarily have a lower per unit exergy content than if it were transported via a work interaction. In addition, similar to the energetic efficiency, the exergetic efficiency is expressed as

$$\psi \equiv \frac{Exergy\ Rate\ Ouput}{Exergy\ Rate\ Input} \tag{1.3}$$

If the energy rate input for the system of Figure 1.2 is for a fuel then the exergy rate input varies by as much as ±10% from the energy value depending on the fuel used. The exergy to energy ratio is given by

$$\varphi \equiv \frac{Exergy\ Rate\ Input}{Energy\ Rate\ Input} \tag{1.4}$$

The ratio, φ, is a value somewhat greater or somewhat less than unity for most fuels.

1.3 District Heating

District heating (DH) is a technique used for distributing hot water generated in a centralized location for residential, commercial, and industrial requirements such as space heating, water heating, and other industrial processes requiring steam or hot water. DH is most commonly used in city settings where the energy demand is high and the area densely populated. According to [8], the most important characteristic for a true district heating system is that it collects as much waste heat from the district as possible. This may include but is not limited to waste heat from the community, industrial processes, refuse incinerators, and sewage works. Geothermal heat can also be used. A wide variety of fuels such as hard-to-dispose-of municipal wastes, wood, and biogases can also be used to generate heat for district heating systems. This flexibility allows for the substitution of cheaper fuels rather than more expensive oil or gas.

For some cities, a district heating system is more energetically efficient than generating heat from boilers in each building or even using heat pumps in each building. This is achievable by economies of scale. If a district heating system reduces overall energy usage, then the fuel costs and environmental pollution can be reduced. Because heat production is centralized in a district heating system, the combustion process can be monitored and controlled, thus, increasing the overall combustion efficiency. Also, large producers can be placed on the outskirts of the city so that the effects of the gases emitted during production are less severe within the city limits.

1.3.1 Common District Heating Technologies

Typical district heating systems consist of (but are not limited to) three kinds of producers: Combined heat and power (CHP) plants, heating plants (or boilers), and heat pumps. A CHP plant has a large capital cost for construction and installation, but it possesses advantages in the long run. A CHP plant takes advantage of the low temperature and low pressure (low quality) steam that results from generating power. In a conventional power plant, this low quality steam is "dumped" into the environment because it is not in a state where it is able to be easily converted to work. Therefore, conventional power plants waste large amounts of energy. A CHP plant takes advantage of this steam and supplies the district heating system with the otherwise wasted energy. Figure 1.3 compares the energy inputs and outputs from a CHP plant with that of

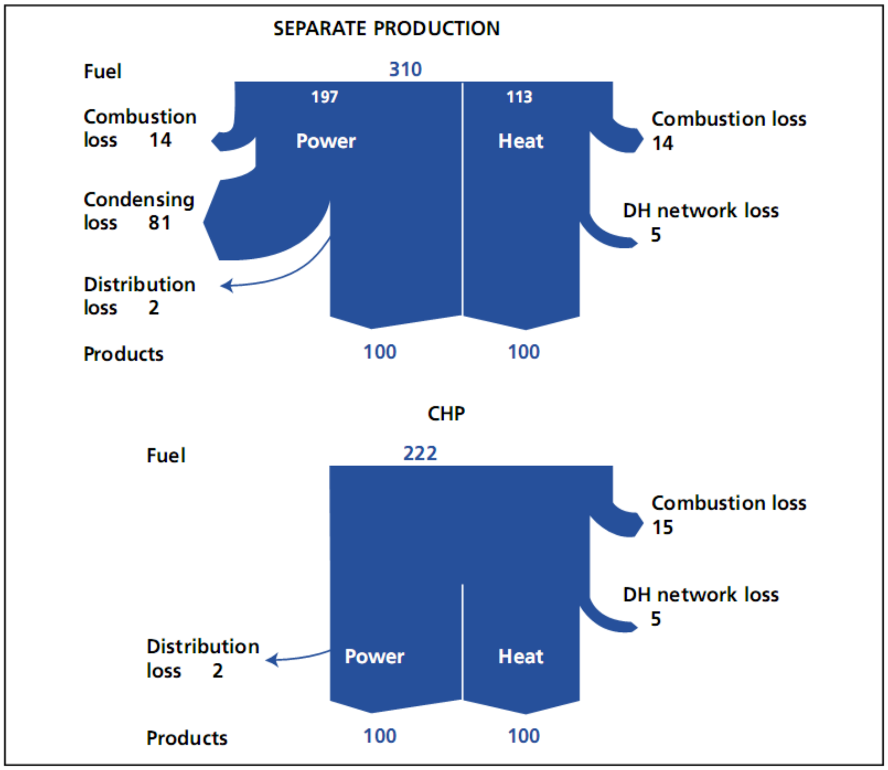

Figure 1.3 Diagram that compares CHP production to separate power and heating production [9].

a conventional power plant and heat generated from a separate boiler plant [9].

The diagram depicts two separate cases: 1) power and heat generated separately and 2) power and heat generated from a CHP plant. In both cases 100 units of heat and 100 units of power are generated, yet in case 1, 310 units of fuel energy are needed whereas in case 2, 222 units of fuel energy are needed. The largest loss in case 1 is due to condensing losses (waste heat). This diagram shows that case 1 has an overall energetic efficiency of 64.5% whereas case 2 has an overall energetic efficiency of 90%. All of the energy that is not used to generate electricity in case 2 goes to heat. Of course, these energetic efficiencies are not entirely consistent with all similar technologies, but nevertheless it is an example that illustrates the usefulness of the cogeneration of heat and power from a single source. The energetic efficiency of a CHP plant is expressed as

$$\eta_{CHP} = \frac{\dot{W}_{out} + \dot{Q}_{out}}{\dot{m}_f LHV} \tag{1.5}$$

where $\dot{W}_{out}$ is the rate of the work out, $\dot{Q}_{out}$ the rate of the heat out, $\dot{m}_f$ the mass flow rate of the fuel, and LHV the lower heating value of the fuel. The exergetic efficiency of a cogeneration plant is

$$\psi_{CHP} = \frac{\dot{W}_{out} + \left(1 - \frac{T_o}{T_k}\right)\dot{Q}_{out}}{\dot{m}_f LHV\varphi} \tag{1.6}$$

Heating plants, also called boilers, generate heat only. Heating plants can be part of the main setup of the district heating network or they can be fringe producers. The energetic efficiency of a heating plant is

$$\eta_{heat} = \eta_{boil} = \frac{\dot{Q}_{out}}{\dot{m}_f LHV} \tag{1.7}$$

Note that the efficiency of the heating plant differs from the efficiency of the CHP plant solely because it does not produce work. This difference is the same when considering the exergetic efficiency of the heating plant where

$$\psi_{heat} = \psi_{boil} = \frac{\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_{out}}{\dot{m}_f LHV\varphi} \tag{1.8}$$

Although the yearly peak demand of Helsinki's DH system is only 2,100 MW, the system can reach a maximum capacity of 3,722 MW. The reason for this is due to the amount of time it takes to transfer hot water to a distant location. For example, if a demand occurred that exceeded the DH system's capacity of main producers, then production from a boiler(s) would be necessary. If the distance to the nearest producer is 5 km and the DH system transfer water at a rate of 5 m/s [10], then it will take about 17 minutes for the water to reach the demand location once it has left the boiler. Boilers are located strategically in the demand area so that hot water can be provided quickly regardless of where the demand is.

Heat pumps are unique relative to the previous technologies because they do not convert chemical energy into electrical energy. Instead, heat pumps use electrical energy and free energy from the environment (or another free source) in order to generate heat. Heat pump performance greatly depends on the free source of energy that is available. The performance of a heat pump is given by the coefficient of performance (COP). On an energetic basis the COP is given by

$$COP_{en} = \frac{\dot{Q}_{out}}{\dot{W}_{in}} \tag{1.9}$$

where $\dot{Q}_{out}$ is the rate of heat transferred out of the heat pump into the DH system and $\dot{W}_{in}$ is the rate of electrical work transferred into the compressor of a vapor-compression heat pump or pump of an absorption heat pump. It is typical for a COP to be greater than unity. This is due to the fact that the free energy is not counted as an energy cost. On an exergetic basis, the COP is given by

$$COP_{ex} = \frac{\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_{out}}{\dot{W}_{in}} \tag{1.10}$$

1.3.2 Transmission and Distribution

The transmission and distribution system transports the thermal energy to the users through a network of insulated pipes. Most piping systems are buried directly underground or placed in tunnels or concrete culverts. In hot water systems, delivering energy is typically effective up to about 15 miles from the source of generation. This distance can be increased to over 50 miles by the use of booster pumps located between the source of generation and the user. Most steam systems have much shorter ranges and reach to only about 3 miles. It should be noted that newer steam systems have longer ranges but are still not as effective at piping long distances as hot water systems [11].

From an economics standpoint, the distribution system is important in determining service areas for new or expanding systems. Some areas of a city cannot be profitably served if they are located too far from a source of generation. This is due to heat and pressure losses in the pipes, and it is also due to the capital costs of the pipes and their installation. Because of the high capital costs of a DH system, it is typical for this type of system to serve high-load, high-density areas such as large business districts, first, with expansion to lower density areas later [11].

1.3.3 Hot Water and Steam Systems

Hot water and steam systems are systems that are used for DH. They both possess advantages over one another, and these are discussed here. Steam systems are useful because pumps are not required for the system and steam systems can be one-way piping systems with no return. The end-process steam or condensate is simply discharged into the atmosphere at a suitable temperature. One of the principal disadvantages of a steam system is its limited piping range as previously discussed. Another disadvantage is the degradation of high temperature, high pressure steam. If steam is extracted from a cogenerator, which is often the case, a great deal of electricity generation can be sacrificed. From a transmission standpoint, losses tend to be greater in steam pipes, and steam pipes must be metal. These are expensive and tend to corrode quickly unless the water is conditioned to prevent mineralization [11].

Hot water systems, on the other hand, have a much longer piping range, use less cogenerator steam, can use plastic pipes for transmission due to lower water temperatures, and lose a much smaller amount of energy during distribution. Hot water systems also have the advantage of being closed loop systems so that water and low-grade energy is not wasted. One of the main disadvantages is that pumps are required. This obviously increases the overall capital and operational cost. With a closed loop system, capital costs increase because twice as much piping is needed for the system. Instead of just having a supply pipe, as in the steam system case, the hot water system must have a supply pipe and a return pipe. Of course, an advantage is that there does not have to be a continued resupply of water as in a steam system. A hot water system also cannot provide high temperature, high pressure steam to a customer on the circuit. At best, the system can only be used to preheat [11].

1.4 Electricity Networks

Electricity networks are discussed here, but in less detail than DH networks since they are not the main focus of this thesis work. An electricity network may be thought of as consisting of three main divisions: production or generation, delivery or transmission and distribution, and consumption [12]. Electricity is modern society’s most convenient and useful form of energy transport. Without such a convenient and high quality form of energy transport, the world’s present social infrastructure would not be feasible. The general concept of an electricity network is quite simple, however, in practice, it can become quite complicated. For example, each network may have a number of different kinds of power stations interconnected by a system of tielines, transmission lines, subtransmission lines, and distribution networks. This overall network provides various customers with different voltage levels of electricity [13].

Electricity networks can provide energy in the form of electricity from many different sources. The most common source is that from fossil fuel technologies, but other sources include nuclear, hydroelectric, geothermal, solar, and wind technologies. Figure 1.4 is a pie chart provided by the International Energy Agency (IEA) from member countries of the Organisation for Economic Co-operation and Development (OECD) [14] from January to November 2012. Finland became an OECD country in 1969. All OECD countries are developed countries and a list can be found from [15]. As can be seen from the pie chart, combustible fuels (or fossil fuels) dominate in electricity production with 63%. Nuclear power generation and hydroelectric power generation are close, generating 18% and 14% of the total electricity production, respectively. All other sources, including geothermal and renewable energy, other than hydroelectric power, make up a small 5% of the electricity production.

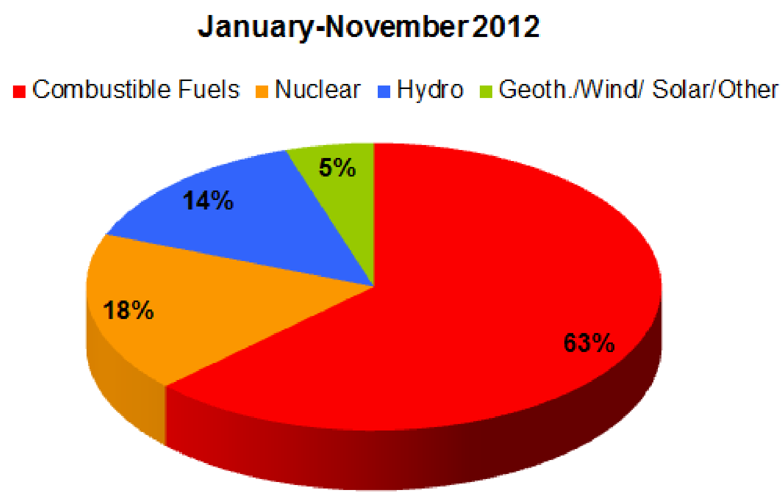

Figure 1.4 Electricity Generation by source from OECD countries from January-November 2012. Provided by the IEA [14].

1.5 Thesis Objectives and Tasks

The objective of this thesis work is the application of modeling and optimization techniques to the Helsinki DH system and the establishment of the basis for modeling and optimizing the Finnish power network. In the future, these two models may be combined and connected to existing models in central and northern Europe and become part of a larger optimization problem. Tasks specific to the Helsinki DH system include the following:

- Gather Data on the Helsinki DH system and understand its operation
- Develop a quasi-stationary model of this system with linear and non-linear constraints using the node method
- Select and use criteria that will offer important economic, environmental, and technological tradeoff information
- Use a multi-objective optimization technique to generate tradeoff curves among the selected criteria

- Determine which of the optimal solutions generated are the best by applying post-processing techniques
- Use a sensitivity analysis for fuel costs to determine how the optimal solutions will change depending on fluctuating fuel prices

Tasks specific to the Finnish national power network include the following:

- Gather data on the Finnish electric power grid and understand its operation
- Develop a model with nonlinear constraints using the node method
- Select and use criteria that will offer important economic, environmental, and technological tradeoff information

Chapter 2 Review of the Literature

2.1 Introduction

This section discusses the application in the literature of some relevant modeling and optimization approaches to the synthesis and design of district heating systems and electricity networks. This chapter is divided into three sections: (1) district heating system modeling and optimization, (2) electricity network modeling and optimization, and (3) conclusions. The modeling and optimization of both DH systems and electricity networks have many similarities in that they both deal with the production of energy from generators, the transmission and distribution of that energy, and the consumption of that energy by users. Although only a basis for a model of the Finnish electricity network is developed in this thesis work, electricity network modeling and optimization techniques are discussed in this chapter because some of these concepts are adapted to the Helsinki DH system.

Subsections of the first two sections are divided on a paper-by-paper basis. The papers chosen are ones that provide relevant modeling and optimization concepts and information for the research conducted in this thesis work. In the third section, conclusions are drawn. These conclusions are carefully chosen and are useful in the research presented in the following chapters.

2.2 District Heating Modeling and Optimization

2.2.1 An Environomic Approach for the Modeling and Optimization of a DH Network: Methodology [16]

Curti, von Spakovsky, and Favrat [16] is the first part of a two part journal series. It includes the problem definition and methodology. The succeeding subsection discusses part two [17] of this series. Curti, von Spakovsky, and Favrat model and optimize a DH network that consists of a central plant and decentralized heat pumps. The central plant includes a centralized heat pump, a gas turbine cogeneration unit, a cogeneration gas reciprocating engine unit, and a gas furnace. While the use of heat pumps in a DH network can offer an energy of conversion or coefficient of performance of over 100%, heat pumps cannot produce the high temperature energy of which a gas turbine or furnace, for example, are capable. Because adapting the delivery temperature to the highest temperature user is of paramount importance, heat pumps cannot be the only source of heat production in a DH network. Therefore, the best system configuration, discussed by the authors, consists of the main supply coming from a centralized plant augmented by that coming from the decentralized heat pumps.

The system under consideration can be seen in Figure 2.1. The diagram includes resource processing and energy conversion, the central plant, heat exchangers and heat pumps of the users, and supply and return lines. This so-called super-configuration is used to determine a set of optimal configurations based on a set of technical, economic, and environmental criteria. The

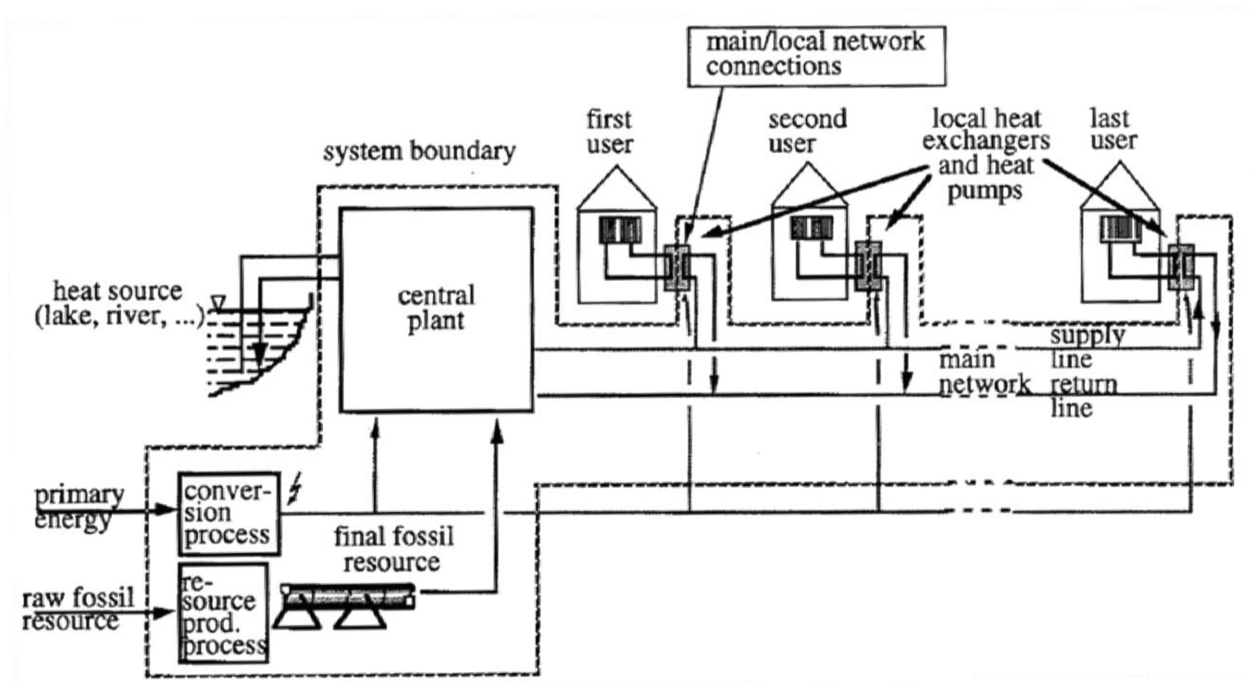

Figure 2.1 Diagram of the DH system under consideration [16].

system does not include any of the distribution network located between the heat exchangers and the users. Instead, only the main network is part of the system. Also, as can be seen, the central plant is connected to a heat source (lake, river, etc.) for the purpose of supplying the heat pumps with free energy.

This model developed by the authors is classified as an environomic model [18-20] because it simultaneously takes into account the economic, environmental and technological aspects of the system. In this case, these aspects are taken into account in a single objective function. The model of the system consists of thirty-three independent variables and is described as

Minimize: $$\dot{C}_{total\ln et}(\vec{x},\vec{y}) = \dot{C}'_{equip}(\vec{x},\vec{y}) + \dot{C}'_{res}(\vec{x},\vec{y}) + \dot{C}_{pol}(\vec{x},\vec{y}) - \dot{B}_{prod}(\vec{x},\vec{y}) + \dot{K} \tag{2.1}$$

w.r.t. $\vec{x}$

subject to: $$h_j(\vec{x},\vec{y}) = 0 \quad j = 1,...,J \tag{2.2}$$

$$g_k = (\vec{x},\vec{y}) \geq 0 \quad k = 1,...,K \tag{2.3}$$

where $$\vec{x} = (x_1, x_2, ..., x_I) \tag{2.4}$$

$$\vec{y} = (y_1, y_2, ..., y_J) \tag{2.5}$$

$$x_{i\_\min} < x_i < x_{i\_\max} \quad i = 1,...,I \tag{2.6}$$

$$y_{i\_\min} < y_i < y_{i\_\max} \quad j = 1,...,J \tag{2.7}$$

where $\dot{C}_{total\ln et}$ is the total cost rate, $\dot{K}$ a fixed cost rate not associated with the operation of the system, $\dot{B}_{prod}$ the rate of revenue gained, $\dot{C}_{pol}$ the pollution cost rate incurred while the system is operating, $\dot{C}'_{res}$ the resource cost rate and $\dot{C}'_{equip}$ the equipment cost rate. The single quotation mark (′) signifies that these are extended cost rates which include external costs such as those associated with a cradle-to-grave Life Cycle Analysis. The inequality constraints of Equation (2.6) represent the limits placed on decision variables while those of Equation (2.7) represent the limits placed on a number of the dependent variables.

Going in to more detail, the pollution cost is determined by

$$\dot{C}_{pol} = c_{pol_i} f_{p_i} p_i \tag{2.8}$$

where c_{pol_i} is the unit pollution damage cost of the emitted substance i which can either be expressed in terms of monetary units or exergy, f_{p_i} the penalty factor assigned to emission i, and p_i the measure of emitted substance i. The penalty factor f_{p_i} takes the location of the emitted substance into account as well as assigns a critical value to each emission. Therefore, the same measure of pollutant i may have a different penalty factor if it is emitted in a different area. Furthermore, the same percentage increase in an emission does not always result in the same percentage increase in the penalty factor. The extended equipment cost rate $\dot{C}'_{equip}$ takes the equipment cost rate $\dot{C}_{equip}$ as well as the cost rate for pollution emitted for equipment usage $\dot{C}_{pol\_equip}$ in to account. In the same manner the extended resource cost rate $\dot{C}'_{res}$ takes the resource cost rate $\dot{C}_{res}$ as well as the cost rate for pollution emitted for resource production $\dot{C}_{pol\_res}$ into account. The rate of revenue gained $\dot{B}_{prod}$ takes takes the sales of services/products by the system into account. For the cogeneration units this includes the sales of heat and electricity, and for the heat-only production units this includes the sales of heat.

In this problem, all units are converted to costs. While this cradle-to-grave Life Cycle Analysis is able to offer a good solution for the problem at hand, there is an inherent loss of data due to the conversion of all units, namely units for emissions, to monetary units. Multi-objective optimization techniques which offer a broad range of solutions for a single optimization are discussed in later sections in Chapter 2.

2.2.2 An Environomic Approach for the Modeling and Optimization of a DH Network: Application [17]

The second part of this series, of papers by Curti, von Spakovsky, and Favrat discusses the application of the methodology briefly described in the previous section and the results. A genetic algorithm is used to optimize the optimization problem. A demand is met based on four categories of users as seen in Figure 2.2. The demand categories are temperature based and are based on real data from a neighborhood of Lausanne, Switzerland called Lausanne-Ouchy [21]. Each of the four categories contains three separate districts. The numbers below each category represent the supply temperature and the return temperature, respectively. The a) district is shown first in each category, the b) district second, and the c) district third. The a), Lausanne-Ouchy, district contains an older system with less than optimal insulation and heating losses. Therefore, the district requires a larger amount of high temperature heat (see categories 3 and 4) compared to the other two districts. District b) and c) represent more modern districts, and

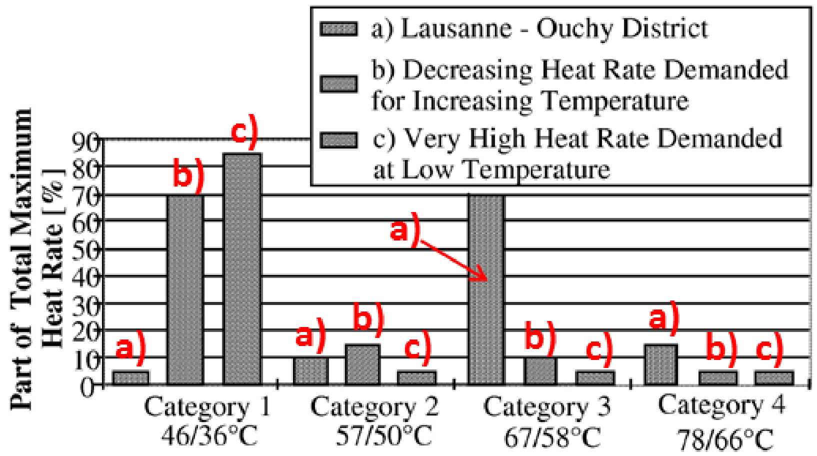

Figure 2.2. Typical heating demand for Lausanne-Ouchy and lower temperature districts [17].

therefore less high temperature heat is needed. District c), furthermore requires less high temperature heat than for district b).

The first set of solutions consists of two scenarios, one including pollution costs and one excluding pollution costs for the Lausanne district. Each of the scenarios is considered for three sets of gas prices (2, 5 and 8 CHcts/kWh)[1]. The result is a set of six optimal system configurations involving different combinations of gas prices and optimization criteria. The price for electricity used is 13 CHcts/kWh. The results can be seen in Figure 2.3.

The network supply temperature is listed above the bar for each of the optimal six configurations. In the first three, no emissions (CO_2 and NO_x) are taken into account (scenario 1) and the system does not incur a pollution cost. In the next three, the system does take emissions into account (scenario 2). For the first optimal configuration (2 CHcts/kWh, scenario 1), the best setup results when the gas furnace supplies most of the load, with the cogenerating gas reciprocating engine supplying a very small amount. This is because pollution is not taken into account, and natural gas is cheap. The gas engine contributes such a small amount of supply that it is does not even register as a contributor on these plots. For the second and third optimal configurations (5 and 8 CHcts/kWh, scenario 1), as the price of natural gas increases, more of the supply comes from the centralized heat pump. This shows that if the price of natural gas is high enough then, economically, heat pumps can be a better choice. For the fourth optimal

[1] CHcts represents a centime which is one hundredth of a swiss franc.

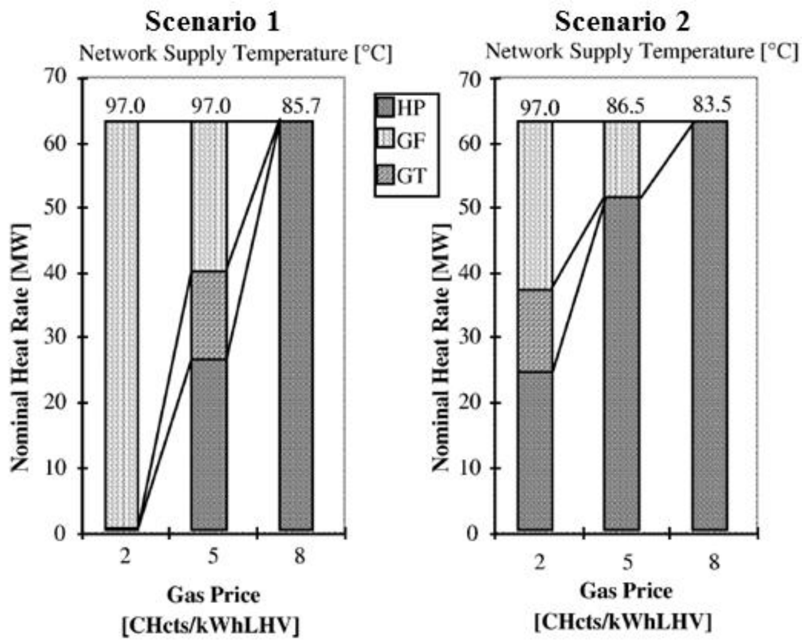

Figure 2.3 Results for six optimizations (3 thermoeconomic and 3 environomic) with a breakdown of the supply contributed to each user [17].

configuration, even though the price of natural gas is low (2 CHcts/kWh, scenario 2), the pollution cost keeps the system from operating only natural gas technologies. For configurations five and six (5 and 8 CHcts/kWh, scenario 2), once natural gas prices are sufficiently high, the heat pump is utilized. In configuration five the heat pump dominates the supply with a small amount coming from the gas furnace, and in configuration six, the heat pump supplies the entire network.

Results are also generated for demand a) of Figure 2.2 for an exergy life cycle analysis.

Table 2.1 Life cycle exergy distribution from an optimization based on exergy terms alone (without pollution costs) for the demand of Lausanne-Ouchy [17].

Life cycle exergy amounts	[kWh·year^{-1}]
Equipment	1.12 E+05
Network	7.52 E+05
Operation	1.72 E+07
Total	1.81 E+07

This means that the optimization is done based on an exergy formulation alone. For the optimization, pollution costs are neglected. These results can be seen in Table 2.1. It can be seen that the largest exergy cost comes from operation of the system (95%) while the construction of the network (4%) and manufacturing of the equipment (1%) contribute a significantly smaller amount of the exergy cost. While the configuration is not explicitly discussed, the authors mention that decentralized heat pumps, while still not a significant part of the solution, are shown to be useful when the optimization is based on this exergy formulation. For these results, the optimum network configuration gives an optimal supply temperature of 68.9 °C. At this temperature, the network can satisfy the first three temperature categories in Figure 2.2, but it cannot satisfy the fourth. Therefore, in all but the fourth category a lower optimal supply temperature is possible since the decentralized heat pumps can be used to raise the temperature for users who require higher temperature heat.

The conclusion is that a best configuration may consist of the use of several technologies, a single technology, or any number of technologies with the inclusion of decentralized heat pumps. Optimal system configurations are sensitive to market conditions as well as the criteria selected for their optimization. The results also demonstrate the usefulness of such an approach to the synthesis and design of a DH network.

2.2.3 Environomic multi-objective optimization of a DH network [22]

In [22], Molyneaux, Leyland, and Favrat take the optimization process from [16, 17] one step further and use a multi-objective optimization technique in order to optimize the cost and pollution criteria without combining them into a single objective function. The main goal of this paper is to reproduce the results of the previous work using a new and improved technique, decrease the simulation time of the previous work, offer a more complete solution than the previous work, and consider more tradeoffs from different technology types. This is accomplished by using a Clustering Pareto Evolutionary Algorithm (CPEA) [23, 24]. The advantage of this algorithm and other multi-objective algorithms is that the objectives are kept separate for the entire optimization process and the resulting tradeoff curve, called a Pareto frontier or front, is composed of a set of solutions which provides the designer with not only a greater number of possible optimal solutions but also a clearer understanding of how each is arrived at. This Pareto frontier is illustrated in Figure 2.4.

This tradeoff curve represents a set of optimal solutions for two criteria, in this case cost and pollution. The assumption is that when cost is at its lowest value, pollution is at its highest value, and when pollution is at its highest value, cost is at its lowest value. All solutions on the curve are considered non-dominated solutions, meaning that they are mathematically equivalent.

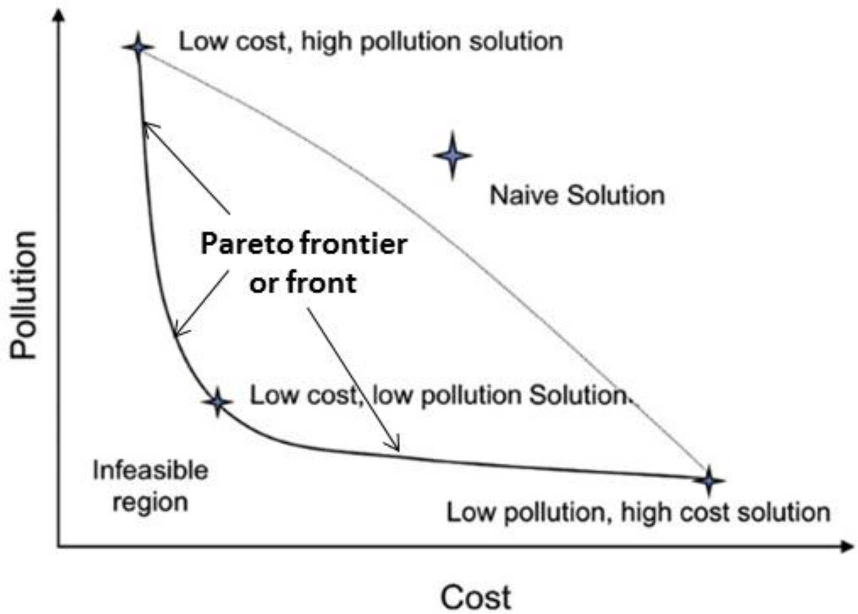

Figure 2.4 Multi-objective tradeoff curve; also known as a Pareto frontier [22].

Because of this, subjective post-processing techniques must be applied to solution set in order to determine the best solution from the set of optimal solutions. The space located below the curve is the infeasible region and the space above the feasible, although not optimal region. The authors also include a naïve solution in the figure to illustrate the point that this solution is feasible, but it is far from the optimal tradeoff curve, the Pareto front.

CPEA performance is compared with the performance of the GA from [16, 17] by running the single objective environomic optimization in the CPEA and comparing the results to the previous GA results. This is done for a single natural gas and electricity price with and without pollution costs considered. For the minimization of costs case (no pollution considered), ten optimizations (for verification) showed optimal results that are equal. Furthermore, the algorithm proved to be much quicker, reaching a solution with about 40 times fewer evaluations.

For the case with pollution included, the configuration was slightly different, allocating costs to different parts of the objective function from the previous solution, yet retaining the same overall cost.

The multi-objective optimization technique simultaneously optimizes the cost and CO_2 of the DH network resulting in a tradeoff curve of solutions. The results for this optimization can be seen in Figure 2.5 and show optimal solutions for CO_2 emissions versus the total system costs.

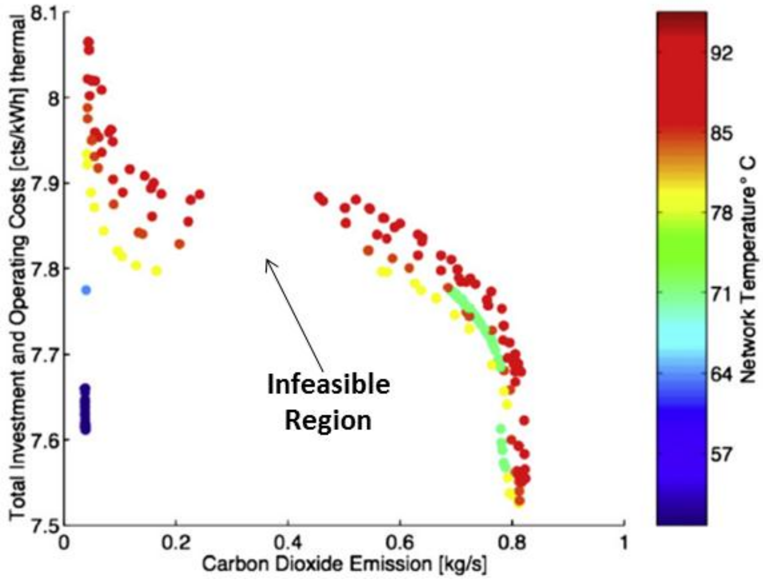

Figure 2.5 A tradeoff Pareto front of optimal solutions for the DH system [22].

There happens to be a region that is infeasible due to operational constraints; this is labeled in the figure. The tradeoff Pareto front also displays the network supply temperature. Note that the Pareto front does not mimic the commonly depicted Pareto front as in Figure 2.4. The behavior of a Pareto front depends on the problem formulation and therefore not all Pareto fronts will display the same kind of behavior. Generally, in Figure 2.5, solutions with a lower cost have a larger amount of emissions, and solutions with a small amount of emissions have a larger cost. The dark blue dots represent solutions with a relatively low cost and low level of emissions; yet, the drawback of these solutions is that the temperature is too low to satisfy all of the categories of users in Figure 2.2.

A post-processing sensitivity analysis is conducted for a range of costs in the Pareto solution set and this can be seen in Figure 2.6. There is a sudden sharp change in the figure which represents the change from multiple technologies being used (heat pump, gas turbine, heater) to a single large heat pump being used. It is determined that the best economic solution is one which involves heat generation from a gas turbine cogeneration unit, a heat pump, and an auxiliary boiler (heater). Yet, this solution involves high amounts of CO_2 emissions. An alternative solution offered is the use of a single large heat pump. This increases the overall cost

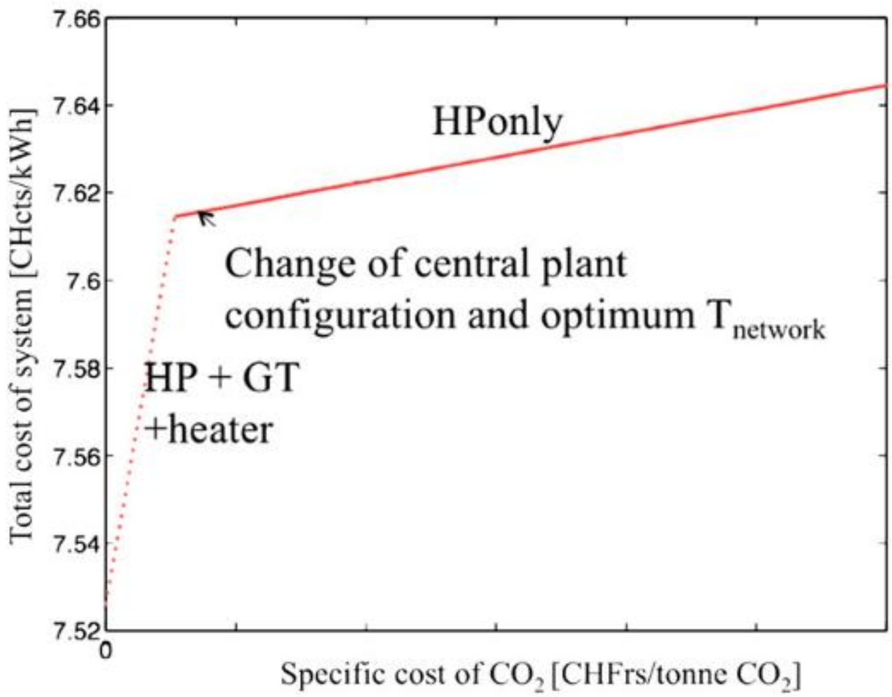

Figure 2.6 Specific cost of CO_2 versus the total cost of the system for a range of total system costs [22].

by a small amount while reducing CO_2 emissions significantly. Note that a high specific cost of CO_2 corresponds to a relatively low amount of CO_2 emissions produced.

2.2.4 Operational Optimization in a DH System [25]

Benonysson, Bøhm, and Ravn [25] discuss a method for the operational optimization of a DH network while taking into account supply and return temperatures as well as time delays in the piping system. The need for such a method is due to the dynamic and complex nature of a DH network. Time delays in the piping network tend to be large compared to other time delays experienced in the system, and, therefore, only these are considered. The authors have developed a model that simulates the flow and temperature of a DH network as it responds to the consumer demand and supply temperatures from the producers.

The objective to be minimized is the operational cost of the system. This includes fuel costs for the producers, electrical energy costs for the pumps, and negative costs (i.e., revenues) for the electricity produced from the CHP plants. The strategy for solving the model then becomes to (1) solve for the supply temperatures assuming time delays and (2) use the supply temperatures calculated in order to run the main model. The general methodology is shown in Figure 2.7. The first block of the flowchart represents the initial guess for the supply

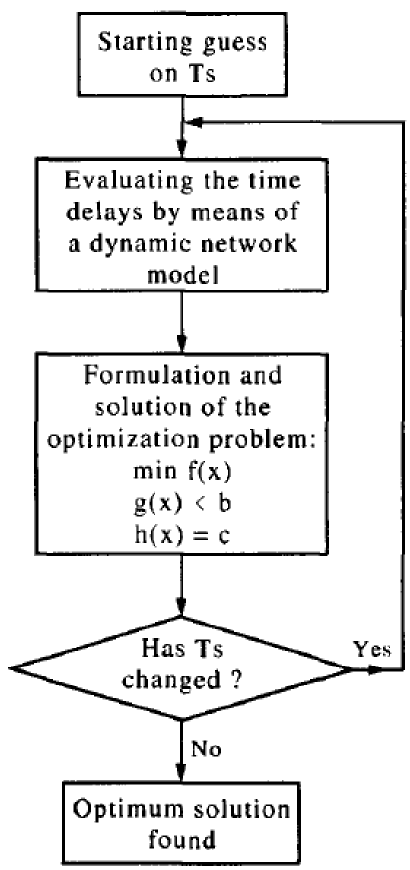

Figure 2.7 Flowchart of the general optimization method used with this model [25].

temperature. The second block represents the evaluation of the time delay based on the initial temperature guess. The third block represents the actual optimization problem. Here, $f(x)$ is minimized subject to inequality constraint, $g(x)$, and equality constraint, $h(x)$. The fourth block represents a decision that must be made by the model. If the supply temperature has been changed from the starting supply temperature, then the system configuration must be reevaluated. If the starting temperature is the same as the final temperature, then the problem ends at block five because an optimum solution has been found.

Boiler units, back pressure units, and extraction units are the three producers used in this model. The cost function for a boiler unit is given by

$$\text{minimize } \sum_{t=1}^{T}\left(\frac{Q_{b_t}}{\eta_b}c_b + \frac{P_{p_t}}{\eta_p}c_e\right) \tag{2.9}$$

where t is the time, Q_{b_t} is the heat production of the boiler at time t, η_b is the efficiency of the boiler, c_b is the unit cost associated with boiler operation, P_{P_t} is the pumping energy at time t, η_p is the efficiency of the pump, and c_e is the cost for electricity. For the boiler plant, Equation (2.9) takes into account both the fuel cost of running the boiler as well as the cost to pump water. Of course, when more production units are considered, the goal is to minimize the costs from the sum of all the producers. The objective function for the CHP plants, i.e., both the back pressure and extraction units, include terms for fuel consumption, electricity production, and pumping costs.

The model is run for a set of heat demands, which vary or remain constant from hour to hour. The demand period under consideration is a twenty-four-hour time period. Figure 2.8 shows demand hour versus transport time (from a plant to a chosen substation) for two cases: (1) the temperature is constant over the twenty-four hour demand period and (2) the temperature is changing over the course of the demand period. The constant supply temperature curve and the varying supply temperature curve exhibit similar behavior, but they are very different at many of the demand hours. It is important to note that for a number of the demand hours, the optimized temperature has a longer transport time, while for others as shorter. An optimized temperature does not always correspond to an optimized transport time and, thus, the two must be considered

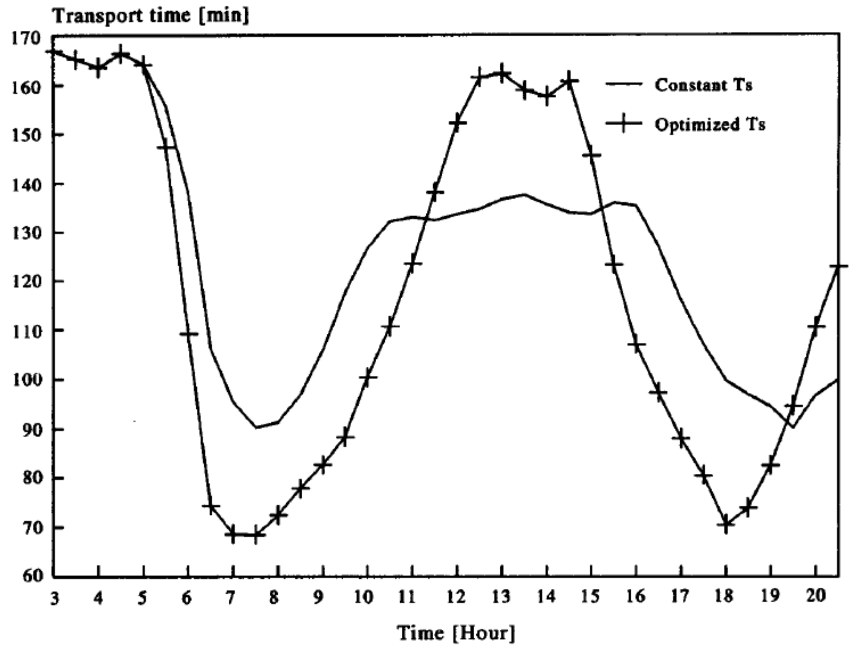

Figure 2.8 Transport time versus the time of day for a particular plant to reach a substation [25].

together in order to produce the best solution.

This model offers important DH information that is often neglected. The methodology presented here is able to closely monitor supply temperatures and transport times, while minimizing costs. Optimizing the supply temperature can result in monetary savings and emission abatement. A method for optimizing the transport time can result in satisfied customers and a better knowledge of the system supply temperature.

2.3 Electricity Network Modeling and Optimization

2.3.1 Summary of Environmental/Economic Dispatch Algorithms [26]

Talaq, El-Hawary, and El-Hawary [26] summarize environmental/economic dispatch algorithms dating from 1970 to the early 1990s. The authors discuss the different ways in which problems have been formulated in order to abate emissions. In the classical economic dispatch problem, the goal is to supply the required demand at the lowest cost possible. Obviously, this cannot be the only criterion considered if such a complex problem is to address a variety of concerns. As such, much thought has been given to considering economic, technological, and environmental concerns simultaneously. Four notable strategies to reduce emissions using one objective function are listed below:

1. Minimize emissions
2. Minimize emissions with a constrained cost
3. Minimize costs with controlled emissions
4. Minimize a weighted sum of costs and emissions

Strategy 1 [27], of course, reduces emissions to their lowest value possible, but it completely neglects costs. This method can be just as troublesome as solely minimizing costs, because low emission values generally correspond to high fuel costs. For strategy 2, the operator chooses a maximum allowable cost at which the system operates and then minimizes emissions. For strategy 3 [28], the operator chooses a maximum allowable level of emissions and then minimizes the costs. Strategy 4 includes both costs and emissions in a single weighted objective function. This is similar to the technique used in [29], by Lamont and Gent, where pollution is turned into a cost and the sum of the costs is minimized. The objective function for this method is described by

$$C = \sum_{i=1}^{I} \alpha_{1i} F_i + \alpha_{2i} M_i \qquad (2.10)$$

where C is the total cost, F_i is the fuel cost and tax on sulfur for each producer, M_i is the tax attached to each producer for other emissions, α_{1i} is the weight attached to the fuel cost and sulfur tax for each producer, and α_{2i} is the weight attached to the other emissions cost for each producer. It is up to the operator to determine the balance between the two weights and how this affects the behavior of the system.

This weighting technique plays a large role in the development of the tradeoff relations between costs and emissions developed by others. Delson's method [30] involves an objective function of the form

$$C = F + \alpha M \qquad (2.11)$$

where C is the total cost, F is the fuel cost, α is the weighting assigned to the emissions, and M represents the harmfulness of the emissions. The classic economic dispatch problem corresponds to $\alpha = 0$ (neglects emissions completely) and $\alpha = \infty$ the case where emissions are minimized and costs neglected. By changing α, one can conduct a sensitivity analysis on the solution space from one extreme (minimize costs solely) to the other extreme (minimize emissions solely). Using the same technique, Zahavi and Eisenburg [31] formulate the cost function as

$$C = \alpha F + (1-\alpha)M \tag{2.12}$$

where α is now a weight varying from 0 to 1 where sum of the weights is always equal to unity.

While this paper [26] discusses objective functions for costs and emissions, it does not go into great detail about system constraints. The discussion of this paper is simply meant to expose the reader to the evolution of economic and environmental objective functions. Furthermore, since this paper is a review of algorithms, no results are presented. The next paper [4] discusses constraints and a mathematical formulation which are much more useful for this research.

2.3.2 Multi-Objective Optimization of a Power Network Coupled to Distributed Producers and Microgrids [4]

In [4], a multi-objective optimization technique is applied to an electricity network and producers coupled to distributed producers via microgrids. A microgrid is a small-scale version of a centralized power system. Microgrids may include fossil and/or renewable fuel technologies, and are self-sustaining, i.e., are able to produce their own power. This paper shows that microgrids are able to increase network efficiency, reduce life cycle costs, and improve resiliency. Resiliency is defined as a network's or system's ability to recover to some normal state of meeting some part if not all of the demand after it has experienced an unexpected catastrophic event. The authors also introduce a new index for resiliency in this paper.

The general electricity network node model is illustrated in Figure 2.9 [4]. This figure is taken from concepts in [32-34]. Nodes, i, are locations that contain a number of power producers, q. Nodes have the ability to transfer energy to other nodes if they are connected by a high-voltage transmission line, y. Nodes can also be connected in such a way that they form a loop or arc, a. The optimization problem for this power network whether for planning or operation is defined by Equation (2.13) through Equation (2.17).

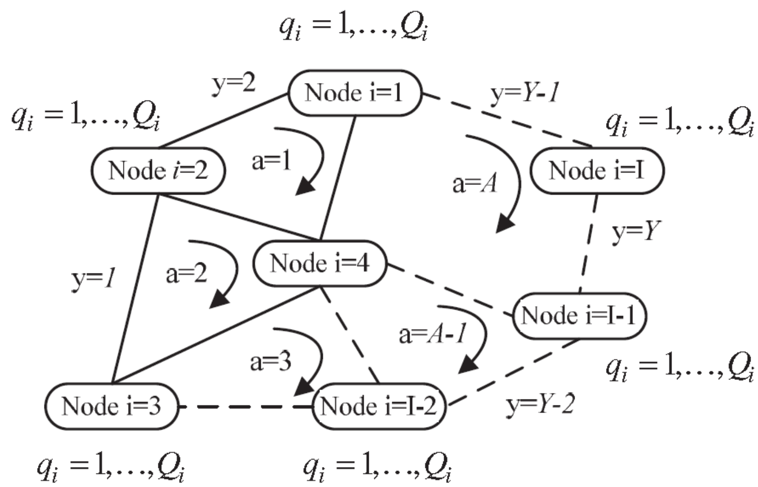

Figure 2.9 Schematic representation of a power network [4].

Minimize $$\bar{F} = \{\pm F_1, \pm F_2, ..., \pm F_{k-1}, \pm F_k\}^T \quad (2.13)$$

w.r.t. nonnegative P_{iq}^t and f_{ij}^t

subject to: $$P_{D_i}^t - \sum_{q=1}^{Q} P_{iq}^t - \sum_{j=1}^{J} \left[f_{ji}^t \left(1 - \alpha S_{ji} f_{ji}^t\right) f_{ji}^t - f_{ij}^t \right] \leq 0 \text{ for all } t \text{ and } i \quad (2.14)$$

$$\sum_{m=1}^{M} \pm S_{aim} \left(f_{aim}^t - f_{ami}^t \right) = 0 \text{ for all } t \text{ and } a \quad (2.15)$$

$$P_{iq}^{\min} \leq P_{iq} \leq P_{iq}^{\max} \text{ for all } i \text{ and } q \quad (2.16)$$

$$f_{ij}^{\min} \leq f_{ij} \leq f_{ij}^{\max} \text{ for all } i \text{ and } j \quad (2.17)$$

where F_k are different objective functions and depend on the nature of the problem. If an objective function is to be minimized, then the function F_k will have a plus sign in front of it. If it is to be maximized, then the function will have a minus sign in front of it. The inequality constraints in Equation (2.14) indicate that at each node the user demand must be satisfied by power produced within the node via producers and/or by power transferred into the node from other nodes. If the node under consideration is transferring power to other nodes without a reduction in the demand, then more power must be generated in this node or transferred to this node to meet the demand. The demand at node i and time t is represented by $P_{D_i}^t$. The term P_{iq}^t

is the (nonnegative) production of producer q from node i at time t. The power transferred from node j to node i at time t and the power transferred from node i to node j at time t is given by nonnegative f_{ji}^{t} and f_{ij}^{t}, respectively. The term $f_{ji}^{t}\left(1-\alpha S_{ji} f_{ji}^{t}\right)$ represents the total transfer of power to node i from node j at time t. Since there are losses in transmission lines, node i does not receive the full amount of power transferred from node j. The constants S_{ji} and α represent the reactance and transmission loss constants, respectively. These two constants take into account losses due to the size of the transmission line and the distance over which the line stretches between two nodes.

The remaining equations in this problem definition are the equality constraints of Equation (2.15) and the inequality constraints of Equations (2.16) and (2.17). The former represents Kirchhoff's voltage law (KVL). The value M is the total number of transmission corridors located in arc a (see Figure 2.9). The purpose of using KVL for the loops is to satisfy the energy balance when nodes are part of multiple loops. The latter, Equation (2.16) and Equation (2.17), represent the bounds on the decision variables for producer generation and flow through the transmission lines, respectively.

An SQP (derivative-based) algorithm [35] is used to carry out the optimization. Although the algorithm is a single objective optimization tool, the algorithm is used in such a way as to create Pareto fronts such as the one illustrated in Figure 2.10. To create Pareto fronts, all of the

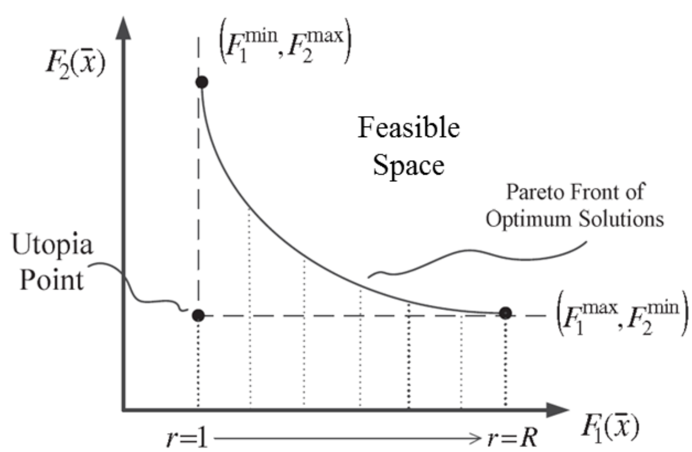

Figure 2.10 Representation of the Pareto front of optimum solutions [4].

objective functions are minimized and maximized independent of the other objective functions. This creates a feasible region for each objective function. This region is then discretized in order to include a sufficient number of objective function values between the minimum and maximum. For example, since costs and emissions are the objective functions of interest, the cost is first discretized and at each discretized value, the emissions are minimized. The process is then reversed and a particular emission's objective function is discretized and for this discretized value the costs are minimized. The result is a tradeoff curve including a set of solutions. This technique is repeated for all combinations of objective functions. An example of a resulting tradeoff curve or Pareto front from [4] can be seen in Figure 2.11 where two Pareto fronts are provided, one for scenario 1 and the other for scenario 2. The former is represented by blue line and is the scenario for a power grid and producer configuration without microgrids while the latter is represented by the red line and is the scenario for when microgrids as distributed producers are included. For this particular set of Pareto fronts, there is not much of a difference between the two scenarios. The figure does show, however, that microgrids are effective at improving or equaling the decreases in SO_2 emissions seen by the optimal scenario 1

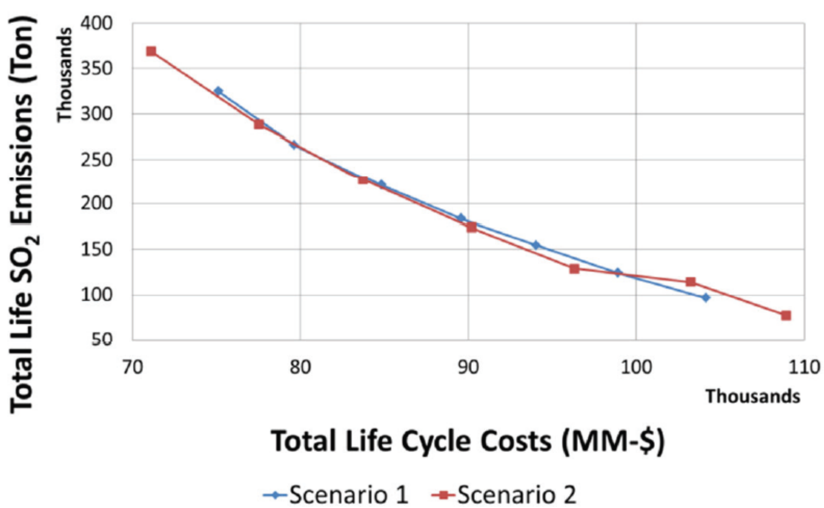

Figure 2.11 Tradeoff curve for total life cycle SO_2 emissions versus total life cycle costs [4].

configurations at all total life costs except the highest. Similar Pareto fronts for other combinations of the objective functions for costs, emissions, efficiency, reliability, and resiliency are given in [4].

In order to determine the best solution among the sets of optimal solutions which result from this multi-objective optimization, post-processing techniques are applied. In this case, fuzzy logic [36] and a weighting process are used. The fuzzy logic technique normalizes all objective functions so that units are comparable. The best case for the objective function is assigned a value of unity, while the worst case is assigned a value of zero. All values in between are ranked based upon a linear scale. For each solution, all objective functions are added. The best solution has the highest value. In contrast, the weighting process [37] requires interactions with decision makers and experts. Based on experience and reputation, these decision makers and experts are assigned values. Those more experienced and reputable receive higher values. These decision makers and experts then rank each objective function based on their perceived importance. The experience/reputation and decisions are combined in order to form a weight for each objective function. Again, the best solution is the case with the highest value.

2.4 Conclusions

From the review of the literature, the following conclusions are made about the modeling and optimization approaches for DH networks:

- The temperature at which a DH network operates is crucial to system performance. This is due to the fact that consumers require heating demands at various temperatures. Therefore, the temperature must be taken into account in any DH model.

- A single-objective optimization approach, whether considering costs or emissions, does not thoroughly capture the set of decisions that must be made for such a complex problem.

- Considering multiple objectives in a single objective function can offer an insightful result, yet there is an inherent "loss" of data associated with this method upon the conversion of non-commensurable units before the optimization is executed.

- A “thorough” model should include at the least technological, economic, and environmental aspects. It should also include the part-load behavior of producers as well as transmission losses.

- Data from objective functions in solutions sets can be conserved by using multi-objective optimization techniques to produce trade-off curves (Pareto fronts). Pareto fronts offer a large number of solution sets that are mathematically considered equivalent.

- The node method for a power network is useful in defining a large system while taking into account major transmission losses.

- The choice of post-processing techniques can greatly affect the nature of the solution. A thorough assessment of solution sets may take more than one method into account.

Chapter 3 Physical Systems and Models

This chapter describes the Helsinki DH network and the Finnish power network as well as the modeling techniques and mathematical optimization problem developed for the DH network and the information gathered to establish the basis of the model for the power network. In section 3.1, the DH network is described in general and is then discussed by each of the regions into which it is divided in sections 3.1.1 through 3.1.4. Next, in section 3.1.5, the system boundaries are discussed in terms of the production, transmission, and distribution systems. This is followed in section 3.1.6 by a description of the heat losses and pumping costs in the DH network. In section 3.1.7, the mathematical optimization problem is described for a single demand, while in section 3.1.8, a demand curve for the system is introduced, and the mathematical optimization problem for multiple demands is presented. Section 3.1.9 discusses the part-load efficiency curves developed for producers. The efficiency curves are important because all the objective functions are in some fashion a function of these curves. Lastly, in section 3.1.10, the optimization criteria are discussed. This section is further divided into sections 3.1.10.1 through 3.1.10.3 which discuss the economic, environmental, and technological criteria separately.

In the second principal section of this chapter, section 3.2, the information needed to establish the basis for the Finnish power network model is discussed. This includes defining the number of nodes and transmission lines; defining the voltage, length, and losses for transmission lines; and providing all of the necessary information (e.g. that on producers, etc.) needed to develop objective functions. Section 3.2.1 discusses the transmission and distribution network while section 3.2.2 discusses the model setup. This section goes into detail about the regions as well as the transmission lines connecting regions. Section 3.2.3 discusses all of the information collected for the development of objectives functions. Lastly, yearly demands and net imports are discussed in section 3.2.4.

3.1 Helsinki DH Network

The DH network located in Helsinki, Finland is a hot water DH system operated and owned by Helsinki Energy. All information gathered about the DH system is from Helsinki

Energy employees and consultants, the Helsinki Energy website [38], the Finnish Energy Industries [39], and the Energy Market Authority in Finland [40]. Links to each of the websites are provided for the sources, but some of the information was gathered from meetings and personal communications with these companies/organizations during a research trip to Finland. The DH system provides 93% of Helsinki's heating energy requirement to about 14,000 customer facilities of which most are residential buildings [38]. Over 6,000 GWh of heat is sold to customers per year. This averages to about 16.4 GWh per day. The system has a capacity of 3,172 MW with a peak load of 2,100 MW [41] in the coldest month. The system consists of 50 main producers of which 4 are CHP plants, 1 is a hot water storage tank, 5 are heat pumps, and 40 are boilers. According to [42], these producers are divided among 4 regions (North, South, East, West) and 11 sub-regions. The regions, sub-regions, and boundaries of the system can be seen in Figure 3.1.

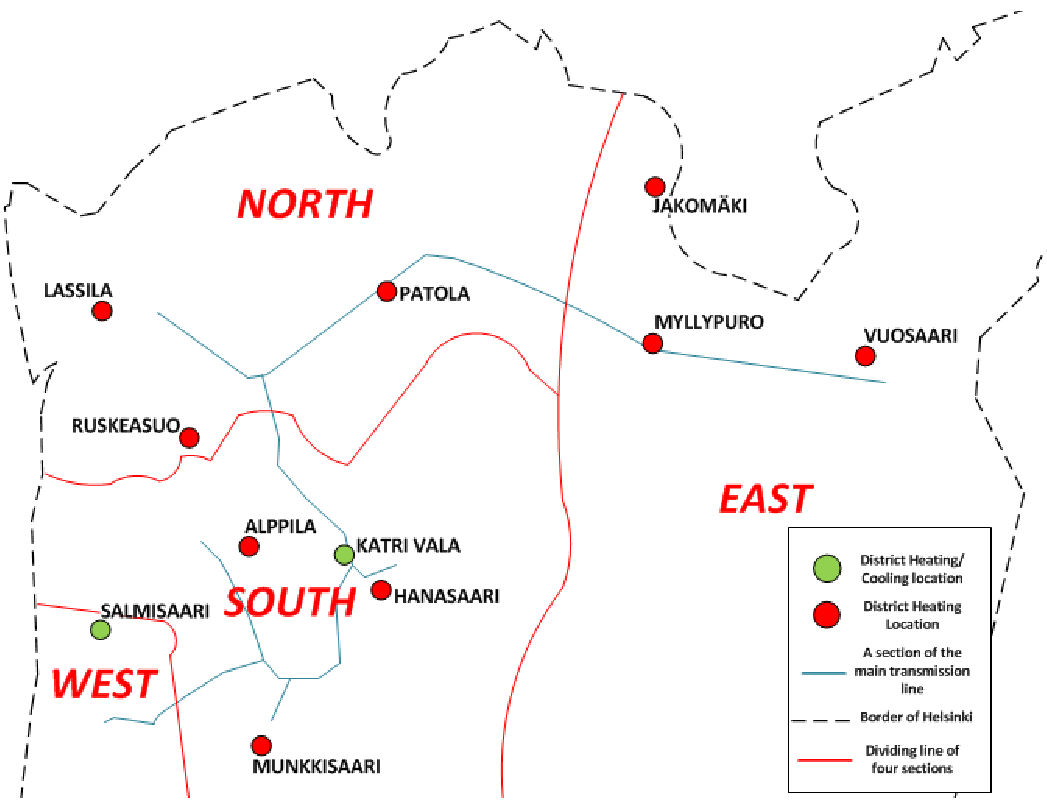

Figure 3.1 Helsinki DH and district cooling (DC) network divided into regions and sub-regions.

The black dotted line represents the border of Helsinki. The city is split into 4 regions divided by the red lines. Each region contains a number of locations or sub-regions where heat is produced. Locations that produce district heat only are designated by a red circle. Locations that produce both DH and district cooling (DC) are designated by a green circle. DC is not discussed in this paper, but Helsinki does have a separate DC system, which provides cold water to customers for chilling water and refrigeration processes. The main DH transmission lines are designated by the blue line. The transmission lines have both a supply and return section. It is strategically located close to locations of production. Each of the regions is discussed in more detail in the sections below. The efficiency values provided in each section are maximum efficiency values provided by brochures, articles, or personal communications. Part-load efficiencies are discussed later.

3.1.1 North Region

The North region consists of three sub-regions: Lassila, Patola, and Ruskeasuo. The peak capacity of this region is 826 MW. Table 3.1 is a list of the producers. The north region consists

Table 3.1 Producers in the North region.

North					
Sub region	**Generator Name**	**Generator Type**	**Fuel Type**	**Generator Capacity (MW)**	**Efficiency**
Lassila	Lboil1	Boiler	Oil	120	85%
	Lboil2	Boiler	Oil	120	85%
	Lboil3	Boiler	Oil	47	85%
	Lboil4	Boiler	Oil	47	85%
Patola	Pboil1	Boiler	Oil	40	85%
	Pboil2	Boiler	Oil	40	85%
	Pboil3	Boiler	Oil	40	85%
	Pboil4	Boiler	Oil	40	85%
	Pboil5	Boiler	Oil	40	85%
	Pboil6	Boiler	Oil	40	85%
Ruskeasuo	Rboil1	Boiler	Oil	63	85%
	Rboil2	Boiler	Oil	63	85%
	Rboil3	Boiler	Oil	63	85%
	Rboil4	Boiler	Oil	63	85%

only of boilers. This is due to the large industrial demand present in the region. Since industrial demands can be large and change very quickly, producers in the North region can be switched on and off quickly. It is important to note that all boilers are given the same maximum efficiency of 85% [43], since efficiencies are not known for individual boilers. In this way, one boiler is not given an advantage over another boiler.

3.1.2 South Region

The South region consists of four sub-regions: Alppila, Hanasaari, Katri Vala, and Munkisaari. The peak capacity of this region is 1167 MW. Table 3.2 is a list of the producers.

Table 3.2 Producers in the South region.

South					
Sub region	**Generator Name**	**Generator Type**	**Fuel Type**	**Generator Capacity (MW)**	**Efficiency**
Alppila	Aboil1	Boiler	Oil	35	85%
	Aboil2	Boiler	Oil	35	85%
	Aboil3	Boiler	Oil	35	85%
	Aboil4	Boiler	Oil	35	85%
Hanasaari	Hanasaari B	CHP	Coal	420	85%
	Hboil1	Boiler	Oil	47	85%
	Hboil2	Boiler	Oil	47	85%
	Hboil3	Boiler	Oil	47	85%
	Hboil4	Boiler	Oil	47	85%
	Hboil5	Boiler	Oil	47	85%
	Hboil6	Boiler	Oil	47	85%
Katri Vala	Hpump1	Heat pump	Electricity	18	3.5 (COP)
	Hpump2	Heat pump	Electricity	18	3.5 (COP)
	Hpump3	Heat pump	Electricity	18	3.5 (COP)
	Hpump4	Heat pump	Electricity	18	3.5 (COP)
	Hpump5	Heat pump	Electricity	18	3.5 (COP)
Munkkisaari	Muboil1	Boiler	Oil	47	85%
	Muboil2	Boiler	Oil	47	85%
	Muboil3	Boiler	Oil	47	85%
	Muboil4	Boiler	Oil	47	85%
	Muboil5	Boiler	Oil	47	85%

This region consists of 1 CHP plant, 5 vapor-compression heat pumps, and 15 boilers. This region is located in the downtown district of the city. The heat demand, therefore, represents industrial, commercial, and residential needs. While the Hanasaari B CHP plant produces a maximum of 420 MWth, it is also capable of simultaneously producing a maximum of 228 MWe. This CHP plant operates using a Rankine cycle. The 5 heat pumps are located underground in Katri Vala. These can be used for DH or DC. The COP listed is for winter operation. Winter and summer operations are significantly different due to the temperature of the resources available and the consumer's needs. A diagram of one of the heat pumps, illustrating operation during the summer and winter months can be seen in Figure 3.2 [44].

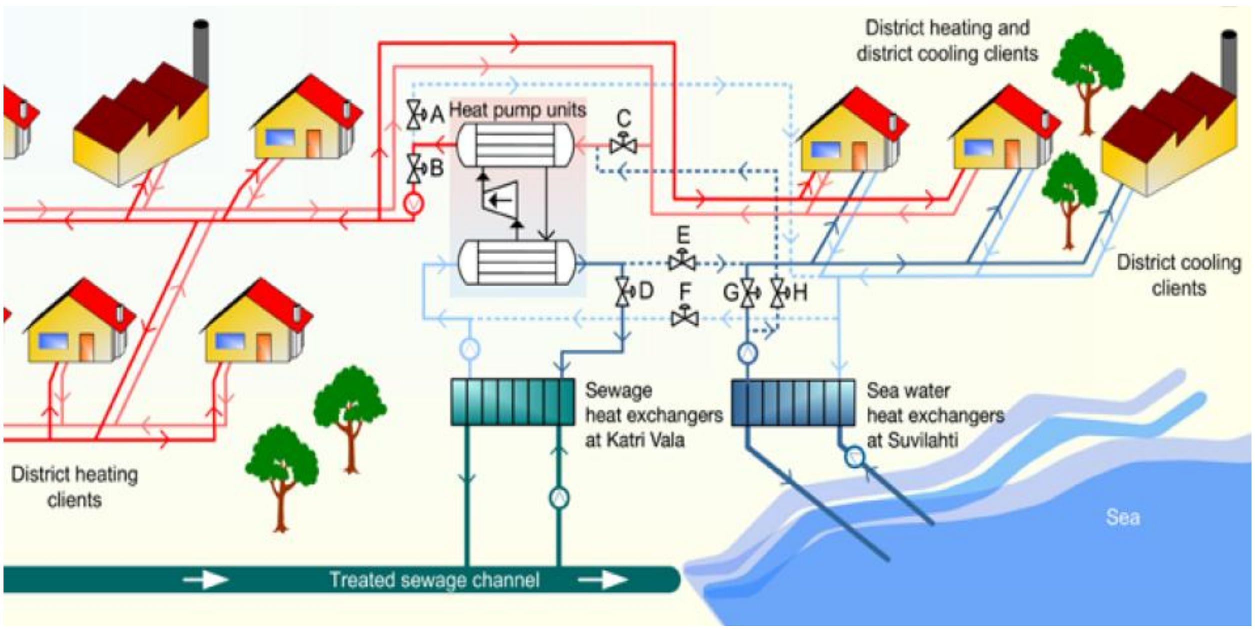

Figure 3.2 Schematic of a heat pump unit located at Katri Vala [44].

In this diagram, both DH and DC customers are represented. Each of the valves, labeled with a letter, represents a part of the system that can either allow fluid to flow through or redirect fluid flow. For winter operation, sewage is used to transfer energy into the heat pumps. Since the sewage is at a higher temperature than the seawater, more energy is transferred into the heat pump; and this results in a more favorable COP than if seawater were used. Any of the DC requirements are satisfied by seawater. For DH purposes, valves B, C, and D are open, while valve A is closed. For DC purposes, valve G is open. The diagram also displays the operation of

DC during the summer. Since the heating demand is lower during summer months, the heat pumps are used for DC. The high temperature heat exchanger (condenser) releases energy to the the seawater, and the low temperature heat exchanger (evaporator) supplies the cooling water. Valves A, C, E, F, and H are open while valves B, D, and G are closed.

3.1.3 East Region

The East region consists of three sub-regions: Jakomaki, Myllypuro, and Vuosaari. The peak capacity of this region is 1109 MW. Table 3.3 is a list of the producers. This region consists

Table 3.3 Producers in the East region.

East					
Sub region	**Generator Name**	**Generator Type**	**Fuel Type**	**Generator Capacity (MW)**	**Efficiency**
Vuosaari	Vuosaari A	CHP	Natural Gas	160	91%
	Vuosaari B	CHP	Natural Gas	415	92%
	Vuosaari Tank	Storage Tank	Natural Gas	130	92%
	Vboil1	Boiler	Oil	40	85%
	Vboil2	Boiler	Oil	40	85%
	Vboil3	Boiler	Oil	40	85%
Myllypuro	MBoil1	Boiler	Oil	120	85%
	Mboil2	Boiler	Oil	120	85%
Jakomaki	Jboil1	Boiler	Oil	22	85%
	Jboil2	Boiler	Oil	22	85%

of 2 CHP plants, 1 hot water storage tank, and 7 boilers. The Vuosaari A CHP plant is able to generate a maximum capacity of 160 MWe, while also generating heat. The power plant consists of two gas turbines, rated at 53 MWe, which operate in a combined cycle. The gas turbines are able to produce more power than their rated values during Helsinki's cold winters. The flue gas from these gas turbines vaporizes water, which in turn runs a steam turbine. This turbine is capable of producing 40 MWe of power. The maximum cogeneration energetic efficiency of the plant is 91% [45]. The Vuosaari B CHP plant has a maximum capacity of 470 MWe. It also operates as a combined cycle with two gas turbines rated at 163 MWe and one steam turbine at 145 MWe. The maximum cogeneration energetic efficiency of the plant is 92% [45]. The hot water storage tank receives energy from Vuoasaari B. It is filled during off peak hours when the

maximum capacity of Vuosaari B is not needed to meet the demand. The tank is insulated and the water remains in the tank at an acceptable DH temperature until it is needed (no longer than one day). The maximum discharge capacity of the tank is 130 MWth. It can store 25,000 m^3 of hot water at close to 100 °C.

3.1.4 West Region

The West region consists of one sub-region: Salmisaari. The peak capacity of this region is 620 MW. Table 3.4 is a list of the producers. The region consists of 1 CHP plant, 1 heating

Table 3.4 Producers in the West region

West					
Sub region	**Generator Name**	**Generator Type**	**Fuel Type**	**Generator Capacity (MW)**	**Efficiency**
Salmisaari	Salmisaari A	Boiler	Coal	180	92%
	Salmisaari B	CHP	Coal	320	88%
	Sboil1	Boiler	Oil	40	85%
	Sboil2	Boiler	Oil	40	85%
	Sboil3	Boiler	Oil	40	85%

plant and 3 boilers. The Salmisaari A and Salmisaari B CHP plants are fueled by coal while the other boilers are fueled by oil. The CHP plant is able to meet a thermal load and has a maximum capacity of 160 MWe. It operates using a Rankine cycle.

3.1.5 Production, Transmission and Distribution of Heat

This section provides a description of how the production system and the transmission and distribution networks are connected. A schematic of the systems can be seen in Figure 3.3. The production system is outlined by a blue dotted line, the transmission network by a red dotted line, and the distribution network by a green dotted line. The production system consists of the CHP plants, boilers, a water storage tank, and the electricity into the compressor of the heat pump. Whereas the CHP plants and boilers are connected to the DH system via heat exchangers, the storage tank and heat pumps are directly connected to the system. The electricity production of the CHP plants is not considered in this model. Since the model only considers short run

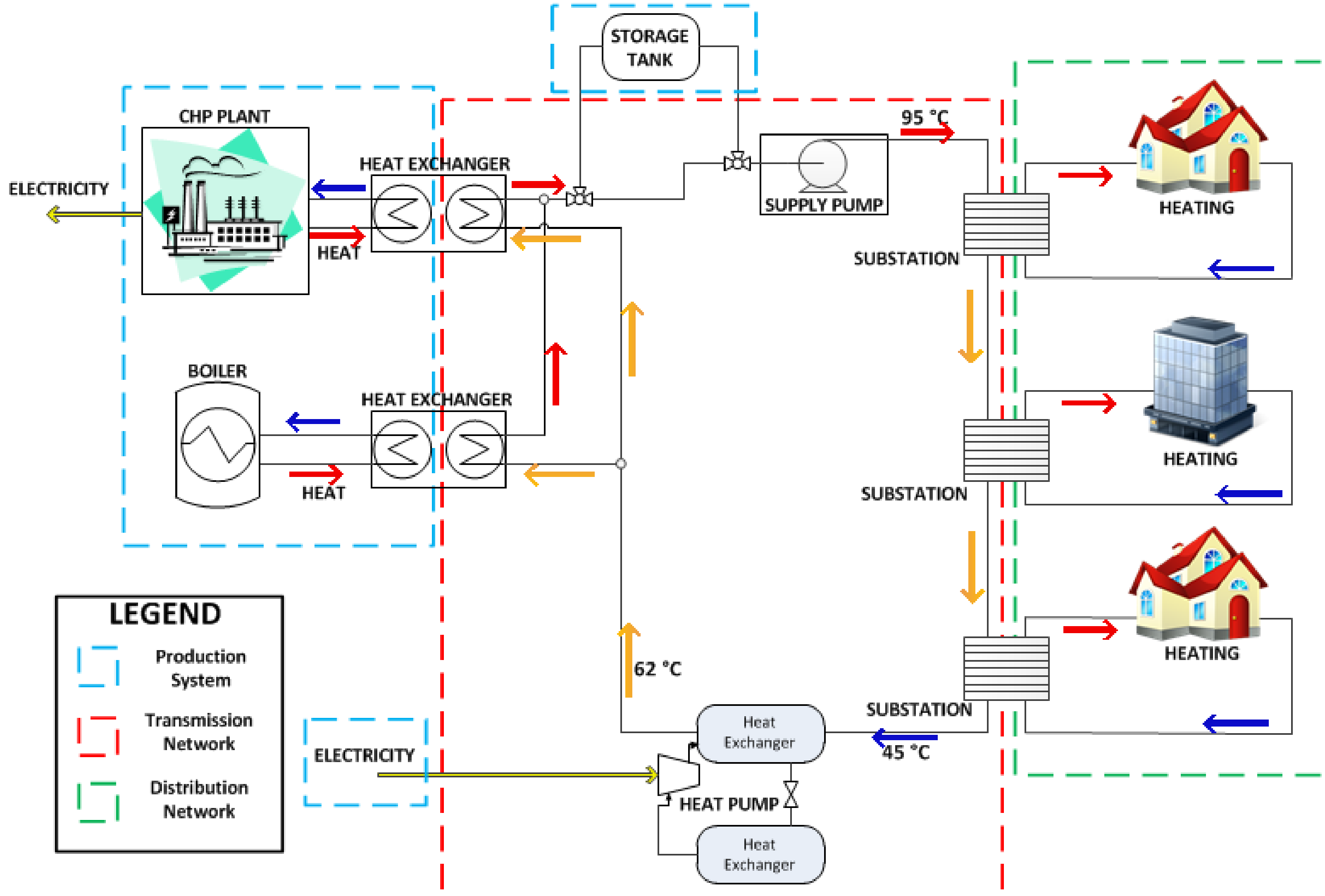

Figure 3.3 Schematic of the production system and the transmission and distribution networks.

criteria, the CHP plants would be given an unfair advantage if they were allowed to sell electricity as well. A model that incorporates capital costs could include electricity sales because the high capital costs for a CHP plant would offset gains in electricity sales. On a cost basis, a CHP plant may still be more beneficial than a boiler or heat pump, but the comparison is more accurate.

The storage tank is able to provide 130 MW of heat to the DH system at 95 °C. It is assumed that the temperature that the storage tank supplies hot water to the consumers is the same temperature as the average supply temperature in the transmission network. Since the amount of water in the tank and its temperature are known, the time that the tank can empty at full capacity can be determined. At 95 °C, 25,000 m^3 of water weighs 24,050,000 kg. Using Equation (3.1), which will be discussed briefly, the mass flow rate for 130 MW is 619.05 kg/s. Therefore, the mass of the water in the tank divided by maximum mass flow rate gives the time that the tank is able to discharge. This time is 10.8 hours. An assumption, for the sake of the model, is that the hot water storage tank contains enough water to provide the system with heat at its maximum capacity continuously for one day. This assumption is made for model simplicity, and it is a good assumption for most cases. In fact, model results demonstrate that the storage tank never discharges continuously for a 24-hour period. The three-way valves are used to direct flow into the storage tank as needed. While the storage tank is not directly connected to Vuosaari B, it does receive energy from the CHP plant within the transmission network.

The heat pumps are able to raise the temperature of the return water to 62 °C during winter operation. The transmission network delivers hot water at a temperature of 95 °C, which is represented by the red arrows, and returns water at a temperature of 45 °C, which is represented by the blue arrows. The orange arrows represent intermediate water temperatures and the yellow arrows represent electricity flow. The distribution network, which consists of the consumers, is connected to the transmission network by substations. The substations are simply large heat exchangers. The customers represented are residential, commercial, and industrial consumers.

3.1.6 Heat Losses and Piping Costs

In a DH system, it is important to consider network losses in terms of heat and pressure. It is also important to consider pumping costs due to these pressure losses. Information regarding pipes and losses were provided by a personal contact [41], and other necessary assumptions were made. This information can be seen in Table 3.5. Values for the heat loss, pressure loss, and

Table 3.5 Values for pipe and network losses.

Information	Value
Heat Loss (W/m)	38
Pressure Loss (bar/km)	0.5
Common Pipe Size (m)	0.2
Water Density (kg/m^3)	978
Water Velocity (m/s)	5
Water Specific Heat (kJ/kg-K)	4.2

common pipe size are found from [41]. The water velocity is taken from [10] as a typical DH water flow for a pipe size of 0.2 m. The density and specific heat of the water are calculated for water at 70 °C. The temperature is an average temperature determined from an average DH supply temperature of 95 °C and an average district heating return temperature of 45 °C.

In the model developed, heat losses are considered to be linear. The value provided for heat loss, 38 W/m, is for a 0.2 m diameter pipe. The maximum flow rate in the pipe can be determined by

$$\dot{m} = \rho v A \tag{3.1}$$

where ρ is the density of the fluid, v is the bulk flow speed of the fluid, and A is the cross-sectional area of the pipe through which the fluid moves. Based on the values from Table 3.5, the mass flow rate is 153.62 kg/s. Furthermore, the maximum rate of heat that can be transferred through the pipe is given by

$$\dot{Q}_{supply} = \dot{m} c_p \Delta T \tag{3.2}$$

where c_p is the specific heat at constant pressure of the fluid and ΔT is the temperature change that the fluid incurs. The temperature difference, calculated as 50 °C is determined from the difference in the DH supply temperature of 95 °C and the DH return temperature of 45 °C. From this, the maximum amount of energy that can be transferred in a 0.2 m diameter pipe is 32.26 MW. This data can be used to estimate the heat losses for all amounts of flow.

For example, one 0.2 m diameter pipe transfers 32.26 MW (maximum amount of heat transfer in a 0.2 m diameter pipe) a distance of 10 km. Assuming that the losses are linear along the entire length of the pipe, 38 W/m multiplied by the distance traveled in meters (10,000 m) provides a heat loss of 0.38 MW. The percentage of heat loss from the original flow is 1.18%. This means that, even though 32.26 MW is supplied by a producer, only 31.88 MW reaches the consumer. Therefore, supply loads must be adjusted to account for network losses. If an amount of heat other than 32.26 MW is transferred, which is practically always the case, the heat loss must be adjusted. For any amount of heat transfer, the heat loss rates are determined by

$$\dot{Q}_{loss} = \left(0.038\frac{MW}{km}\right)\left(\frac{\dot{Q}_{\mathrm{sup}ply}}{32.26MW}\right)(L) = (0.000118)(\dot{Q}_{\mathrm{sup}ply})(L) \tag{3.3}$$

where L is the length of the pipe in kilometers. In this manner, the heat losses are determined in proportion to the maximum amount of heat loss that can occur in a 0.2 m diameter pipe.

Heat losses in the heat exchangers are not considered. Since limited to no information is known about individual heat exchangers, it cannot be determined how to accurately model the heat exchangers at each site. If a method is chosen to model the heat exchangers, then losses would have to be approximated. Not wanting to give one heat exchanger an advantage over any other heat exchanger, each heat exchanger would have to be modeled similarly and incur the same amount of losses. Also, assuming that state-of-the-art heat exchangers are used, the heat losses should be very small. Therefore, losses are assumed to be negligible.

In order to determine the cost for pumping, the rate of work required for pumping must be determined. This is given by

$$\dot{W}_{pump} = \frac{\Delta P\left(\frac{\dot{m}}{\rho}\right)}{\eta_{pump}} \tag{3.4}$$

where ΔP is the change in pressure of the water and η_{pump} is the efficiency of the pump. The change of pressure under consideration is 0.5 bar [41] and the pump efficiency is assumed to be 0.85. The pressure loss of 0.5 bar/km is assumed to be that for an amount of flow equal to the maximum that can be achieved in a 0.2 m diameter pipe, i.e., 153.62 kg/s. The work required for the pump to increase the pressure of the water by 0.5 bar is then 9240 W or 0.00924 MW. Based on an electricity cost of \$0.1/kWh [46], or equivalently \$0.0278/MJ, the pumping cost is then \$0.00026/s. All pumping cost rates in dollars per second can then be determined by

$$\dot{C}_{pump} = \left(\frac{\$0.00026}{s}\right)\left(\frac{\dot{Q}_{\sup ply}}{32.26MW}\right)\left(\frac{1}{km}\right)(L) = (0.00000806)(\dot{Q}_{\sup ply})(L) \tag{3.5}$$

3.1.7 Model Description

The DH model is developed using the node method as discussed in. Each region (North, South, East, and West) is considered as a node. The nodes are connected via the main transmission line. A schematic of the model broken into nodes can be seen in Figure 3.4. The schematic provides information pertaining to each node, including the number of producers, the maximum capacity of the producers, and the peak demand experienced at that node. Distances between nodes are also included. These distances are measured from the middle of one node to the middle of the other node. The double arrowheads on the transmission lines indicate that the nodes can either receive or transfer energy. For example, the east node can transfer energy to the north node, or the north node can transfer energy to the east node. Equally, the north node can receive energy from the east node, or the east node can receive energy from the north node. Of course, any energy transferred between two nodes incurs heat losses and pumping costs consistent with the length of pipe. Any energy that is produced in a node and consumed in that same node, does not incur heat losses or pumping costs since it is assumed that any pipe losses within a given node are negligible since the transfer distance is small in comparison to

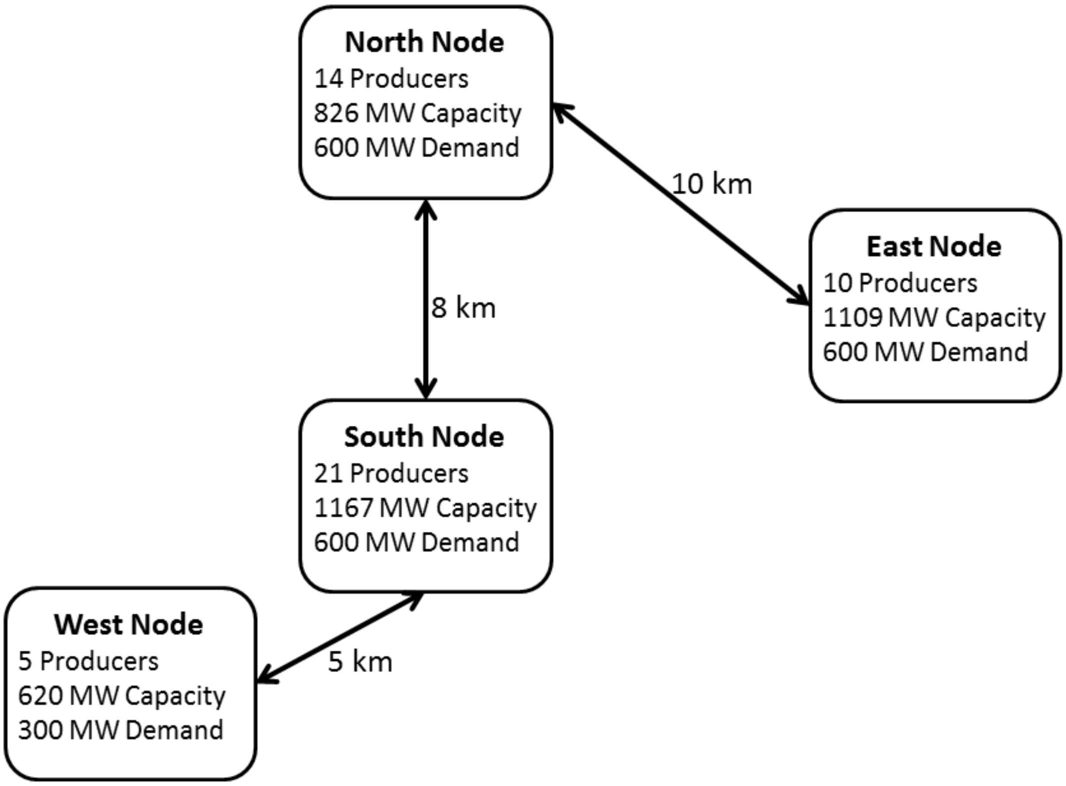

Figure 3.4 Schematic of the DH system divided into nodes.

transferring into or from another node.

In the model, a heat loss factor, δ, accounts for the heat loss when heat is transferred between two nodes. The values are determined by multiplying the constant in Equation (3.3) by the length of the pipe. The product of the heat loss factor and the amount of energy transferred from node i is the heat loss incurred by the time the energy reaches a neighboring node j. The heat loss factors between neighboring nodes can be seen in Table 3.6. These heat loss factors are used in the mathematical optimization problem of the system. The heat loss factor is the largest

Table 3.6 Heat loss factor between neighboring nodes.

Locations		**Heat Loss Factor**
From	**To**	
East	North	0.0118
North	South	0.0094
South	West	0.0059

from East to North because it is the longest distance between any two nodes. The heat loss factor from South to West is the smallest and the heat loss factor from North to South is in between. Note that, regardless of the direction of the transfer, the heat loss factor is still the same. For example, the heat loss factor is the same from the East to North as it is from the North to East.

The mathematical optimization problem of the system for a 1-hour demand is described by Equations (3.6) to (3.10). The optimization problem for multiple demand hours is discussed in the following section.

Minimize $$\overline{F} = \{F_1, F_2, ..., F_{k-1}, F_k\}^T \tag{3.6}$$

w.r.t. P_{iq}, f_{ji}, and f_{ij}

subject to: $$P_{D_i} - \sum_{q=1}^{Q} P_{iq} - \sum_{j=1}^{J} \left[(1-\delta) f_{ji} - f_{ij} \right] \leq 0 \text{ for all } i \tag{3.7}$$

$$P_{iq}^{\min} \leq P_{iq} \leq P_{iq}^{\max} \text{ for all } i \text{ and } q \tag{3.8}$$

$$f_{ij}^{\min} \leq f_{ij} \leq f_{ij}^{\max} \text{ for all } i \text{ and } j \tag{3.9}$$

$$f_{ji}^{\min} \leq f_{ji} \leq f_{ji}^{\max} \text{ for all } j \text{ and } i \tag{3.10}$$

where $\overline{F}$ is the set of objective functions being minimized, i represents a node and q represents the producers in a node. Equation (3.7) is an inequality constraint that must be met. P_{D_i} is the demand at node i, P_{iq} is the production from producer q at node i, f_{ji} is the heat transferred from node j to node i, f_{ij} is the heat transferred from node i to node j and δ is the heat loss factor. The non-negative decision variables P_{iq} are bounded at one end by zero and at the other by a maximum production capacity, while the decision variables f_{ij} and f_{ji} are bounded by zero and a maximum transfer capability. The maximum transfer capability is determined by the maximum amount of production in the node.

3.1.8 Network Demand and Multiple Demand Hour Problem

The network demand is chosen for a winter day in January. Figure 3.5 represents a set of typical heat demand curves for a DH system over the course of a 24-hour period for each month of the year [47]. The coldest months represent the curves on top, and the warmer months the curves on the bottom. The color-coded key is not provided because only one curve is of interest, i.e., that for the coldest winter day. This day in Figure 3.5 and in Helsinki is in January. It is represented by the yellow line. The trend of this line is used for the Helsinki DH system adjusted

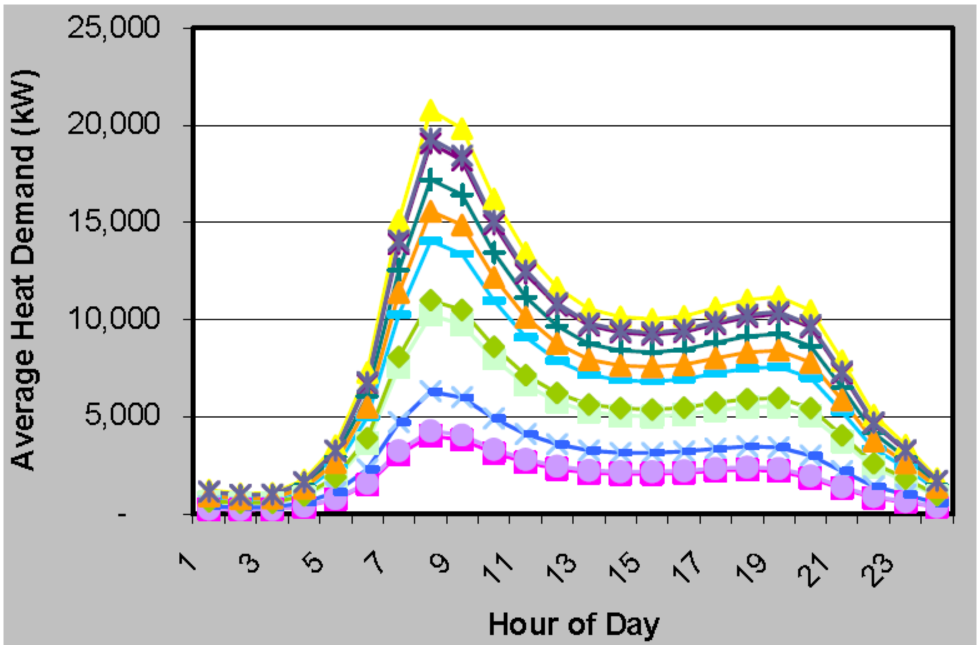

Figure 3.5. Typical heat demand curves for a DH system, the different colored lines represent different months [47].

to the peak demand of this system which is found by summing the peak demands provided for each of the four locations (North, South, East, West). The resulting demand curve for the coldest day in January for the Helsinki DH system is then the one given in Figure 3.6. This curve represents the demand for the entire DH system. The maximum load is 2100 MW, while the minimum is 105 MW. Realistically, the demand changes over the course of each hour, but representing the demand on an hourly basis is assumed to be sufficient for this problem. Furthermore, the size and computational time of the model increases with every demand hour.

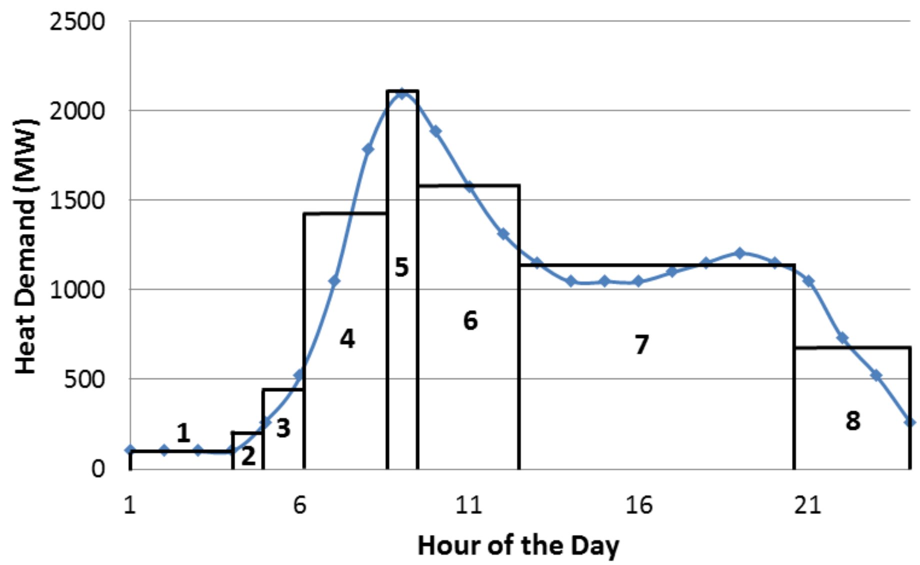

Figure 3.6. Adjusted demand curve for the Helsinki DH system; the curve is divided into 8 demand sections.

Therefore, it was decided that the demand of the system could be sufficiently represented by dividing the demand curve into 8 sections. Each section represents a single demand. The height of each interval represents the load, and the width of the interval represents the number of hours the load is present in a 24-hour period. The demand for each section is labeled in Table 3.7 along with the number of hours for which it occurs for.

Table 3.7 Demand and hours represented for each demand period in Figure 3.6.

Demand Period	Demand (MW)	Hours per Period
1	105	4
2	183.75	1
3	393.75	1
4	1277.5	2.5
5	2100	1
6	1592.55	3
7	1120	8
8	707.4375	3.5

The demands for periods 2, 3, 4, 6, and 8 are determined by averaging the highest and lowest demand on the interval. For these intervals, it is assumed that the slope is constant. Interval 5 is the peak interval, and it is kept at a value of 2100 MW. Intervals 1 and 7 are determined by taking the average of all points on the interval. When modeled, the demand hours are inserted into the optimization problem in descending order based on the magnitude of the demand. Also, each demand is divided among each of the four regions. The demand is divided based on the peak demands given for each region. For example, the North region has a peak demand of 600 MW while the entire system has a demand of 2100 MW. Therefore, the North region consumes approximately 29% of the system demand. This percentage of consumption is kept constant for all off-peak hours. If a system demand of 1120 MW is present, then the North, South, and East regions will have a demand of 320 MW each since the peak demand for these regions are the same value while the West's demand will be 160 MW. In addition, all the demands are adjusted slightly by either rounding or truncating. This is simply done for convenience. The adjusted demands for each hour by regions can be seen in Table 3.8.

Table 3.8 Demand hours divided into regions.

Demand Section	**Demand**				
	Total	***North***	***South***	***East***	***West***
Peak	2100	600	600	600	300
Off 1	1590	454	454	454	227
Off 2	1280	366	366	366	183
Off 3	1120	320	320	320	160
Off 4	700	200	200	200	100
Off 5	400	114	114	114	57
Off 6	185	53	53	53	26
Off 7	105	30	30	30	15

The multiple-demand-hour optimization problem is set up so that the peak hour "fixes" the configuration for each iteration of the optimization and for each off-peak hour. The latter is done for the purposes of continuity from one load period to another, i.e., to avoid the issue of new start-ups. The decision variables for the peak hour are the producer loads and transmission line loads. For the off-peak hours the decision variables are of two types. The first are fractions of the plant loads from the peak hour. The second are transmission line loads which are not fractions of the transmission loads for the peak hour. They are completely separate. This concept can be better understood by the illustration given in Figure 3.7.

The figure displays the relationship between the peak and off-peak hours. The numbered "tanks" represent producers. A producer running at full load is represented by a tank completely filled with green, while a producer that is not running is represented by a tank that has no green filling. A producer running at part-load will be filled partially with green, such as tank 3. The scenario is that there are four demands represented: 1 peak hour and 3 off-peak hours. The peak hour has the highest demand while the off-peak hours have successively lower demands. It can be seen that the off-peak hours cannot have a higher load for a producer than the peak hour

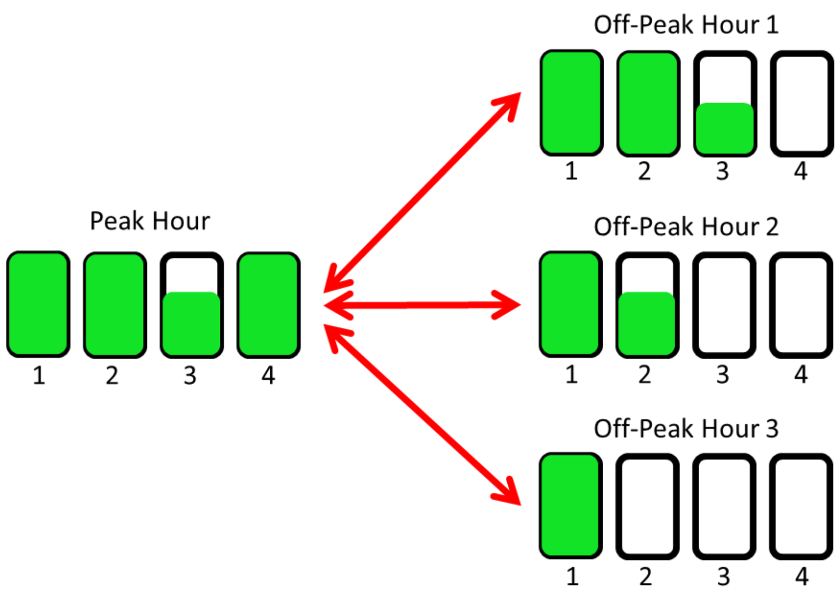

Figure 3.7 Illustration of the relationship between peak and off-peak hours; the numbered "tanks" represent producers in each hour.

does[2]. For example, producer 3 is at a part load during the peak hour so it will never be at a load higher than this in the off-peak hours. In addition, the doubled-headed red arrows display that the off-peak hours obtain their producers from the peak hour, but also that the off-peak hours aid in the selection of the peak hour. For the best configuration to be chosen for the off-peak hours,

[2] Note that this constrains the off-peak production too severely since the constraint should in actuality be that off-peak production is constrained to be some fraction of the maximum capacity of the peak-hour configuration producer.

these off-peak hours must have the best producers to choose from in the peak hour. This means that not all demand hours may necessarily be performing at their best result, but instead sacrifice their best to obtain better results in other hours. This sacrifice, of course, results in an overall better system configuration.

This can be further understood by the following mathematical optimization problem:

Minimize $$\overline{F} = \{F_1, F_2, ..., F_{k-1}, F_k\}^T \tag{3.11}$$

w.r.t. P_{iq}, f_{ji}, f_{ij}, and S_{iq}

subject to: $$P_{D_i} - \sum_{q=1}^{Q} P_{iq} - \sum_{j=1}^{J} \left[(1-\delta) f_{ji} - f_{ij}\right] \leq 0 \text{ for all } i \text{ in the peak hours} \tag{3.12}$$

$$P_{D_i} - \sum_{q=1}^{Q} S_{iq} P_{iq} - \sum_{j=1}^{J} \left[(1-\delta) f_{ji} - f_{ij}\right] \leq 0 \text{ for all } i \text{ in the off-peak hours} \tag{3.13}$$

$$P_{iq}^{\min} \leq P_{iq} \leq P_{iq}^{\max} \text{ for all } i \text{ and } q \text{ in the peak hour} \tag{3.14}$$

$$S_{iq}^{\min} \leq S_{iq} \leq S_{iq}^{\max} \text{ for all } i \text{ and } q \text{ in the off-peak hours} \tag{3.15}$$

$$f_{ij}^{\min} \leq f_{ij} \leq f_{ij}^{\max} \text{ for all } i \text{ and } j \tag{3.16}$$

$$f_{ji}^{\min} \leq f_{ji} \leq f_{ji}^{\max} \text{ for all } j \text{ and } i \tag{3.17}$$

where the new decision variable, S_{iq}, represents a fraction from zero to unity of the production of P_{iq}. Also, the inequality given by Equation (3.13) is for the off-peak hours. Notice that the second term is the sum of the product of decision variables from the peak hour and off-peak hours.

Each demand hour contains 52 decision variables and 4 inequality constraints. For the peak hour, the first 46 decision variables are the loads of the producers and the next 6 are the loads of the transmission lines. For the off-peak hours, the first 46 decisions variables are fractions of the loads of the producers in the peak hour and the next 6 are loads of the transmission lines. The inequality constraints in each hour are for the demands in each region. There are a total of 416 decision variables and 32 inequality constraints. In the case of a multi-objective optimization problem where one objective is constrained, another inequality constraint is added to the model, resulting in 33 inequality constraints.

3.1.9 Part-Load Efficiency Curves

Efficiency values were previously discussed for full load operation, yet producers do not always operate at full load. Efficiency curves provide an efficiency value at any percentage of the maximum load. Data for efficiency curves were not provided by Helsinki Energy for individual producers, because this information is proprietary. Instead, data from similar producer types are found in the literature and adapted to the DH producers. An example of data provided for a combined cycle natural gas plant is seen in Figure 3.8 and is based on [48]. The data

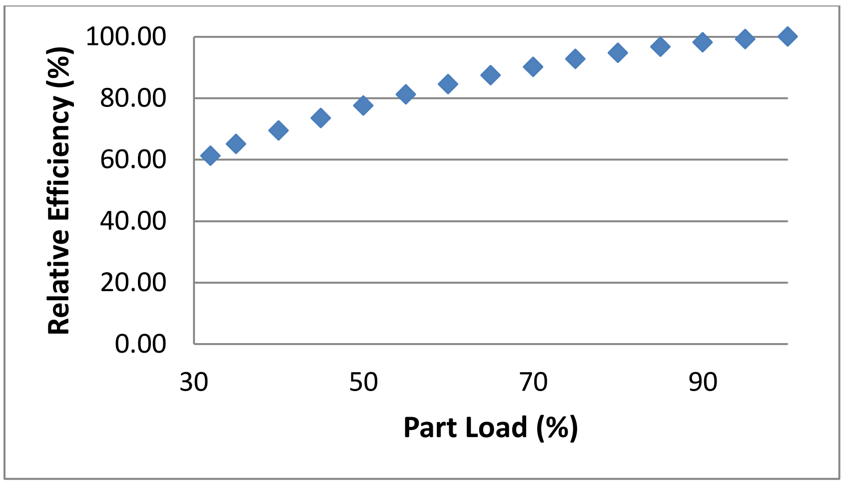

Figure 3.8 Part load efficiency curve for a combined cycle natural gas plant [48].

provided is for part loads of 32% to 100% of the full load. The efficiency is represented as a relative efficiency, i.e., as a percentage of the maximum efficiency. Although the data is in terms of relative efficiency, it can be adapted to fit any maximum efficiency value. An adjusted curve, representative of Vuosaari B with a maximum cogeneration energetic efficiency of 92%, can be seen in Figure 3.9. This data is appropriate to use for the estimation of an efficiency curve for Vuosaari B because it is the same technology that Vuosaari B operates. Of course, this assumes that the cogeneration energetic efficiency for this type of technology follows the same trend as that for the electrical energetic efficiency. The data in Figure 3.9 is fit well by a power curve

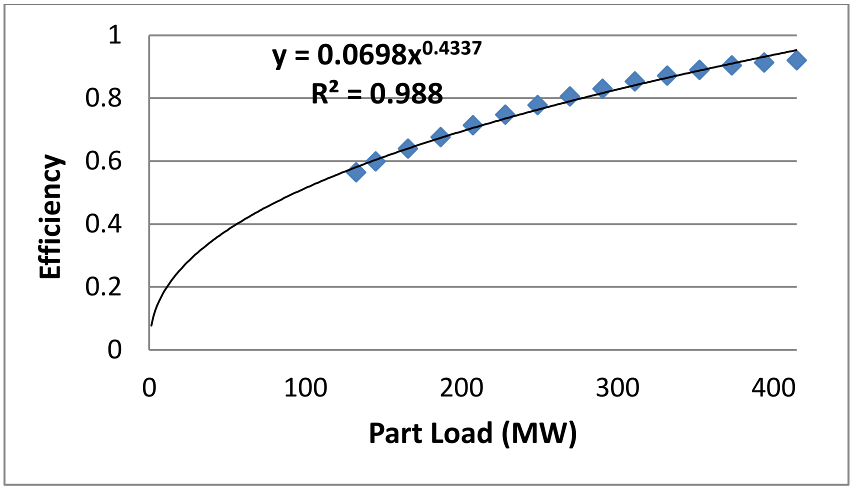

Figure 3.9 Part load efficiency curve with curve fit for Vuosaari B.

with an R^2 or coefficient of determination value of 0.988. This value provides a measure of how well outcomes are likely to be predicted by the model. An R^2 value of zero means that the data is fit with no accuracy and an R^2 value of unity means that the data is fit with complete accuracy. As noted above, the efficiency provided in [48] is for the electric load. To relate this to the cogeneration load, it is assumed that the power to heat ratio is constant. This constant ratio is determined from the maximum heat and the maximum power production. Therefore, the cogeneration load imitates the electric load. Efficiency curves are developed for each producer using

$$\eta_{producer} = (\eta_{\max})\left(\frac{\dot{Q}}{\dot{Q}_{\max}}\right)^{b} \tag{3.18}$$

where $\eta_{\max}$ is the maximum efficiency of the producer, $\dot{Q}_{\max}$ is the maximum load of the producer, and b is the exponent that best fits the efficiency data. Efficiency curves are partly written in this form for convenience. In this form, the maximum efficiency and maximum load, which are readily available, can be used. Also, the exponent, b, is the same for the same technologies. For example, all boilers have the same b value. Also, all natural gas combined cycles have the same b value. In addition to convenience, this function fits the data well. Most efficiency data is only available at loads of 30% or higher. Therefore, it is not known how the system behaves if the part load is below the minimum part load data provided. The curves fit the data well for what is known and then approach an efficiency of 0 as the part load approaches 0. Therefore, the curves insure that it is not desirable for producers to run at relatively small loads, because the efficiency is so low. Exponents for each of the technologies are listed in Table 3.9.

Table 3.9 Exponents for the technologies in the DH system [48-51].

Technology	Power Coefficient
NG Combined Cycle	0.4337 [48]
Pulverized Coal	0.4 [49]
Boiler	0.2408 [50]
Heat Pump	0 [51]

Even the heat pumps can be modeled well with Equation (3.18). According to [51], the COP of the heat pump remains constant regardless of the load. Therefore, if the exponent is zero, the efficiency is equivalent to the maximum efficiency for all cases. Because the COP exceeds unity, Equation (3.18) should be rewritten as

$$COP_{producer} = (COP_{\max})\left(\frac{\dot{Q}}{\dot{Q}_{\max}}\right)^{b} \tag{3.19}$$

During winter months, the coefficient of performance (COP) is 3.5. If the electricity input into the heat pump is considered from its source of fuel, then the energy of conversion is much lower. For example, it is assumed that electricity into the heat pumps is converted from its fuel input at an efficiency of 40% (a mix of coal and natural gas technologies). Therefore, the effective energy of conversion for the heat pumps is 40% of 3.5, or 1.4. This value is still significantly larger than any other producer in this model.

3.1.10 Optimization Criteria

The five optimization criteria or objective functions, which are functions of the efficiency curves, are costs (fuel and pumping), carbon dioxide (CO_2) emissions, sulfur oxide (SO_x) emissions, particulate matter (PM_{10}) emissions, and the exergetic efficiency. The costs and emissions are at ideal values when they are minimized, while the exergetic efficiency is at its ideal value when maximized. Now, the optimization program used in this model is a Sequential Quadratic Programming (SQP) program [35]. This means that it is a gradient-based approach. Developing a large optimization model can be tedious, as the form in which equations are written can affect the convergence of the model. According to [32], the best form to enter objective functions, when using a gradient-based optimization program, is the quadratic form. Equations in this form happen to be easily differentiable and not too complex. This form can be expressed as

$$A_{iq}P_{iq}^2 + B_{iq}P_{iq} \tag{3.20}$$

where A_{iq} and B_{iq} are coefficients determined by a curve fit. Note that when the production is equal to zero, the criterion value is as well. A producer that is turned off has no costs or emissions, and its efficiency is zero. An example of a curve fit for the fuel cost of a boiler (VBOIL1) can be seen in Figure 3.10.

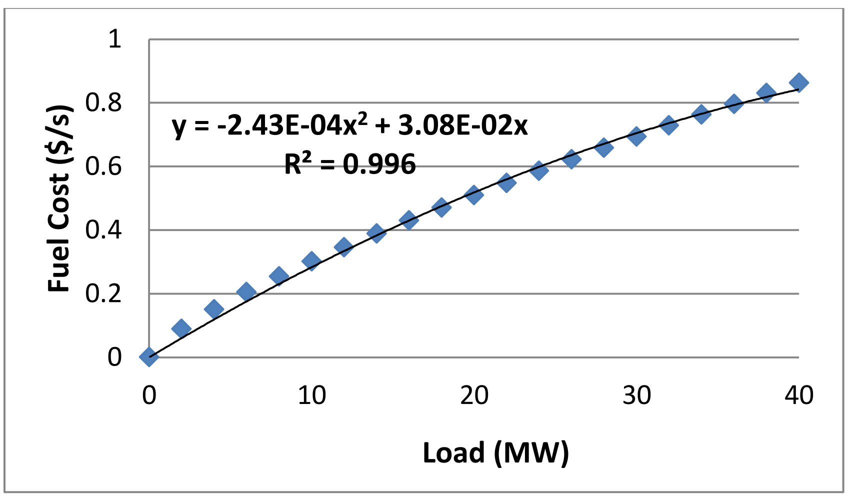

Figure 3.10 Fuel cost curve for VBOIL1.

This curve represents the fuel costs in dollars per second for VBOIL1. The maximum load for this boiler unit is 40 MW. At this load, the efficiency is 0.85. Any load that is below the maximum load has a lower efficiency. It should be noted that the curve fit is accurate with an R^2 value of 0.996. The importance of a producer running at a high load is illustrated by Figure 3.11. The curve shows the load of the boiler versus the cost per unit energy. It is shown that the closer the boiler is running to its full load, the lower the cost is per unit of energy output. At a load of

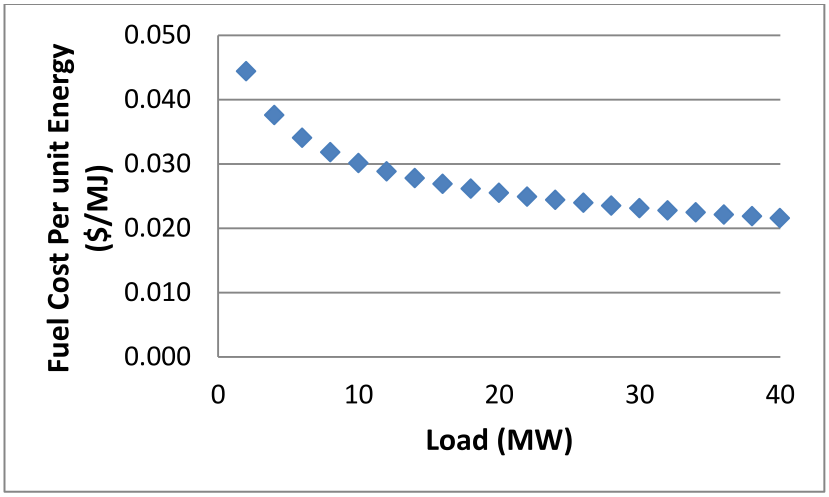

Figure 3.11 Fuel cost per unit energy versus load for VBOIL1.

5% (2 MW) of the maximum, the cost is $0.044/MJ. At a load of 100% (40 MW) of the maximum, the cost is $0.022/MJ. This means that twice the amount of fuel costs are incurred per unit of energy for running at an efficiency of 5% rather than 100%.

The general form for an objective function is then given by

$$F = \sum_{i=1}^{I}\sum_{q=1}^{Q}\left(A_{iq}P_{iq}^{2} + B_{iq}P_{iq}\right) \text{ for the peak hours} \tag{3.21}$$

and

$$F = \sum_{i=1}^{I}\sum_{q=1}^{Q}\left[A_{iq}\left(S_{iq}P_{iq}\right)^{2} + B_{iq}\left(S_{iq}P_{iq}\right)\right] \text{ for off-peak hours} \tag{3.22}$$

These equations are valid for minimizing fuel costs, emissions and the exergetic efficiency. If pumping costs are minimized along with fuel costs, then an extra term must be added. This term can be given as follows:

$$C_{pump} = (0.00000806)\sum_{i=1}^{I}\sum_{j=1}^{J}\left(f_{ij} + f_{ji}\right)L_{ij} \tag{3.23}$$

Notice that the total pumping cost considers flow in both directions of the pipe. For example, it is feasible for node i to transfer heat to node j at the same time that node j is transferring to node i. Of course, this is not cost effective, so this will not happen in an optimal case.

The next sections discuss each of the objective functions or criteria and how they are developed. Coefficients for the criteria are provided in Table A.1 and Table A.2 in Appendix A. Note that the values provided are for fuels at a medium cost. Other fuel costs are discussed in a later section.

3.1.10.1 Economic Criteria

In this optimization problem, the economic criterion is taken into account by considering fuel costs and pumping costs. Determination of the pumping cost is as previously discussed. The fuel cost rate can be determined from

$$\dot{C}_{fuel} = \frac{\dot{Q}_{supply}\left(LHV_{fuel}\right)c_{kg}}{\eta_{producer}} \tag{3.24}$$

where LHV_{fuel} is the lower heating value of the fuel and c_{kg} is the unit cost of the fuel in dollars per kilogram. The lower heating values and unit costs used in this model can be seen in Table 3.10. High, medium, and low fuel costs are used in separate optimizations. The scheme used to decide the combination of costs used in each optimization is discussed later.

Table 3.10 Costs and LHV for fuels used in the model [52-56].

Fuel	Fuel Costs ($/kg)			Fuel LHV (MJ/kg) [52]
	High [53]	Medium [53]	Low	
Natural Gas	0.43	0.28	0.08 [54]	47
Oil	0.97	0.77	0.20 [55]	42
Coal	0.15	0.09	0.04 [56]	25

The high and medium costs are determined from the high values from 2021 and the medium values from 2011 [53], respectively. The low values are determined from historical data. The lowest price back to the year 2001 is considered as the low value. In order to compare the fuel costs, they must be compared on a “per energy” basis and not a “per kilogram” basis. Costs per unit energy can be seen in Table 3.11.

Table 3.11 Fuel costs in dollars per unit energy.

Fuel	Fuel Costs ($/MJ)		
	High	Medium	Low
Natural Gas	0.0091	0.0060	0.0017
Oil	0.0231	0.0183	0.0048
Coal	0.0060	0.0036	0.0016

As can be seen, for all cases (high, medium, low), coal is the cheapest, natural gas the second cheapest, and oil the most expensive. Therefore, if the system is optimized based solely on fuel costs, producers using coal will dominate the best configuration. It should be noted that heat pumps are given a fuel cost as well as emissions amounts, based on the fuel used to generate the electricity. From a 2010 Helsinki Energy Annual Report [46], it is determined that the yearly electricity production is from about 72% natural gas technologies and 28% coal technologies. Therefore, the fuel usage is based on this fuel mix of electricity generation. For simplicity, this fuel mix is used for heat pumps regardless of the actual system configuration.

3.1.10.2 Environmental Criteria

The three environmental criteria are CO_2, SO_x, and PM_{10} emissions. The equation used to model emission rates is as follows:

$$\dot{E} = \frac{\dot{Q}_{supply}(E_{kg})}{\eta_{producer}} \tag{3.25}$$

where E_{kg} is the mass of emissions per unit energy of fuel consumed. Emissions on a mass per unit energy basis can be seen for each fuel in Table 3.12.

Table 3.12 Emissions considered for each fuel used in the model [57-58].

Fuel	Emissions (kg/MJ)		
	CO_2 [57]	SO_x [58]	PM_{10} [58]
Natural Gas	4.993E-02	3.446E-08	0
Oil	7.149E-02	6.387E-04	1.468E-05
Coal	8.582E-02	8.080E-05	3.440E-06

3.1.10.3 Technological Criteria

The technological criterion or objective function considered is the exergetic efficiency, which takes the the exergetic fuel consumption and the temperature of the heat supplied into account. Ideally the exergetic fuel consumption is low and the temperature of heat production is high. This can be achieved by maximizing the exergetic efficiency. Now, if the efficiency is directly optimized, this adds model complexity to the optimization problem. For example, the average efficiency is calculated by dividing the summed efficiencies of the plants operating by the number of plants operating. Thus, the number of plants operating must be summed in real time. An expression that avoids this problem, without sacrificing any information is

$$\dot{\varepsilon} = \frac{\dot{m}_f LHV\phi}{\left(1-\frac{T_o}{T_k}\right)} \tag{3.26}$$

Like the other objective functions, there is no average taken. Rather, the sum of the criterion for the plants operating gives the appropriate value for the objective function. This objective function is the equivalent of the exergetic efficiency with respect to the optimization and it is called the exergetic efficiency parameter for the purposes of this thesis work. Furthermore, the heat transfer temperature T_k, which appears in this expression, varies for each producer. Boilers tend to have high heat transfer temperatures, followed by CHP plants, and then heat pumps. The temperatures for boilers are provided by Helsinki Energy [38], while those for the CHP plants and heat pumps are taken from [48] and [44], respectively. These values can be seen in Appendix A in Table A.3.

3.2 Finnish Power Network

The Finnish power network produces most of its power from conventional power plant technologies. According to [59], in 2008 the total installed electrical capacity was 16,642 MWe. Of this amount, 10,726 MWe was from conventional plants, 2,671 MWe from nuclear power, 3,102 MWe from hydroelectric power, and 143 MW from wind power. Conventional plants include plants that produce steam for the conversion of electricity, combined cycles, gas turbines, and combustion engines. The fuels used can be fossil fuels such as coal and natural gas, or they can be renewables such as biogas or biomass. The breakdown of technologies can be seen in Figure 3.12. As can be seen in this figure, conventional technologies dominate, while nuclear and

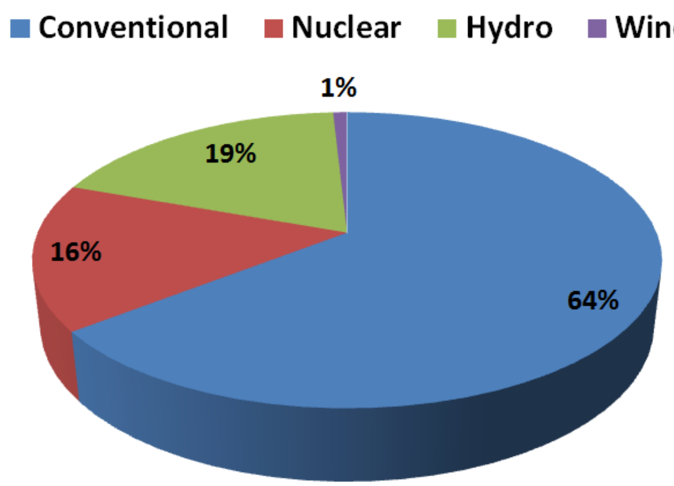

Figure 3.12 Breakdown of technologies available in Finnish electricity network.

hydroelectric provide a significant amount. Wind capacity is approximately 1% of the national capacity. Finland uses some solar photovoltaic panels for the production of electricity, but this amount is very small and not well documented.

Finland generates 85% of the electricity it consumes and imports the rest. Of the approximately 70 TWh generated within the country, there is a balanced mix of generation technologies. The largest producer of energy is nuclear power, contributing 33% of the total electricity generation [39]. Hydropower is the next largest with 18%, followed by coal with 15%, natural gas with 13%, biomass with 12%, peat with 6%, and wind power and oil with less than 1% each [40]. Figure 12 shows the percentage of capacity for each technology and the percentage of generation for each capacity for 2009 [40].

Nuclear power and oil display the most interesting behavior. While nuclear power has a capacity of less than 20%, it produces about 33% of the generated electricity. On the other hand, while oil has a capacity of about 7% it produces about 1% of the generated electricity. The difference is that nuclear power is used as a base-load generator whereas oil is used as a fringe generator. Nuclear plants operate for many more hours over the course of a year than oil plants

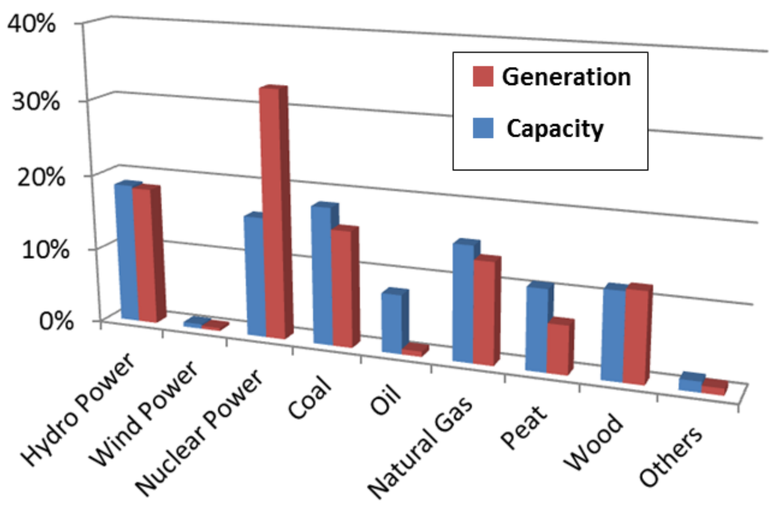

Figure 3.13 Generation and capacity for various energy technologies [40].

do. Hydroelectric power, coal, natural gas, peat and wood plants operate for fewer hours during the year than nuclear plants, but more hours than oil plants.

3.2.1 Transmission and Distribution Network

An example of a power network can be seen in Figure 3.14 [60]. This diagram shows

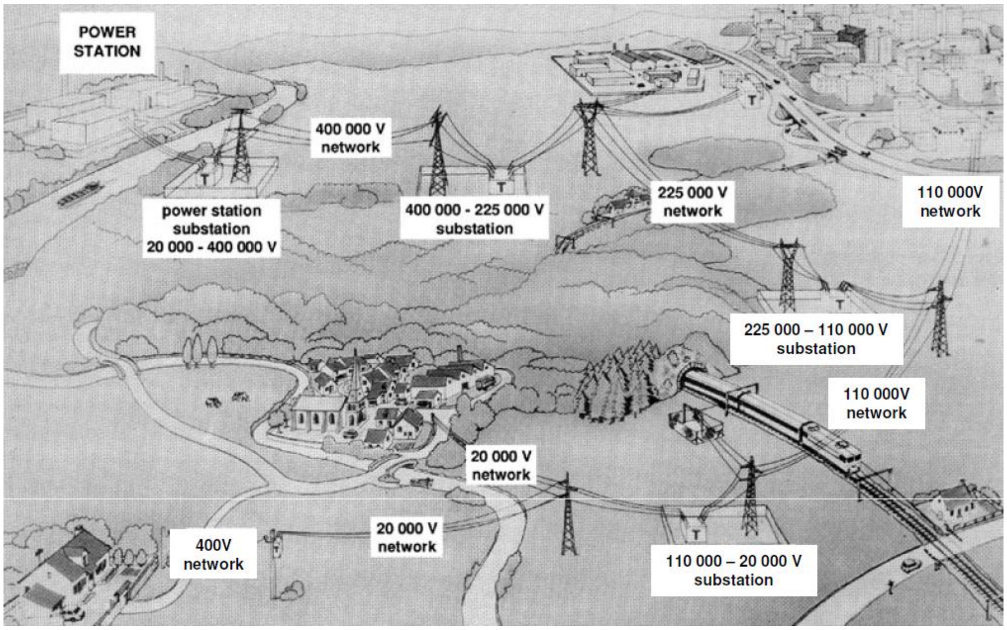

Figure 3.14 Power network with voltages representative of those used in Finland [60].

how electricity is distributed from a power station to several diverse groups of users. The voltage values provided are typical for voltage lines in Finland. The first substation converts the voltage to 400 kV. The second substation converts the voltage to 225 kV. These high voltages are used for carrying large loads over long distances. If the network provides electricity to a city, a voltage line of 110 kV is used. In contrast, if the network is provides electricity to a small town, a 20 kV line is used. Once the network reaches individual dwellings, the voltage is reduced significantly to about 400 V. A diagram of high voltage lines present in Finland can be seen in Figure 3.15 [61].

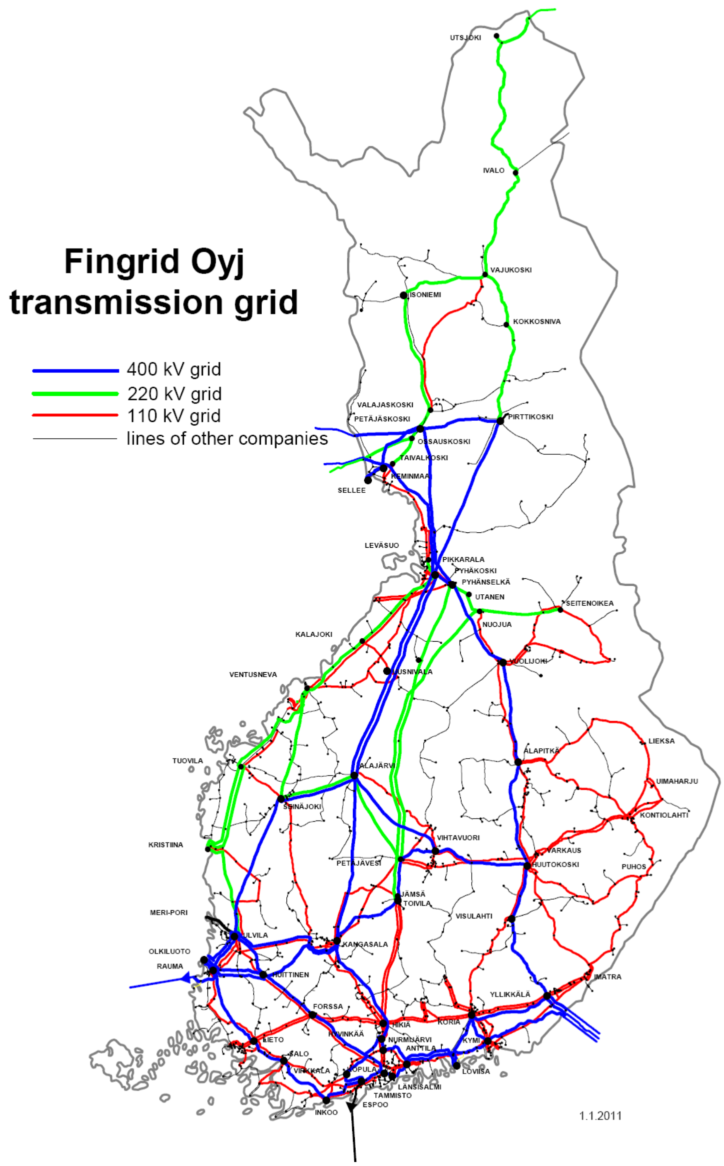

Figure 3.15 High voltage transmission lines available in Finland [61].

The transmission lines provided are for 400 kV (blue), 220 kV (green), and 110 kV (red). The black lines represent lower voltage transmission lines. The black dots are substations. Small dots represent small substations, while large dots represent large substations. Knowing the voltage of transmission lines is important for the determination of losses from the transfer of electricity between nodes as described in the previous chapter.

3.2.2 Model Setup

The Finnish power system is setup in a fashion similar to that of the Helsinki DH system previously discussed. The system is divided into nodes based on political boundaries. Finland has 19 regions or nodes that can be seen in Figure 3.16 [62]. Each region consists of a number of

Figure 3.16 Finland divided into its 19 regions [62].

producers. The number of producers and capacity of each node can be seen in Table 3.13.

Table 3.13 The number of producers and the capacity of each region in Finland.

Region	Number of Producers	Capacity (MW)
Aland Island	17	48.3
Central Finland	15	423.1
Central Ostrobothnia	8	51.5
Southern Savonia	12	324.1
Kainuu	12	369
Tavastia Proper	6	216.6
Lapland	40	1313
North Karelia	18	470.3
North Ostrobothnia	59	1296.7
Ostrobothnia	29	1821.8
Päijät-Häme	14	475.2
Pirkanmaa	19	663.8
Northern Savonia	14	321.3
Satakunta	39	3451.8
South Karelia	9	674.7
South Ostrobothnia	16	153.9
Uusimaa	42	4083
Finland Proper	13	346.1
Kymenlaakso	29	722.6
TOTAL	*411*	*17227*

It should be noted that the capacity used in the model may not match the exact capacity of the physical system, although it is close. It can be assumed that the capacity of the power network has increased from the 2008 capacity upon which these numbers are based [59]. Data regarding producers is often difficult to obtain because it is not part of the public record. Most of the data presented here is provided by the Finnish Energy Industries and the Energy Market Authority in Finland. This data was collected primarily from meetings and personal communication during a research trip to Finland. Unfortunately, industrial CHP plants, totaling a maximum of 2,100 MWe of power production, do not report to either of these groups. Therefore, a number of CHP plants are duplicated to raise the total production of the system by approximately 2,100 MW. The technologies and fuels used in the model setup can be seen in Table 3.14.

Table 3.14 Capacity and number of producers for technologies and fuels used in the model setup.

Technology	Number of Producers	Capacity (MW)	Capacity %
Conventional	153	11136.4	64.6
Biogas	3	1.4	0.0
Coal	18	2815.5	16.3
Heavy Fuel Oil	29	1812.3	10.5
Hydrogen	1	4.5	0.0
Natural Gas	33	2448.3	14.2
Peat	30	1317.6	7.6
Waste	1	8	0.0
Wood	38	2728.8	15.8
Hydroelectric	178	3184.2	18.5
Nuclear	4	2736	15.9
Wind	76	170.1	1.0
TOTAL	*411*	*17227*	*100.0*

The technologies in this table are divided into conventional, hydroelectric, nuclear, and wind technologies. The conventional technologies are divided on a fuel basis. The system is mostly comprised of conventional technologies with coal, natural gas, and wood having the largest capacities. Oil and peat have the ability for significant production, while biogas, hydrogen, and waste do not. The system also has the ability to generate large amounts of electricity from hydroelectric and nuclear power.

It is also necessary to discuss the adjustments made to the data provided for wind production. Figure 3.17 is a map of the wind turbines in Finland in 2010 [63]. Although data was provided for wind turbines, it is not clear how many wind turbines are present at each location. Therefore, an assumption is made about the size of the wind turbines. With performance data provided for 1 MWe and 3 MWe wind turbines from WinWinD [64] and wind speeds from the Finnish Wind Atlas [65], it is possible to determine the power production. Since this is the only data provided from WinWinD and since most of the recent wind turbines built are of 1 MW and 3 MW capacities, it is assumed that locations with an unknown number of wind turbines but a known capacity use 1 MWe and 3 MWe wind turbines to satisfy the total capacity. For these locations, as many 3 MWe capacity wind turbines as possible are used with 1 MW wind turbines filling out the remaining capacity. For example, if the total capacity at a location is 11 MWe,

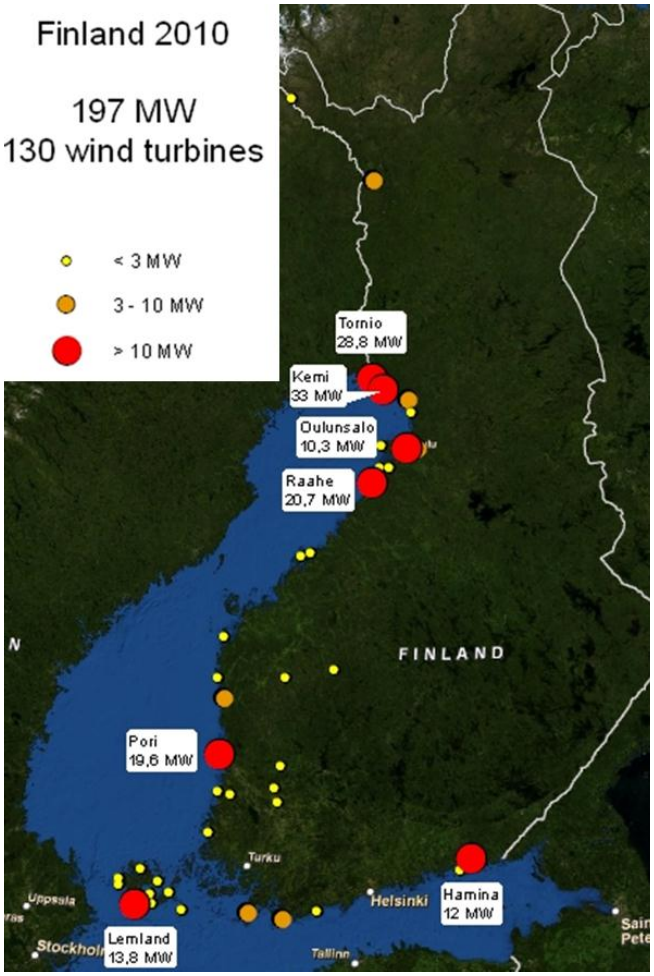

Figure 3.17 Number and total capacity of wind turbines in Finland in 2010 [63].

then three 3 MWe turbines and two 1 MWe turbines are used.

In order to determine the transmission lines present between each node, Figure 3.15 is made translucent and laid on top of Figure 3.16. The result is Figure 3.18. The nodes are designated by boxes and the transmission lines by the lines connecting the nodes. Note that there a 2 nodes representing Russia, 2 Sweden, 1 Estonia, and 1 Norway. Although the actual producers at these nodes are not known, electricity can be transferred to or from the node. In this manner, electricity is either sold or bought. Also, it is assumed that each neighboring country node transfers electricity from one 400 kV transmission line. The color and number of transmission lines, consistent with Figure 3.15, are listed on the transmission lines between each node connection. In addition, the distance between neighboring

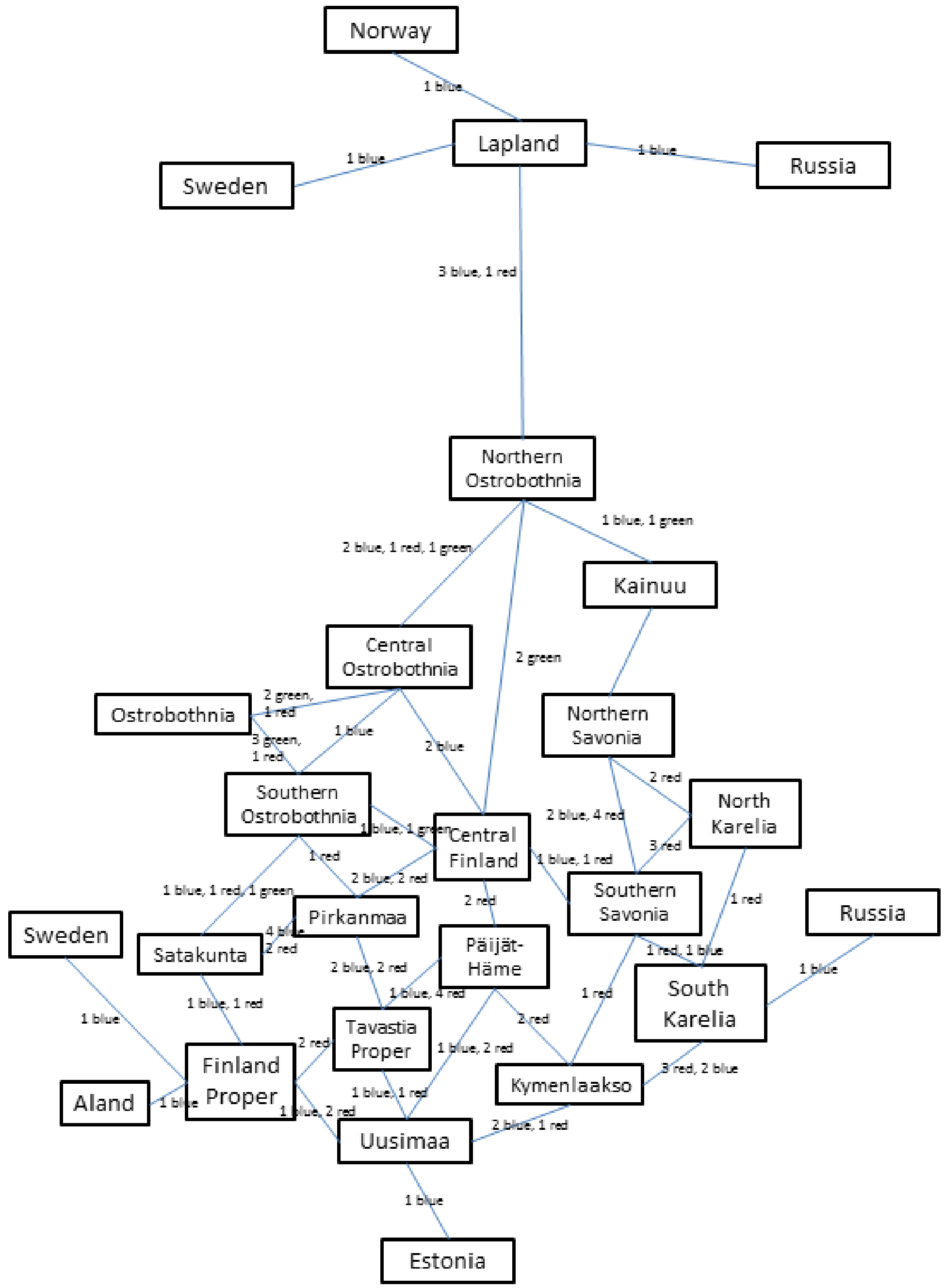

Figure 3.18 Finnish power network divided by nodes and connected by transmission lines.

nodes is important for determining transmission line losses. These distances are listed in Appendix A in Table A.4 through Table A.6. The information is divided into three tables because it could not all fit into one.

3.2.3 Optimization Criteria

The criteria or objective functions considered in this optimization problem are net fuel costs, operating and maintenance costs, capital costs, CO_2 emissions, SO_x emissions, PM_{10} emissions, and energetic efficiency. The fuel costs and emissions are derived in the same manner as for the DH system model. The efficiency exponents and maximum efficiencies for each of the conventional technologies and for nuclear power are given in Table 3.15. The information in this

Table 3.15 Power exponents and maximum efficiencies technologies [34, 48-49, 66-72] .

Fuel	Technology	Power exponents	Maximum Efficiency (CHP, Electric)
Biogas	Gas Turbine	0.3 [48]	0.9 [66], N/A
Peat	Condensing	0.1125 [67]	0.9 [68], 0.35 [68]
Natural Gas	Condensing	0.1125 [67]	0.91, N/A
Natural Gas	Gas Turbine	0.3 [48]	0.91, 0.4 [69]
Coal	Condensing	0.0604 [49]	0.88, 0.4 [69]
Heavy Fuel Oil	Condensing	0.1125 [67]	0.9, N/A
Heavy Fuel Oil	Gas Turbine	0.3 [48]	0.9, 0.43 [69]
Hydrogen	Condensing	0.1125 [67]	0.7 [70], N/A
Wood	Condensing	0.1125 [67]	0.9 [71], 0.36 [72]
Waste	Condensing	0.1623 [67]	0.9 [73], N/A
N/A	Hydroelectric	0	N/A, 1.0 [69]
N/A	Wind	0	N/A, 0.18 [34]
Nuclear	Condensing	0.1125 [67]	N/A, 0.35 [69]

table is used along with the maximum plant capacity to develop an efficiency curve for each plant. Natural gas and coal CHP values are taken from CHP plants used in the DH system, and the CHP efficiency for oil plants is assumed to be 0.9, because most other CHP technologies have this efficiency. It is also assumed that the efficiencies for hydroelectric and wind power are constant. All of the gas turbine technologies are given a power coefficient value of 0.3. The actual value, from [48] is closer to 0.4 but the curve fit is not very accurate. Using a value of 0.3, the objective values still exhibit similar behavior, with a better curve fit. This is illustrated in Figure 3.19.

The two cost curves represent curves for the same power plant but with different power exponents. The first cost curve contains a power coefficient of 0.3 while the second contains a

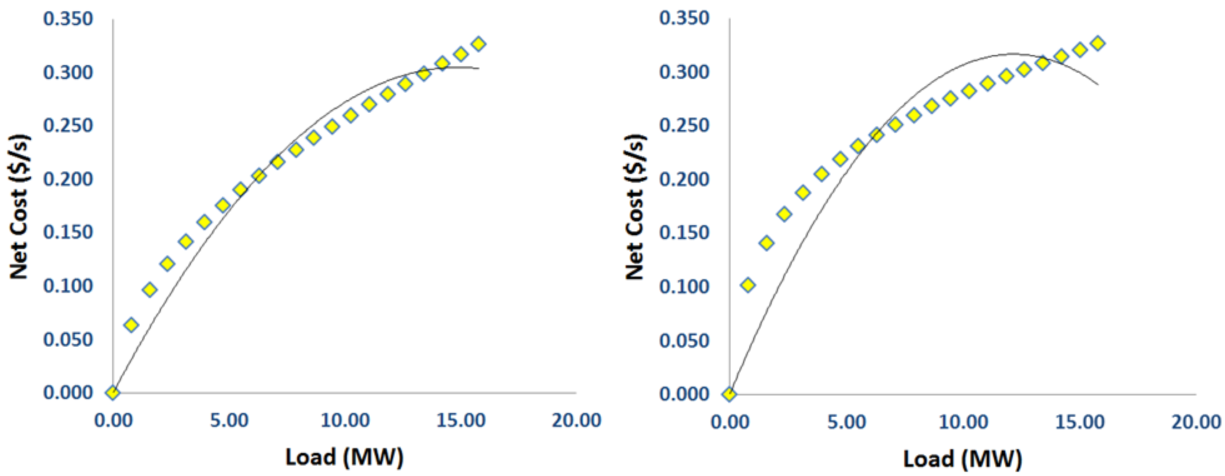

Figure 3.19 Two costs curves for a heavy fuel oil power plant; this is a gas turbine CHP power plant with capacities of 15.8 MWe and 13.5 MWth with the first cost curve being for a power coefficient of 0.3 and the second cost curve is for a power coefficient of 0.4337.

power coefficient of 0.4337. As can be seen, the fit for the first cost curve is better than that for the second. In fact, the second cost curve fit has a maximum net fuel cost at about 12 MW and then decreases as the load increases. Of course, this does not represent realistic operation for a power plant. The first cost curve "flattens" out at about 13 MW and then remains at about the same cost value. Also note that these curve fits are developed using a quadratic equation as in Equation (3.20). A better curve fit may be achieved with a more complex equation, but there is always a tradeoff between the accuracy of curve fits and computational time.

The majority of the condensing technologies are given a power exponent value of 0.1125. This value is based on a typical Rankine cycle from [67]. If values for individual condensing technologies are found later, then these values can be used instead. This is the case for coal [49] and waste [67]. The sources for the maximum efficiency values are given in Table 3.15. The majority of CHP technologies have a maximum efficiency of about 0.9. Electricity-only plants have a significantly lower efficiency of 0.35-0.43, depending on the technology. If the power plant type is not available in the model setup, then the efficiency is listed as N/A.

The lower heating value and fuel cost provided for each fuel are listed in Table 3.16. In order to determine fuel cost rates, Equation (3.24) can be used. The cost for waste is assumed to be zero because waste is collected with no charge to the municipality. A cost for nuclear energy

Table 3.16 Lower heating value and fuel cost for each fuel [52-53, 74-80].

Fuel	LHV (MJ/kg)	Cost ($/kg)
Biogas	23 [74]	0.55 [75]
Peat	20 [76]	0.33 [77]
Natural Gas	47 [52]	0.28 [53]
Coal	25 [52]	0.09 [53]
Heavy Fuel Oil	42 [52]	0.77 [53]
Hydrogen	120 [52]	4 [78]
Wood	20 [52]	0.36 [77]
Waste	9.5 [79]	0
Nuclear	N/A	0.00214 ($/MJ) [80]

could not be found on a dollar per kilogram basis, but it was found on a dollar per MJ basis.

Now, fuel costs are incurred when electricity and heat are produced. This differs from the DH model, because for this, costs are not incurred for the production of electricity. Costs are only incurred for the production of heat. Furthermore, in the DH model, the electricity production is not assumed to be part of the model. For the Finnish power network, the heat produced from CHP plants is sold at a DH price of 0.02 $/MJ [46]. This assumes a 2010 conversion rate of $1.3 to 1€. The net fuel costs are then determined by the cost of the fuel used for electricity and heat production minus the sales in DH. The majority of net fuel cost curves

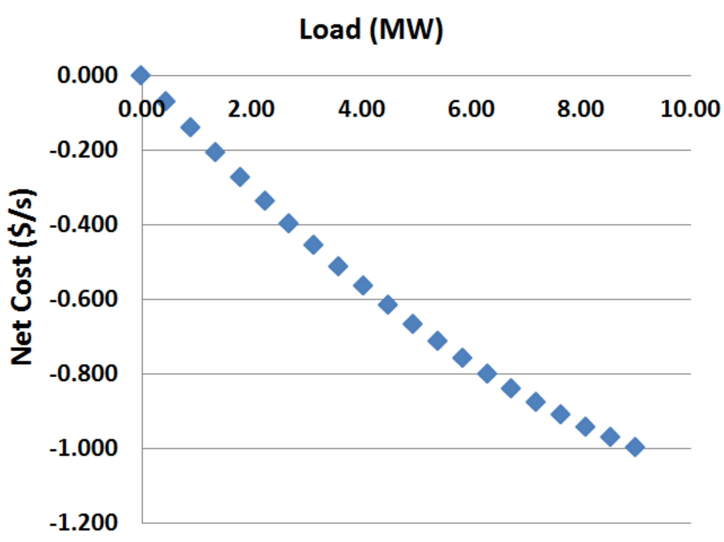

Figure 3.20 Net fuel cost for a 9 MWe, 65 MWth coal power plant.

appear similar to the one in Figure 3.10. In some cases, when the DH sales are greater than the fuel costs, the net fuel cost can be negative. A negative cost indicates that the power plant is gaining money rather than losing money for the time period. An example of this situation can be seen in Figure 3.20. The net fuel cost curve is for a 9 MWe, 65 MWth coal power plant. The x-axis represents the electric load. For this producer, regardless of the electric load, there is a profit. It should be noted that the power to heat ratio is not constant. The power to heat ratio increases as the electric load increases. This behavior is determined by Figure 3.21 [9]. In the last

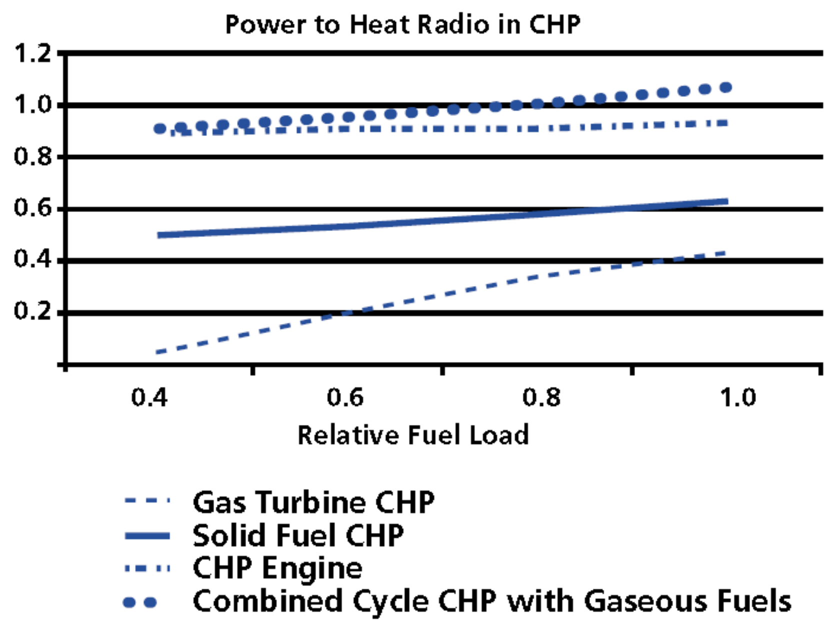

Figure 3.21 Power to heat ratio for various CHP technologies [9].

figure, a power to heat ratio is provided for the most common type of CHP technologies. These power to heat ratios may be typical, but they are not accurate for all plants. For example, the coal power plant discussed in Figure 3.20 does not fit the curve provided in Figure 3.21 for a solid fuel CHP plant. At a relative fuel load of unity, this power plant has a power to heat ratio of approximately 0.14 compared to about a 0.62 in Figure 3.21. Assuming linear behavior, for the entire fuel load range, at a relative fuel load of zero, the power to heat ratio is 0.42 for a solid fuel CHP plant. This means that the power to fuel ratio is 1.476 times greater at full load than at zero load. Inversely, more heat is being generated per unit power at low load than at high loads.

The emissions for each fuel can be seen in Table 3.17 and the capital and operating and maintenance costs can be seen in Table 3.18. Sources for the capital costs, operating and

Table 3.17 Emission values for CO_2, SO_x and PM_{10} for each fuel [57-58].

Fuel	**CO_2 [57]**	**SO_x [58]**	**PM_{10} [58]**
	Values in kg/MJ of fuel consumed		
Biogas	0.0509	4.62E-05	0.00E+00
Peat	0.0943	1.30E-04	1.72E-05
Natural Gas	0.0499	3.45E-08	0.00E+00
Coal	0.0858	8.08E-05	3.44E-06
Heavy Fuel Oil	0.0715	6.39E-04	1.47E-05
Hydrogen	0.0000	2.03E-10	0.00E+00
Wood	0.0994	1.91E-05	8.12E-06
Waste	0.0288	1.81E-04	3.66E-06
Hydro	0.0000	0.00E+00	0.00E+00
Wind	0.0000	0.00E+00	0.00E+00
Nuclear	0.0000	0.00E+00	0.00E+00

Table 3.18 Capital costs and operating and maintenance costs for each technology; also included are the operating hours per year [48, 70, 81-83].

Technology	**Capital ($/kW)**	**O&M ($/MWh)**	**Operating hrs/yr**
Biogas	2200	15.756	5000
Peat	2200	15.756	5000
Natural Gas	800 [48]	74.048 [48]	3150 [48]
Coal	2000 [48]	26.585 [48]	6610 [48]
Heavy Fuel Oil	350 [48]	112.242 [48]	1870 [48]
Hydrogen	680 [70]	26.585	6610
Wood	2200	15.756	5000
Waste	2200 [48]	15.756 [48]	5000 [48]
Hydroelectric	1700 [48]	4.706 [48]	3530 [48]
Wind	900 [81]	15 [82]	5840 [83]
Nuclear	3000 [48]	17.03 [48]	7710 [48]

maintenance costs, and the average operating hours per year are included. The operating hours per year represent the average number of hours per year that a power plant operates. With a plant life and annualization factor, a capital cost can be determined for each plant on a yearly basis. It is assumed that all of the values are the same for biogas, peat, and wood as they are for waste. This assumption is made because these plant types are generally constructed in a similar manner. Also, many plants that use waste are also able to use biomass. Furthermore, the operating hours per year and the operating and maintenance costs are assumed to be the same for hydrogen as they are for coal. This is because specific data for hydrogen plants is difficult to find due to their scarcity. Therefore, it is assumed that the operating and maintenance costs and the operating hours per year are the same as for a common condensing technology.

3.2.4 Regional Demands and Net Imports

Energy demands for each of the regions can be seen in Table 3.19. This information is provided for the year 2009 from [39]. Note that the values are given in energy consumed per

Table 3.19 Energy demands in GWh for each region in the year 2009 [39].

Region	Demand (GWh)
Aland Island	250
Central Finland	5787
Central Ostrobothnia	1993
Southern Savonia	1632
Kainuu	1011
Tavastia Proper	2101
Lapland	4979
North Karelia	1970
North Ostrobothnia	5795
Ostrobothnia	3068
Päijät-Häme	2197
Pirkanmaa	5398
Northern Savonia	3700
Satakunta	5486
South Karelia	5359
South Ostrobothnia	1978
Uusimaa	15920
Finland Proper	4809
Kymenlaakso	5085

year. Furthermore, the net imports from neighboring countries are provided in Table 3.20 [39]. Note that a negative value for a net import represents a positive net export.

Table 3.20 Net imports of electricity from neighboring countries [39].

Country	**Net Import (GWh)**
Sweden	-1307
Norway	-15
Estonia	1698
Russia	11708
TOTAL	*12084*

Chapter 4 Solution Approach

This chapter discusses the methods and processes used to obtain solutions for the DH model and optimization. This includes the methods used for the development of the solution sets in section 4.1, the iterative process for obtaining the solution sets in section 4.2, the post-processing techniques applied to solution sets to obtain a best solution in section 4.3, and the fuel sensitivity analysis of the solution sets discussed in section 4.4.

4.1 Pareto Solution Set Construction

The Pareto solution sets are developed in a manner similar to that discussed in [4]. Since a single-objective gradient-based algorithm [35] is used, multiple objectives cannot be optimized simultaneously by the algorithm. Instead, the minimum value for each objective function is determined first by applying the algorithm to each objective separately. Two objectives at a time are compared next such as, for example, the costs and a particular type of emission as illustrated in Figure 4.1. The two minimum values for these objectives are indicated in the figure. Over the space considered, a minimum point for one objective is a maximum for the other. Between these

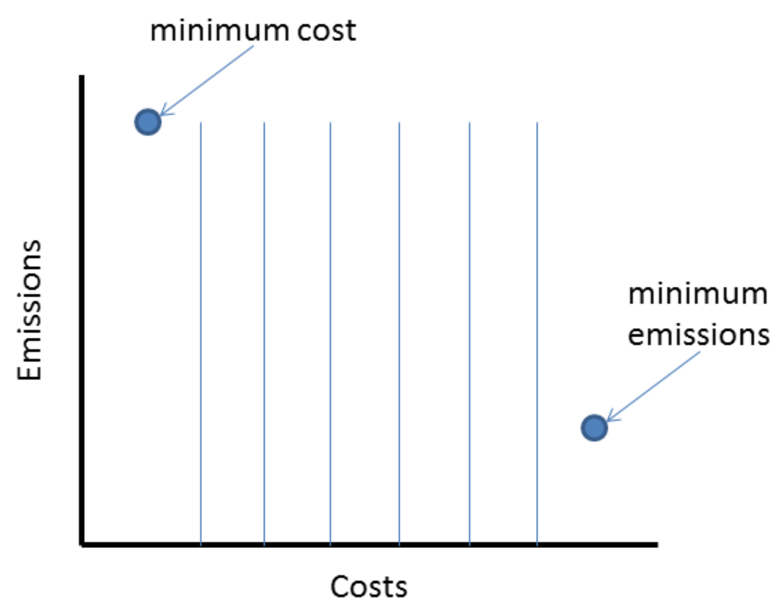

Figure 4.1 Development of a Pareto set solution by discretizing between the minimums of two objective functions.

two minimum objective values is the discretized space, which is discretized by assuming a reasonable number of points that make clear the Pareto front which is to be established. No matter which point is chosen, there is always a tradeoff. This means that one or both of the objectives will always be at a value other than its best value.

To go about developing the solution set, the minimum cost is increased by a relatively small amount to a chosen discretized value. The emissions are then minimized for this constrained cost value. This process is repeated until a sufficient number of solutions are obtained between the two minimized objectives. All solution sets developed are done so with costs on the x-axis. This process is repeated with all the other objective functions until all possible combinations of costs with the other objective functions have been exhausted. Of course, all combinations of objective functions could be compared, but it is concluded that the number of solutions acquired from the aforementioned method is sufficient.

4.2 Obtaining Solutions

When using a gradient-based algorithm to optimize a large problem, solutions cannot simply be obtained by choosing any set of initial values. Instead, initial values should be chosen carefully in order to "lead" the optimizer towards the solution. Furthermore, one optimization is not always enough to converge to the solution. Often, multiple optimizations must be used. Each new optimization refines the result of the previous one. Therefore, the engineer must have an understanding of the tradeoffs of the system. Even if the optimization program claims that it has reached a solution, this solution is not always a global minimum. It could very well simply be a local minimum.

Now, the behavior of a Pareto set solution may appear similar to Figure 2.4 and Figure 2.10 or it may be linear or completely different as in Figure 2.5. This is dependent upon the method used for optimization and the constraints on the system. For the case of the Pareto solution sets developed in this research, they appear similar to Figure 2.4 and Figure 2.10 or have less steep behavior as in Figure 2.11 or are linear. The behavior of the set is also determined by the number of tradeoffs that exist and the magnitudes of these tradeoffs. For example, in this optimization problem, the producers use oil, coal, or natural gas or are heat pumps. Trading out coal for natural gas may result in a better solution than trading out coal for oil. Also, it must be considered that a certain production technology may be the best option for two particular objectives. For example, natural gas may be the best option on a cost and CO_2 basis. Therefore, a maximum amount of natural gas is used for every solution and tradeoffs exist between coal and oil technologies as well as with heat pumps. This affects the slope from point to point in the Pareto sets. More generally, if tradeoffs exist between many technologies, then the slope of the solution set varies from point to point. If, on the other hand, a tradeoff exists between only two technologies, then the slope remains approximately constant for the duration of the solution set. Finally, if no tradeoffs exist, then there is only one solution. This solution is the minimum for both objective functions under consideration. This unique situation occurs once for the present model and is discussed in Chapter 5.

When moving away from a minimized objective function such as cost, a question that can be posed is, "How much can I reduce my emissions if I increase my cost by a certain percentage?". For a case in which multiple tradeoffs occur, the largest reduction in emissions should be observed between the minimum cost and the first discretized value. This means that the slope is the steepest for the first interval. The second interval should have the second steepest slope and so on. This phenomenon is better explained and understood with the introduction of results in Chapter 5.

4.3 Post-Processing Techniques

Post-processing techniques are used to determine the best solution from the solution set when non-commensurable units are used in a multi-objective optimization. Two methods are discussed and implemented: (1) linear value functions with equal weights and (2) linear value functions with survey-defined weights. A value function ranks an objective between 0 and 1. For a minimization problem, the highest value for an objective receives a value of 0, while the lowest value receives a value of 1. If the value function is linear, it will appear as in Figure 4.2. The minimum cost is assigned a value of 1, while the maximum cost is assigned a value of 0.

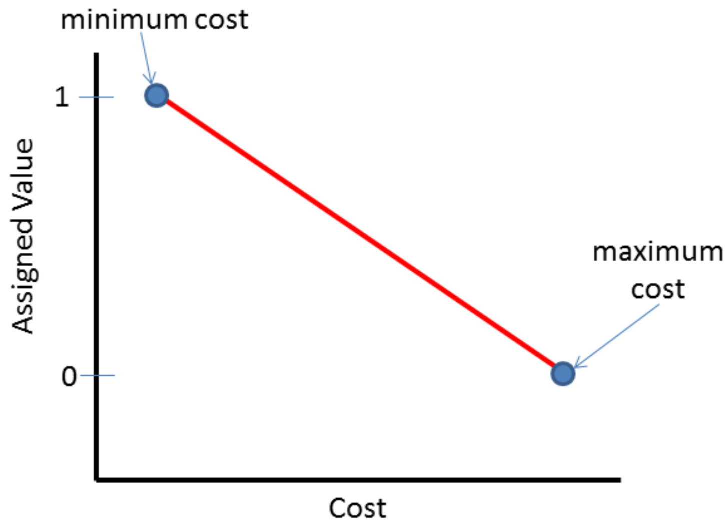

Figure 4.2 Example of a linear value function for cost.

Anything in between can be determined by the value function, namely,

$$V(F)=\frac{F_{max}-F}{F_{max}-F_{min}} \tag{4.1}$$

where F_{max} is the maximum objective value and F_{min} is the minimum value. It must be understood that ranking objectives with a value function is subjective. It may not be reasonable to assume that a value function is linear. For example, if the minimum cost is $1 and the maximum $10, then a cost of $5.5 is assigned a value of 0.5, a cost of $7 a value of 0.33, and a cost of $4 a value of 0.67. However, questions may arise, such as “Is it reasonable to assume that a cost four-times the minimum receives a rank of two-thirds of the minimum cost?” or “Is it possible that a threshold should exist for the cost?” or “Should the behavior of the value function change at a certain cost?”. Although answering these questions would be useful, it could take a considerable amount of time and is not done here since this is not the focus of this research. The questions are made simply to make the reader aware that this is not necessarily the “best” or most widely accepted formulation of a value function.

Each optimal solution solution found has five objective values (costs, CO_2, SO_x, PM_{10}, and the exergetic efficiency parameter). Thus, a value function value is assigned to each of the five. The rank of the solution can then be given by

$$\mu = \sum_{i=1}^{I} \Omega_i V(F_i) \tag{4.2}$$

where
$$\sum_{i=1}^{I} \Omega_i = 1 \tag{4.3}$$

$$\sum_{i=1}^{I} V(F_i) \le I \tag{4.4}$$

Here $V(F_i)$ is the value function for objective i and Ω_i is the weight assigned to objective i. In this case, I is equal to 5. The sum of the weights is unity, and the sum of the value functions cannot be greater than I or 5 in this case. A case where the sum of the value functions is equal to 5 would mean that the best value function value is achieved for all five objectives. While this is possible, it is not probable; and it is never the case for optimal solutions found in this research. For the case where the weights are equal for each objective, Ω_i is 0.2 for all i.

Another way to determine a best solution is to treat the economic, environmental and technological criteria as only three objective functions. This means that a rank is determined for each of these criteria and I is equal to 3. In order to determine the rank for the environmental criteria, the ranks for CO_2, SO_x and PM_{10} are averaged. The economic and technological criteria remain the same because these criteria are associated with one objective function each. This is the manner in which the best solution is determined for the set of optimal solutions for the case of a linear value functions with equal weights. More specifically, it is written as

$$\begin{aligned}\mu = {} & \Omega_{econ} V_{econ}(F_{econ}) + \Omega_{enviro}\left(\Omega_{CO_2} V_{CO_2}(F_{CO_2}) + \Omega_{SO_x} V_{SO_x}(F_{SO_x}) + \Omega_{PM_{10}} V_{PM_{10}}(F_{PM_{10}})\right) \\ & + \Omega_{tech} V_{tech}(F_{tech})\end{aligned} \tag{4.5}$$

where Ω_{econ}, Ω_{enviro}, Ω_{CO_2}, Ω_{SO_x}, $\Omega_{PM_{10}}$, and Ω_{tech} are the weights for the economic, environmental, CO_2, SO_x, PM_{10} and the technological criteria, respectively. Each of these weights is given a value of 0.33.

Survey-defined weights take the view of the public, colleagues, or professionals into account in order to develop weights for solutions. The weights in this case are developed by using the survey given in Appendix B. This survey was completed by two graduate students and three professors. The requirement for the respondents is that they have some expertise in the area of sustainability. The purpose of the survey is to compare the relative importance of economic, technological, and environmental criteria and to also compare the relative importance of individual emissions. For this survey, each respondent is assigned a reliability value based on their position, experience, and reputation. These characteristics can be seen in Table 4.1. For

Table 4.1 Characteristics to determine the reliability of each respondent.

Value	Position	Experience (yr)	Reputation
5	Professor	greater than 25	Known by many, internationally
4	Associate Prof.	18 to 25	Known by many, nationally
3	Assistant Prof.	11 to 18	Known by many, regionally
2	Instructor	5 to 11	Known by many locally
1	Graduate Student	less than 5	Known by few

example, if a graduate student has 10 years of experience (mostly in industry) and is known by many locally, he is given a value of 2. If a professor has 20 years of experience and is known by many regionally, he is given a value of 4. The values assigned to each of the five respondents are reported in Table 4.2. Respondents 1 and 2 are graduate students while respondents 3, 4, and 5

Table 4.2 Reliability value given to each respondent based on the aforementioned characteristics.

Respondent	Value
1	1
2	1
3	4
4	4
5	4

are professors. These values are used in conjunction with the survey data in order to develop weights for each objective.

The survey results for the criteria and emissions can be seen in Table 4.3. For each respondent, the highest value for a criterion or emission is assigned a value of unity. All other values are assigned fractions of this value. For example, in the first column of the survey, graduate student 1 provides a value of 1 for CO_2, 4 for SO_x and 4 for PM_{10}. The normalized

Table 4.3 Results from the survey for all criteria and emissions.

Respondents	Criteria			Emissions		
	Economic	Technological	Environmental	CO_2	SO_x	PM_{10}
Grad. Student 1	0.25	1	0.375	0.25	1	0.25
Grad. Student 2	1	0.5	0.25	0.25	1	1
Professor 1	1	1	0.5	0.25	1	1
Professor 2	0.25	0.5	1	1	0.5	0.25
Professor 3	1	0.25	1	0.25	1	1

values, provided in Table 4.3, are 0.25 for CO_2, 1 for SO_x, and 1 for PM_{10}. Each weight can then be determined by

$$\Omega_i = \frac{\sum_{j=1}^{J} \left(\Omega_s \Omega_c\right)_j}{\sum_{i=1}^{I} \sum_{j=1}^{J} \left(\Omega_s \Omega_c\right)_j} \tag{4.6}$$

where j represents the respondents and i each criteria or emission. Note that the weights for the emissions are evaluated separately from the economic, technological and environmental criteria weights. Ω_s is the weight provided by the respondent for a particular criterion or emission and Ω_c is the weight or character rank assigned to each respondent. The latter is a constant while the former varies for each i. The resulting weights can be seen in Table 4.4. These weights can be

Table 4.4 Survey-defined weight values.

	Criteria			Emissions		
	Economic	Technological	Environmental	CO_2	SO_x	PM_{10}
Weight	0.349	0.289	0.362	0.226	0.417	0.357

used in Equation (4.5) to determine the overall rank for a solution and, thus, the best solution.

4.4 Fuel Sensitivity Analysis

Because fuel prices fluctuate often, it is necessary to consider the effects on the optimal solution set of high, medium, and low fuel prices, i.e., the goal is the determine how sensitive the optimum configuration is to fluctuating fuel prices. These prices can be seen in Table 3.10 of Chapter 3. With three different fuels and three fuel prices for each fuel, twenty-seven combinations are possible. Of these twenty-seven combinations, ten are chosen which bracket the range of sensitivities which the twenty-seven combinations encompass. These ten combinations can be seen in Table 4.5.

Table 4.5 Combinations chosen for the fuel sensitivity analysis; note that H is high, M is medium, and L is low.

Combination number	**Fuel Price Level**		
	Natural Gas	**Coal**	**Oil**
1	M	M	M
2	L	L	L
3	H	H	H
4	H	L	L
5	H	M	L
6	M	M	L
7	M	L	L
8	L	H	L
9	M	H	L
10	H	H	L

The first three combinations in this table are used because they represent how prices are now, how they have been in the past, and what they will most likely be in the future. Since the fuel costs for coal and natural gas are significantly lower than for oil, the remaining seven combinations are for cases that included oil as a low cost fuel. In fact, the last seven combinations have oil as cheaper on a per energy basis than at least one of the two other fuels.

Chapter 5 Results and Discussion

This chapter discusses the results obtained for the Pareto set solution sets, the post-processing, and the sensitivity analysis. Section 5.1 discusses the results for the solution sets generated, while the next two sections, sections 5.2 and 5.3, discuss the post-processing techniques, and ultimately, the best solution for each of these two techniques. The last section, section 5.4, discusses the conclusions drawn from the results.

5.1 Pareto Solution Sets and Optimization Data

This section discusses the Pareto solution sets for all ten fuel cost combinations. In section 5.1.1, results are displayed and discussed for medium fuel costs. This section also discusses important generalizations about the tradeoff behavior of these solution sets. Section 5.1.2 provides some more results for the remaining nine cost combinations without going into as much detail as section 5.1.1. Because results are numerous and not all discussed in great detail, additional results not discussed in this chapter are placed in Appendix A.

5.1.1 Pareto Solution Sets for Medium Fuel Costs

The first Pareto solution sets discussed are from combination 1 in Table 4.5. This

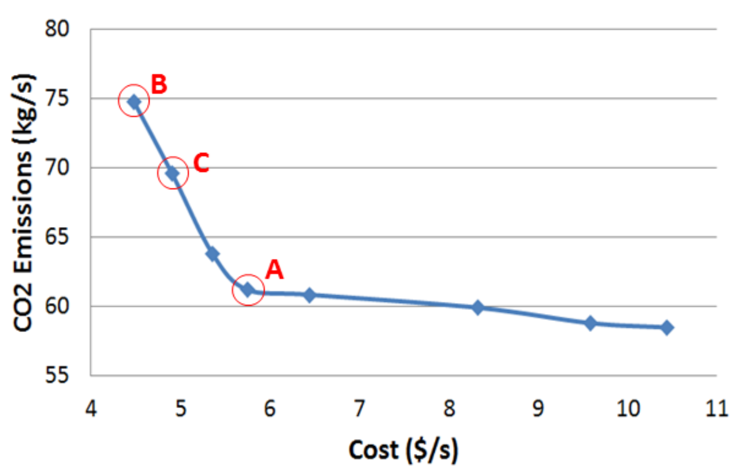

Figure 5.1 Pareto solution set for CO_2 emissions versus cost for medium fuel costs.

combination is the closest representation to today's fuel prices. The CO_2 emissions versus costs (fuel and pumping) Pareto solution set is given in Figure 5.1. The blue diamonds represent actual optimal solutions found, while the blue line is the approximate continuous behavior of the Pareto solution set. This set exhibits behavior similar to that in Figure 2.10 of Chapter 2. Due to the rapid change in slope at about $6 per second, i.e. at the fourth optimal solution from the left, i.e., optimal DH system configuration A, it is apparent that there is a change in tradeoffs between fuel at or around this point. The optimal solution with the lowest cost, i.e., optimal DH system configuration B, can be seen in Figure 5.2.

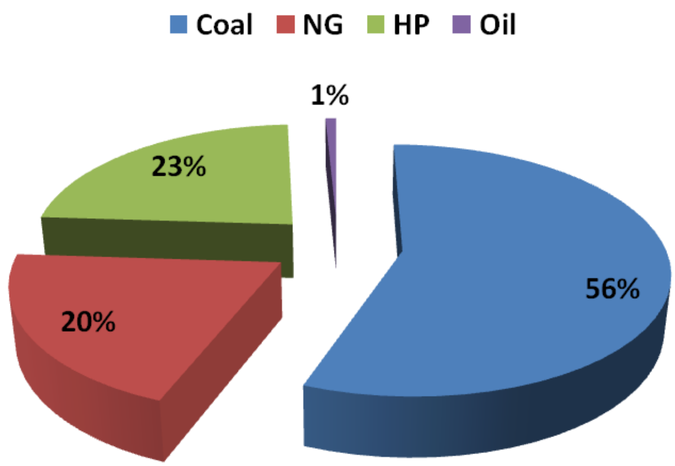

Figure 5.2 Optimal DH system configuration B in Figure 5.1 for medium fuel prices.

This optimal configuration has DH production from each technology type. The configuration chosen depends on the fuel cost as well as the capacity of a certain technology. Even though a technology is the cheapest, it does not mean that the technology has the largest percentage of DH production. For example, heat pumps for this configuration turn out to be cheaper than coal technologies, yet the latter has a much larger capacity. To illustrate this, prices are placed on a per MJ of district heat basis as seen in Table 5.1. This is the adjusted fuel price that the operator can expect to pay for a certain fuel if the technology which uses the fuel is operating at full load. The adjusted prices reported in this table assume a 0.91 efficiency for natural gas technology, 0.88 for coal, 0.85 for oil, and 1.4 for heat pumps. As previously

Table 5.1 Example of medium fuel prices placed on a per MJ of district heat basis for comparison purposes.

Technology	Price per MJ district heat ($/MJ)
Natural Gas	0.0066
Coal	0.0041
Oil	0.022
Heat Pump	0.0038

mentioned heat pumps are given a fuel cost based on the technology from which they are assumed to receive electricity. This fuel cost is based on a mix of natural gas and coal. The order of adjusted fuel costs per technology for this illustration starting from lowest to highest is heat pumps and then coal, natural gas, and oil technologies. Adjusted prices for natural gas, coal, and oil will increase if the technologies are operating at any partial load. In contrast, the adjusted heat pump price remains constant regardless of the load since the heat pump efficiency is constant.

Now, the optimal solution in Figure 5.1 to the right of the minimum cost optimal solution, i.e., optimal DH system configuration C, is a solution in the solution set that does not contain the minimum costs or minimum emissions. Instead, this solution "sacrifices" a certain amount of money in order to improve CO_2 emissions. The technology configuration for this optimal solution can be seen in Figure 5.3.

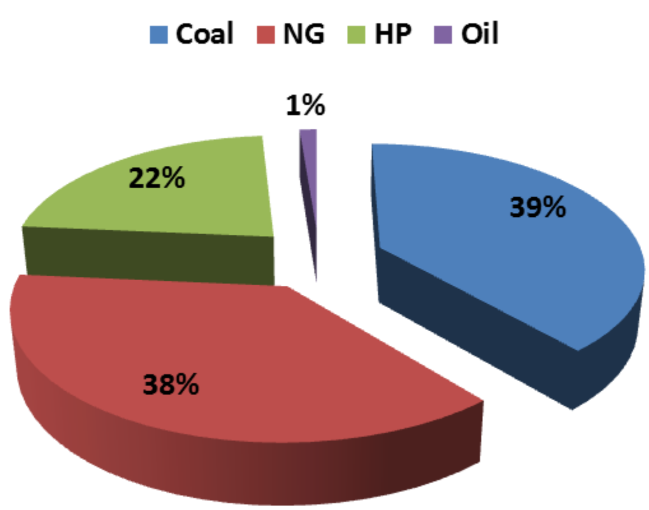

Figure 5.3 Optimal DH system configuration C in Figure 5.1.

While the percentage of heat pump and oil technologies remain approximately the same as the case of optimal configuration B, the percentage of natural gas technologies increases, while that of coal decreases. This is because the substitution of natural gas for coal provides the largest reduction in emissions at the lowest increase in cost. For example, a coal plant operating at an efficiency of 0.88 has an adjusted fuel cost of $0.0041/MJ of district heat and emits 0.0975 kg of CO_2/MJ of district heat. A natural gas plant operating at an efficiency of 0.91 has an adjusted fuel cost of $0.0066/MJ of district heat and emits 0.0548 kg of CO_2 /MJ of district heat, while an oil plant operating at an efficiency of 0.85 has an adjusted fuel cost of $0.022/MJ of district heat and emits 0.0841 kg of CO_2/MJ of district heat. As seen from these numbers, trading oil for coal does reduce emissions, but it reduces them at a very high cost compared to natural gas. With a price increase of only $0.0025/MJ of district heat, natural gas is able to reduce the CO_2 emissions by 0.0427 kg/MJ of district heat while oil is only able to reduce CO_2 emissions by 0.0134 kg/MJ of district heat with a price increase of $0.0179/MJ of district heat. Clearly, natural gas has the advantage over oil. However, when all of the available natural gas technologies have been substituted for coal, oil must then be substituted. This change in tradeoffs can be seen at about a cost of $6/sec in Figure 5.1. The abrupt change in slope is due to the change in tradeoffs.

The second Pareto solution set discussed for the same combination of fuels is for SO_x emissions versus costs. This optimal solution set can be seen in Figure 5.4. the Pareto solution

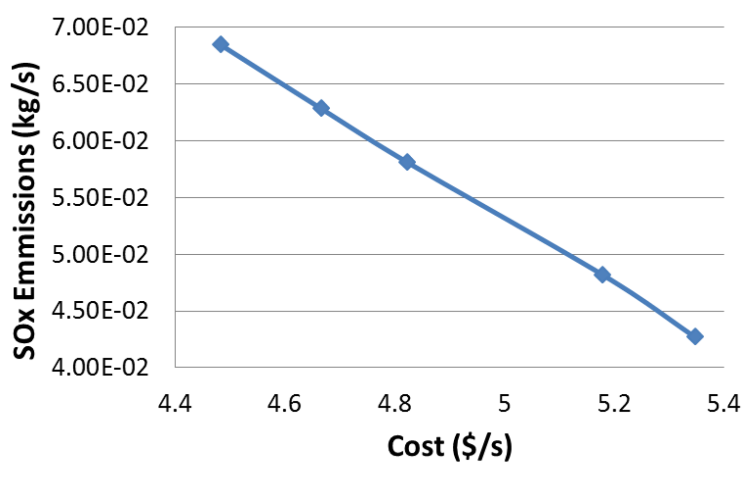

Figure 5.4 Pareto solution set SO_x emissions versus cost for medium fuel costs.

set shows linear behavior. This is because the tradeoff over the entire optimal solution set is between two fuel technologies, i.e., coal and natural gas. Oil does not provide a better solution than coal or natural gas from a cost or emissions standpoint. Therefore, the only time that oil is used is when no other technologies are available, because the demand is so high. Heat pumps are a good choice for this Pareto solution set and, thus, they are employed at the maximum load or close to it for each point on the Pareto solution set.

The third Pareto solution set discussed for medium fuel prices is for PM_{10} emissions versus costs. This optimal solution set can be seen in Figure 5.5. The Pareto set shows linear

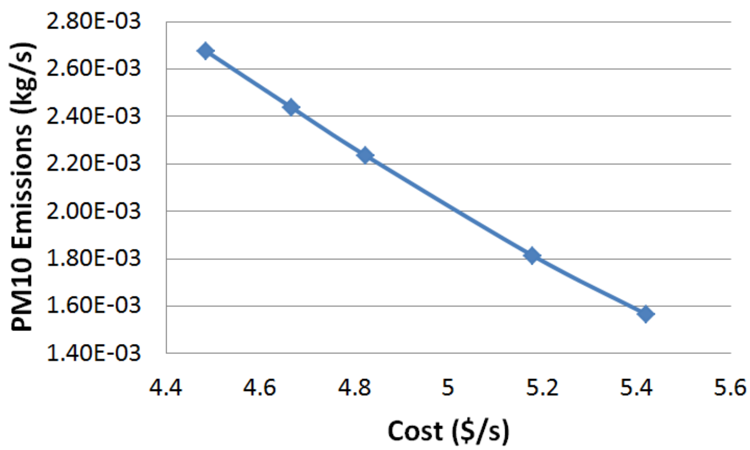

Figure 5.5 Pareto solution set for PM_{10} emissions versus cost for medium fuel costs.

behavior, which is very similar to the case for SO_x emissions versus cost. In fact, in this case, the configuration for a minimum amount of PM_{10} emissions is the same configuration for a minimum amount of SO_x emissions. For all cost combinations, the behavior for SO_x emissions versus cost and PM_{10} emissions versus cost is very similar. Therefore, no "new" information is gained by developing more than one of the two sets. In other words, if the optimal solution sets contain the same configuration at each point, then they also contain the same values for all of the criteria. Nevertheless, Pareto solution sets are developed for both tradeoffs for all fuel combinations since this is not known a priori.

The fourth and last Pareto solution set discussed for medium fuel prices is for exergetic efficiency parameter versus cost. This optimal solution set can be seen in Figure 5.6 and also shows the same type of linear behavior as the previous two Pareto solution sets. Note that the

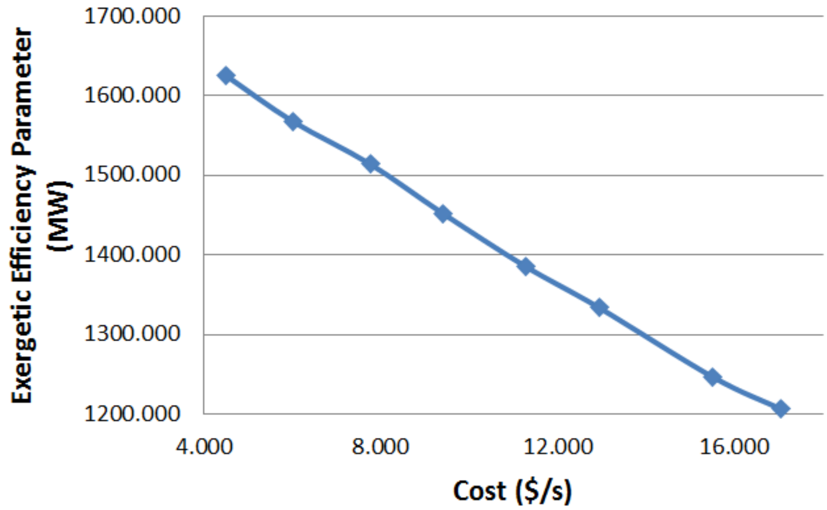

Figure 5.6 Pareto solution set for the exergetic efficiency parameter versus cost for medium fuel costs.

exergetic efficiency parameter only provides implicit information about the exergetic efficiency since it was developed for computational convenience. Minimizing the exergetic efficiency parameter is the same as maximizing the exergetic efficiency.

Up to this point, the magnitude of fuel costs have been discussed but that of pumping costs has not. Pumping costs are significantly smaller than fuels costs. For example, for the minimum costs case (optimal configuration B of Figure 5.1), the fuel costs are $4.478/sec, while the pumping costs are $0.0054/sec. Therefore, the fuel costs represent 99.88% of the total costs and the pumping costs only 0.12% of the total costs. Now, the benefit of including pumping costs is that it keeps as much of the heat production local as possible. For example, if a boiler provides 50 MWth of heat locally, it provides the heat with no pumping costs or heat losses. If an identical boiler from a node 10 km away provides the same amount of heat, then a pumping cost of $0.004/sec is incurred. While this value is small, this pumping cost combined with the pipe heat losses ensures that neighboring nodes are not the preferred source of heat at nodes that can be supplied locally without pumping costs and heat losses.

5.1.2 Solution Sets for Other Fuel Cost Combinations

This section discusses the results for some of the other nine fuel costs combinations. While these results are important, they are not discussed in as much detail as the results in the previous section since the general knowledge from the previous discussion can be extended to these other optimal solution sets. The Pareto solution sets discussed here are for the two cost combinations where oil is the lowest fuel price.

5.1.2.1 Fuel Cost Combination 10

Fuel cost combination 10 is for low oil and high natural gas and coal prices. These prices

Table 5.2 Example of low oil and high natural gas and coal prices placed on a per MJ of district heating basis for comparison purposes.

Technology	Price per MJ district heat ($/MJ)
Natural Gas	0.01
Coal	0.0068
Oil	0.0056
Heat Pump	0.0059

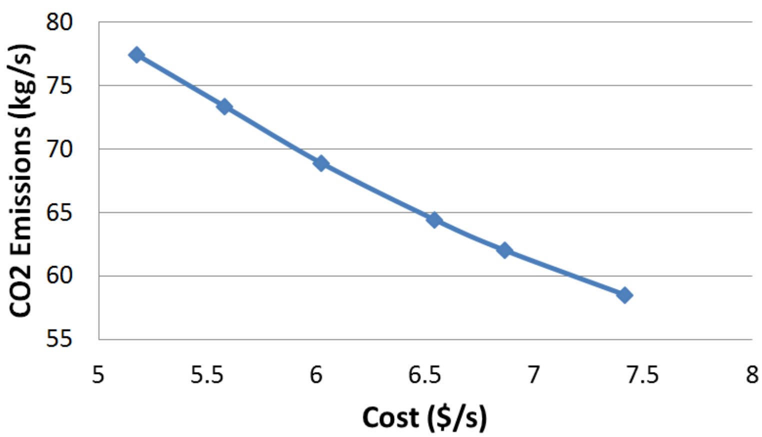

Figure 5.7 Pareto solution set for CO_2 emissions versus cost for low oil and high natural gas and coal prices.

are adjusted with the same efficiencies used in Table 5.1 and the results are presented in Table 5.2. On the basis of cost per MJ of district heat, oil is cheaper than natural gas, coal, and even the heat pumps. A Pareto solution set for CO_2 emissions versus costs can be seen in Figure 5.7. The lowest cost configuration consists of 95% oil and 5% heat pump technologies. The capacity of oil is so large that the entire demand can almost solely be supplied with oil technologies. As the solution set develops from left to right, the tradeoffs are between oil and natural gas followed by oil and coal. The change in tradeoffs is at about 6 $/s.

The Pareto solution set for SO_x emissions versus costs is given in Figure 5.8. The same

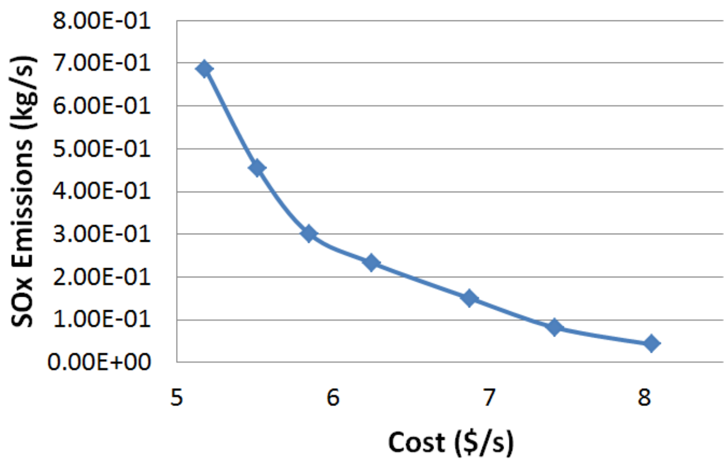

Figure 5.8 Pareto solution set for SO_x emissions versus cost for low oil and high natural gas and coal fuel costs

tradeoffs are present in the same order as for Figure 5.7. The only difference is that natural gas and oil tradeoffs develop a much steeper slope than the tradeoffs for coal and oil.

5.1.2.2 Fuel Cost Combination 8

Fuel cost combination 8 is for low oil and natural gas and high coal prices. These prices are adjusted with the same efficiencies used as in the previous tables and the results are presented in Table 5.3. On the basis of cost per MJ of district heat, oil is only cheaper than coal. For this

Table 5.3 Example of low oil and natural gas and high coal prices placed on a per MJ of district heat basis for comparison purposes.

Technology	Price per MJ district heat ($/MJ)
Natural Gas	0.0047
Coal	0.0068
Oil	0.0056
Heat Pump	0.0034

combination the optimization problem for CO_2 emissions versus cost presents a solution that is unique. This is because there is only one solution in this set. The configuration for the minimum cost is the same as the configuration for the minimum CO_2 emissions. The order in which fuel technologies are chosen are heat pumps, natural gas technologies, and then oil technologies. Because coal is the most expensive and emits the most CO_2 emissions, its use is not beneficial for this combination.

5.2 Post-processing: Application of Linear Value Functions and Equal Weights

The post-processing performed to find the best solution from among all the optimal solutions for each fuel combination is discussed here. Two post-processing techniques are used: that of linear value functions with equal weights and that of linear value functions with survey-defined weights. The former is used in this section. Table 5.4 is the set of solutions with value functions and ranks for medium fuel costs. These solutions were developed from the four combinations of objective functions discussed in section 5.1.1. They are listed based on cost, from lowest to highest. The value assigned to each objective is based on Equation (4.1). For each objective, the minimum value receives a value of unity while the maximum value receives a value of zero. Equation (4.5) is used to determine the rank. The ranks are then normalized and listed in the last column. Note that the highest normalized rank a solution can receive is unity. The best solution is italicized and colored red. This solution has high values for costs and emissions but it has a poor value for the exergetic efficiency parameter.

This with the pie chart of the configuration for the best solution for medium fuel costs in Figure 5.9. In this configuration, natural gas technologies produce the majority of the district

Table 5.4 Set of Pareto solutions for medium fuel costs; value function values for each objective function are included along with the rank for each solution.

Cost		CO_2 Emissions		SO_x Emissions		PM_{10} Emissions		Exergetic Efficiency Parameter		Rank	Normalized Rank
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value		
4.483	1.000	74.762	0.366	0.068	0.953	0.0027	0.910	1625.7	0.062	1.805	0.602
4.666	0.985	72.487	0.454	0.063	0.963	0.0024	0.930	1617.2	0.081	1.849	0.616
4.824	0.973	70.569	0.529	0.058	0.972	0.0022	0.947	1618.9	0.077	1.866	0.622
4.909	0.966	69.574	0.568	0.062	0.964	0.0023	0.941	1624.2	0.065	1.855	0.618
5.179	0.945	66.829	0.675	0.048	0.990	0.0018	0.981	1620.4	0.074	1.900	0.633
5.347	0.931	64.513	0.765	0.043	1.000	0.0016	1.000	1653.3	0.000	1.853	0.618
5.360	*0.930*	*63.794*	*0.793*	*0.058*	*0.973*	*0.0020*	*0.970*	*1575.8*	*0.173*	*2.015*	*0.672*
5.748	0.899	61.201	0.894	0.060	0.968	0.0019	0.975	1628.0	0.057	1.902	0.634
6.001	0.879	79.545	0.179	0.145	0.813	0.0045	0.763	1567.9	0.191	1.655	0.552
6.447	0.844	60.842	0.908	0.087	0.920	0.0024	0.932	1606.1	0.106	1.869	0.623
7.757	0.739	84.152	0.000	0.233	0.652	0.0065	0.596	1514.1	0.311	1.467	0.489
8.328	0.694	59.904	0.944	0.158	0.790	0.0039	0.813	1553.0	0.224	1.767	0.589
9.391	0.609	83.582	0.022	0.296	0.537	0.0078	0.491	1452.3	0.449	1.409	0.470
9.589	0.594	58.790	0.988	0.205	0.702	0.0048	0.735	1503.7	0.334	1.736	0.579
10.438	0.526	58.472	1.000	0.237	0.644	0.0055	0.681	1514.5	0.310	1.611	0.537
11.270	0.460	82.575	0.061	0.367	0.406	0.0093	0.372	1385.5	0.599	1.339	0.446
12.927	0.328	81.427	0.106	0.430	0.291	0.0105	0.267	1333.7	0.714	1.264	0.421
15.505	0.123	80.010	0.161	0.529	0.110	0.0126	0.102	1246.4	0.910	1.157	0.386
17.049	0.000	79.835	0.168	0.589	0.000	0.0138	0.000	1206.0	1.000	1.056	0.352

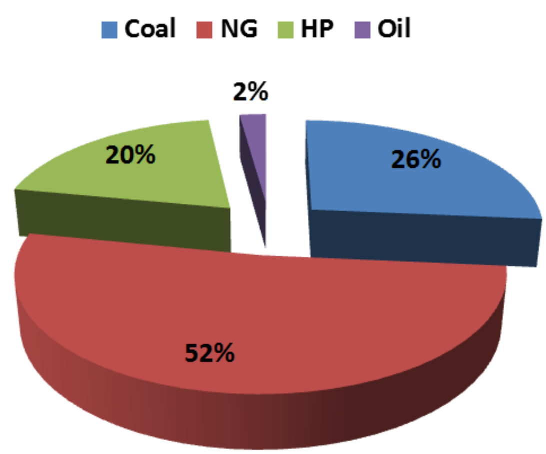

Figure 5.9 Configuration of the best solution for medium fuel costs.

heat, while coal technologies and heat pumps produce a significant amount as well. Oil technologies produce a very small amount. The advantage that the oil boilers have over the other technologies is that they produce energy at a higher temperature. Therefore, the exergy value of the heat produced is beneficial but emissions and fuel costs are not. The best solutions for combinations of all low fuel costs and all high fuel costs display very similar behavior to what is seen in Figure 5.9. Even though the fuel costs change, the order of solutions remains the same from lowest to highest.

Now, the goal of the sensitivity analysis is to determine if other fuels will dominate in the production of heat if the fuel costs are changed from what they currently are today. Because natural gas technologies are the best option for today, it would be interesting to determine if coal or oil are better options if the order of the costs from the lowest to the highest is changed. For oil, this is determined by having oil at its lowest price and coal and natural gas at their highest prices. The best configuration is shown in Figure 5.10. For this best solution, natural gas is not part of

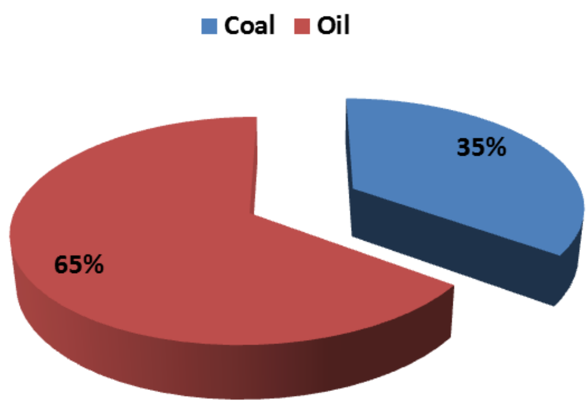

Figure 5.10 Configuration of the best solution for low oil and high coal and natural gas prices.

the configuration. Oil technologies dominate the production, while coal technologies offer a significant amount as well. If low fuel prices for coal and oil and a high fuel price for natural gas is considered instead, the best solution is the one in Figure 5.11. The best configuration is yet

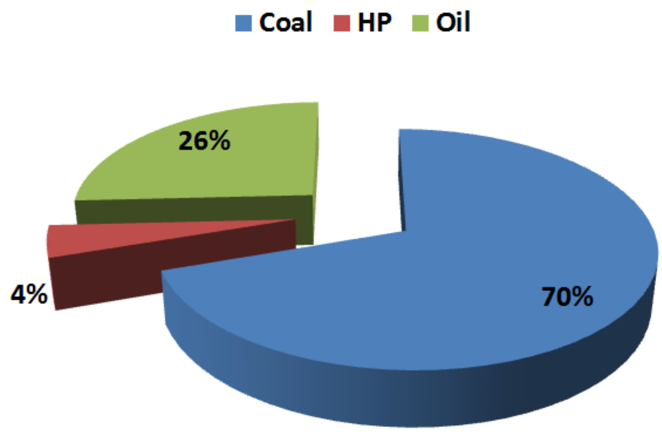

Figure 5.11 Configuration of the best solution for a high natural gas and low oil and coal prices.

another case where there is no production from natural gas. Instead, most of the production is from coal, a significant amount from oil, and a small amount from heat pumps. While it is unlikely that the price for natural gas will be high when prices for oil and coal are low, this solution shows that natural gas has no inherent advantage over other fuels when price signals align themselves in the right way. All of the production configurations for the best solution for all ten fuel cost combinations are given in Table 5.5. The production percentages are the same

Table 5.5 Best solution production configurations for all ten fuel cost combinations.

Combination number	Fuel Price			Best Solution Production Percentage			
	Natural Gas	Coal	Oil	Natural Gas	Coal	Oil	Heat Pumps
1	M	M	M	0.52	0.26	0.02	0.20
2	L	L	L	0.52	0.26	0.02	0.20
3	H	H	H	0.52	0.26	0.02	0.20
4	H	L	L	0.00	0.70	0.26	0.04
5	H	M	L	0.00	0.57	0.38	0.05
6	M	M	L	0.00	0.70	0.26	0.04
7	M	L	L	0.00	0.70	0.26	0.04
8	L	H	L	0.73	0.00	0.23	0.04
9	M	H	L	0.00	0.09	0.84	0.07
10	H	H	L	0.00	0.35	0.65	0.00

for the first three combinations of fuels. This is because the order of fuel prices from highest to lowest remains the same. Combinations 4 to 7 also have the same order of fuel prices amongst from highest to lowest. Therefore, three out of the four combinations are the same, while one is slightly different. It should be noted that these four combinations do not produce energy from natural gas technologies. Instead, coal technologies produce the majority of the production, while oil technologies produce a significant amount as well. Combination 8 is the only other combination that has production from natural gas technologies. With a high price for coal, the use of coal technologies is not found to be beneficial. In contrast, significant production from oil technologies and a small amount from heat pumps are found to be beneficial. The last two combinations have the highest percentage of production from oil technologies. With oil at a very low price and natural gas and coal at much higher prices, oil technologies dominate the production.

5.3 Post-processing: Application of Linear Value Functions and Survey-Defined Weights

From the weights listed in Table 4.4, the rank for each optimal solution can be determined. Table 5.6 shows the set of optimal solutions with value functions and ranks for medium fuel costs. Using this post-processing method, it turns out that the best solution is the same as for the previous post-processing method. Therefore, the best system configuration is the same as that given in Figure 5.9. This case is highlighted in blue and italicized. In fact, there are only two cases out of the ten cost combinations in which the best solution differs between the post-processing techniques. The first case is for a high natural gas price, a medium coal price and a low oil price. The best configurations differ slightly, and this can be seen in Table 5.7 where the second post-processing method with survey-defined weights shows a slight variance from the first post-processing method. As can be seen, the amount of coal technology production increases from the first to the second method, while the amount of oil production technology decreases. The next case is for a medium natural gas price and low prices for coal and oil. The best solution configuration for each post-processing technique can be seen in Table 5.8. The situation is similar here, as the amount of coal production increases from the first post-processing method to the second post-processing method, and the amount of oil production decreases.

Table 5.6 Set of solutions for medium fuel costs; value function values for each objective function are included along with the rank for each solution

Cost		CO_2 Emissions		SO_x Emissions		PM_{10} Emissions		Exergetic Efficiency Parameter		Normalized Rank
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value	
4.483	1.000	74.762	0.366	0.068	0.953	0.0027	0.910	1625.7	0.062	0.658
4.666	0.985	72.487	0.454	0.063	0.963	0.0024	0.930	1617.2	0.081	0.670
4.824	0.973	70.569	0.529	0.058	0.972	0.0022	0.947	1618.9	0.077	0.674
4.909	0.966	69.574	0.568	0.062	0.964	0.0023	0.941	1624.2	0.065	0.670
5.179	0.945	66.829	0.675	0.048	0.990	0.0018	0.981	1620.4	0.074	0.682
5.347	0.931	64.513	0.765	0.043	1.000	0.0016	1.000	1653.3	0.000	0.668
5.360	*0.930*	*63.794*	*0.793*	*0.058*	*0.973*	*0.0020*	*0.970*	*1575.8*	*0.173*	*0.712*
5.748	0.899	61.201	0.894	0.060	0.968	0.0019	0.975	1628.0	0.057	0.675
6.001	0.879	79.545	0.179	0.145	0.813	0.0045	0.763	1567.9	0.191	0.598
6.447	0.844	60.842	0.908	0.087	0.920	0.0024	0.932	1606.1	0.106	0.658
7.757	0.739	84.152	0.000	0.233	0.652	0.0065	0.596	1514.1	0.311	0.524
8.328	0.694	59.904	0.944	0.158	0.790	0.0039	0.813	1553.0	0.224	0.609
9.391	0.609	83.582	0.022	0.296	0.537	0.0078	0.491	1452.3	0.449	0.489
9.589	0.594	58.790	0.988	0.205	0.702	0.0048	0.735	1503.7	0.334	0.586
10.438	0.526	58.472	1.000	0.237	0.644	0.0055	0.681	1514.5	0.310	0.540
11.270	0.460	82.575	0.061	0.367	0.406	0.0093	0.372	1385.5	0.599	0.448
12.927	0.328	81.427	0.106	0.430	0.291	0.0105	0.267	1333.7	0.714	0.408
15.505	0.123	80.010	0.161	0.529	0.110	0.0126	0.102	1246.4	0.910	0.349
17.049	0.000	79.835	0.168	0.589	0.000	0.0138	0.000	1206.0	1.000	0.303

Table 5.7 Comparison between the two post-processing methods of the best solution configurations for a high natural gas, medium coal, and low oil price.

Technology	Equal Weights	Survey-Defined Weights
	Production Percentage	
Coal	57.41%	69.77%
Natural Gas	0.00%	0.00%
Heat Pumps	4.43%	4.43%
Oil	38.16%	25.80%

Table 5.8 Comparison between the two post-processing methods of the best solution configurations for medium natural gas and low oil and coal prices.

Technology	Equal Weights	Survey-Defined Weights
	Production Percentage	
Coal	69.77%	82.93%
Natural Gas	0.00%	0.00%
Heat Pumps	4.43%	4.43%
Oil	25.80%	12.64%

5.4 Wrap-up

The post-processing methods used offer solutions for the best production configuration for a given set of fuel costs. It must be understood that these methods are subjective; and depending on the methods used to determine values functions and weights, solutions may be very different. Using equal weights and linear value functions, it is determined that natural gas technologies are the best option at today's fuel prices. In addition, future projections show that if all prices increase, natural gas technologies will still be the best option.

The second post-processing method with linear values functions and survey-defined weights results in the same solutions for all fuel cost scenarios expect for two. As can be seen in Table 4.4 the weights are not so different from the equal weights. Therefore, the difference in solutions between the two post-processing methods is hardly significant.

Finally, Table A.7 through Table A.16 in Appendix A show the objectives and value function values of the objectives, as well as the best solutions for both post-processing techniques. The best solution for the first post-processing technique is italicized and highlighted in red, while the best solution for the second post-processing technique is italicized and highlighted in blue. If the solutions are the same, then the single best solution for both post-processing techniques is highlighted in red.

Chapter 6 Conclusions, Future Work, and Recommendations

In conclusion, a multi-objective optimization problem with economic, environmental, and technological criteria or objectives was developed for the Helsinki district heating system. This optimization problem with nonlinear objective functions and nonlinear constraints was conducted over a 24-hour winter demand period for ten fuel cost scenarios. Two post-processing techniques were used to evaluate the Pareto optimal solution sets. The results indicate that for today's fuel prices the best solution includes a dominating usage of natural gas technologies, while if the price of natural gas is higher than other fuels, natural gas production technologies may not be included in the best solution. The configurations not dominated by the production of natural gas technologies are either dominated by the production of coal or oil technologies. The capacity of heat pumps is not large enough to dominate the production yet heat pumps offer a sensible solution due to their low costs and emissions. A pitfall of heat pumps is their inability to raise the temperature of the return water to an acceptable supply temperature. Instead, they are only suitable for pre-heating the return water. Therefore, a best solution should include the use of heat pumps and also fossil fuel technologies which are able to raise the return water to an acceptable supply temperature.

While Pareto solution sets have an advantage over single objective solutions in that they offer a large number of non-inferior solutions, the post-processing techniques employed on the solution sets still add subjectivity to the determination of the best solution. This thesis work offers the best solutions from two post-processing techniques, but other post-processing techniques could offer yet other best solutions. As previously mentioned, a linear value function may not best model the level of severity of an objective function from its minimum to its maximum value. Instead, a nonlinear or piecewise function may be more appropriate. The determination of this value function for each objective could even be on a plant by plant basis. For example, the location of a producer could affect the value function for specific emissions. When considering particulate matter a producer located in the center of a city is a larger health hazard than a producer located on the outskirts of the city. The former affects a larger population than the latter. Furthermore, the addition of weights adds more subjectivity. It is a daunting task for an engineer to determine which objectives are more important than others.

The next step in this work is to optimize the Finnish power network based on the criteria provided. The methods for optimization and the post-processing techniques have already been established here from the work done on the DH network. In addition the DH system and the power network could be combined into a single system optimization which meets the electricity and heat demands simultaneously. This would require incorporating electricity production into the CHP plants used in the DH system. In this way, the DH system and the power network would compete to control the production of the CHP plants. If the CHP plants are controlled by the DH company, then it would decide the heat production without monitoring of the electricity production. Any electricity produced would be consumed by the grid. On the other hand, if the CHP plants are controlled by the power network, then the utility company would decide the electricity production without monitoring of the heat production. Any heat produced would be used for the benefit of the DH system. Of course there could also be a tradeoff between these two extremes that would result in a compromise solution.

To improve how the optimizations perform in this thesis work, it would be useful to collect information on how the operators currently run their DH system. Because all of the district heat is supplied by plants that are owned and operated by Helsinki Energy, there is no competition between producers. Yet, plants must be closely monitored to make sure that demands are being met at the appropriate temperatures. For the DH model discussed in this thesis, the temperature is considered, but a particular temperature did not have to be met. In a real DH system, if the temperature demand is not met then the user's needs may not be met appropriately. Also, if the temperature of the transmission network is too high, then exergy will be wasted if the distribution network has to significantly reduce that temperature. Thus, if this information from the operators could be adapted into the DH optimization model then this method could be improved and used for other similar systems.

Finally, improvements can continue to be made to the DH system optimization model. For example, if fuel costs, emissions, and efficiency curves are provided for each individual technology, then the model would be more accurate. Instead of assuming the same performance for each boiler, every boiler would be slightly different or instead of assuming the same emissions for a particular fuel, each plant would have different emission values based on the pollution technology used. Obtaining this information is difficult, because it is not available to the public or even most researchers. With this information, optimal solution sets produced could be used by an operator. The ultimate goal would be to use this model in real time. With weights and value functions already determined and included in the program, the best solution could be found with the post-processing techniques incorporated directly into the optimization program.

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Appendix A

Table A.1 Objective function coefficients for costs, carbon dioxide and sulfur oxides

Producer	Coefficients for Objective Functions					
	Fuel & Pumping Costs		Carbon Dioxide		Sulfur Oxides	
LBOIL1	-6.63E-05	2.92E-02	-2.58E-04	1.14E-01	-2.31E-06	1.02E-03
LBOIL2	-6.63E-05	2.92E-02	-2.58E-04	1.14E-01	-2.31E-06	1.02E-03
LBOIL3	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
LBOIL4	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
PBOIL1	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
PBOIL2	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
PBOIL3	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
PBOIL4	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
PBOIL5	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
PBOIL6	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
RBOIL1	-1.25E-04	2.91E-02	-4.87E-04	1.14E-01	-4.35E-06	1.02E-03
RBOIL2	-1.25E-04	2.91E-02	-4.87E-04	1.14E-01	-4.35E-06	1.02E-03
RBOIL3	-1.25E-04	2.91E-02	-4.87E-04	1.14E-01	-4.35E-06	1.02E-03
RBOIL4	-1.25E-04	2.91E-02	-4.87E-04	1.14E-01	-4.35E-06	1.02E-03
ABOIL1	-2.23E-04	2.91E-02	-8.68E-04	1.13E-01	-7.76E-06	1.01E-03
ABOIL2	-2.23E-04	2.91E-02	-8.68E-04	1.13E-01	-7.76E-06	1.01E-03
ABOIL3	-2.23E-04	2.91E-02	-8.68E-04	1.13E-01	-7.76E-06	1.01E-03
ABOIL4	-2.23E-04	2.91E-02	-8.68E-04	1.13E-01	-7.76E-06	1.01E-03
HANAB	-8.35E-06	7.53E-03	-2.00E-04	1.80E-01	-1.88E-07	1.69E-04
HBOIL1	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
HBOIL2	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
HBOIL3	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
HBOIL4	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
HBOIL5	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
HBOIL6	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
HPUMP	0.00E+00	4.00E-03	0.00E+00	4.35E-02	0.00E+00	1.64E-05
MUBOIL1	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
MUBOIL2	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
MUBOIL3	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
MUBOIL4	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
MUBOIL5	-1.68E-04	2.91E-02	-6.55E-04	1.14E-01	-5.86E-06	1.02E-03
JBOIL1	-3.60E-04	2.91E-02	-1.40E-03	1.14E-01	-1.25E-05	1.02E-03
JBOIL2	-3.60E-04	2.91E-02	-1.40E-03	1.14E-01	-1.25E-05	1.02E-03
MBOIL1	-6.63E-05	2.92E-02	-2.58E-04	1.14E-01	-2.31E-06	1.02E-03
MBOIL2	-6.63E-05	2.92E-02	-2.58E-04	1.14E-01	-2.31E-06	1.02E-03
VUOA	-3.68E-05	1.20E-02	-3.12E-04	1.02E-01	-2.15E-10	7.04E-08
VUOB	-1.42E-05	1.20E-02	-1.19E-04	1.01E-01	-8.21E-11	6.97E-08
VUOT	0.00E+00	6.48E-03	0.00E+00	5.43E-02	0.00E+00	3.75E-08
VBOIL1	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
VBOIL2	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
VBOIL3	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
SALMA	-1.79E-05	6.95E-03	-4.27E-04	1.66E-01	-4.02E-07	1.56E-04
SALMB	-1.05E-05	7.26E-03	-2.50E-04	1.73E-01	-2.35E-07	1.63E-04
SBOIL1	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
SBOIL2	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03
SBOIL3	-1.97E-04	2.91E-02	-7.68E-04	1.14E-01	-6.87E-06	1.02E-03

Table A.2 Objective function coefficients for particulate matter and the exergetic efficiency.

Producer	**Coefficients for Objective Functions**			
	Particulate Matter		**Exergetic Efficiency**	
LBOIL1	-5.30E-08	2.34E-05	-4.10E-03	1.79E+00
LBOIL2	-5.30E-08	2.34E-05	-4.10E-03	1.79E+00
LBOIL3	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
LBOIL4	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
PBOIL1	-1.58E-07	2.34E-05	-1.19E-02	1.78E+00
PBOIL2	-1.58E-07	2.34E-05	-1.19E-02	1.78E+00
PBOIL3	-1.58E-07	2.34E-05	-1.19E-02	1.78E+00
PBOIL4	-1.58E-07	2.34E-05	-1.19E-02	1.78E+00
PBOIL5	-1.58E-07	2.34E-05	-1.19E-02	1.78E+00
PBOIL6	-1.58E-07	2.34E-05	-1.19E-02	1.78E+00
RBOIL1	-1.00E-07	2.34E-05	-9.40E-03	2.20E+00
RBOIL2	-1.00E-07	2.34E-05	-9.40E-03	2.20E+00
RBOIL3	-1.00E-07	2.34E-05	-9.40E-03	2.20E+00
RBOIL4	-1.00E-07	2.34E-05	-9.40E-03	2.20E+00
ABOIL1	-1.78E-07	2.32E-05	-1.70E-02	2.20E+00
ABOIL2	-1.78E-07	2.32E-05	-1.70E-02	2.20E+00
ABOIL3	-1.78E-07	2.32E-05	-1.70E-02	2.20E+00
ABOIL4	-1.78E-07	2.32E-05	-1.70E-02	2.20E+00
HANAB	-8.02E-09	7.22E-06	-3.90E-03	3.56E+00
HBOIL1	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
HBOIL2	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
HBOIL3	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
HBOIL4	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
HBOIL5	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
HBOIL6	-1.35E-07	2.34E-05	-9.70E-03	1.68E+00
HPUMP	0.00E+00	6.98E-07	0.00E+00	1.64E+00
MUBOIL1	-1.35E-07	2.34E-05	-1.12E-02	1.93E+00
MUBOIL2	-1.35E-07	2.34E-05	-1.12E-02	1.93E+00
MUBOIL3	-1.35E-07	2.34E-05	-1.12E-02	1.93E+00
MUBOIL4	-1.35E-07	2.34E-05	-1.12E-02	1.93E+00
MUBOIL5	-1.35E-07	2.34E-05	-1.12E-02	1.93E+00
JBOIL1	-2.88E-07	2.34E-05	-2.72E-02	2.20E+00
JBOIL2	-2.88E-07	2.34E-05	-2.72E-02	2.20E+00
MBOIL1	-5.30E-08	2.34E-05	-4.40E-03	1.94E+00
MBOIL2	-5.30E-08	2.34E-05	-4.40E-03	1.94E+00
VUOA	0.00E+00	0.00E+00	-1.01E-02	3.29E+00
VUOB	0.00E+00	0.00E+00	-3.80E-03	3.26E+00
VUOT	0.00E+00	0.00E+00	0.00E+00	1.82E+00
VBOIL1	-1.58E-07	2.34E-05	-1.42E-02	2.10E+00
VBOIL2	-1.58E-07	2.34E-05	-1.42E-02	2.10E+00
VBOIL3	-1.58E-07	2.34E-05	-1.42E-02	2.10E+00
SALMA	-1.71E-08	6.65E-06	-5.50E-03	2.12E+00
SALMB	-1.00E-08	6.93E-06	-4.90E-03	3.43E+00
SBOIL1	-1.58E-07	2.34E-05	-1.42E-02	2.10E+00
SBOIL2	-1.58E-07	2.34E-05	-1.42E-02	2.10E+00
SBOIL3	-1.58E-07	2.34E-05	-1.42E-02	2.10E+00

Table A.3 Heat transfer temperature used for each producer.

Producer	Heat Transfer Temperature, T_k (K)	Producer	Heat Transfer Temperature, T_k (K)
LBOIL1	456	HBOIL5	477
LBOIL2	456	HBOIL6	477
LBOIL3	477	HPUMP	335
LBOIL4	477	MUBOIL1	433
PBOIL1	457	MUBOIL2	433
PBOIL2	457	MUBOIL3	433
PBOIL3	457	MUBOIL4	433
PBOIL4	457	MUBOIL5	433
PBOIL5	457	JBOIL1	403
PBOIL6	457	JBOIL2	403
RBOIL1	403	MBOIL1	433
RBOIL2	403	MBOIL2	433
RBOIL3	403	VUOA	373
RBOIL4	403	VUOB	373
ABOIL1	403	VUOT	368
ABOIL2	403	VBOIL1	413
ABOIL3	403	VBOIL2	413
ABOIL4	403	VBOIL3	413
HANAB	373	SALMA	477
HBOIL1	477	SALMB	373
HBOIL2	477	SBOIL1	413
HBOIL3	477	SBOIL2	413
HBOIL4	477	SBOIL3	413

Table A.4 First table of distances between neighboring nodes.

From	To	Distance (km)	To	Distance (km)
Central Finland	Northern Ostrobothnia	250	Central Ostrobothnia	135
Finland Proper	Aland	150	Satakunta	110
Southern Ostrobothnia	Central Ostrobothnia	120	Central Finland	130
Southern Savonia	South Karelia	85	Kymenlaakso	120
Uusimaa	Finland Proper	125	Tavastia Proper	70
Central Ostrobothnia	Central Finland	135	Northern Ostrobothnia	160
Kymenlaakso	Uusimaa	110	Paijat-Hame	70
North Ostrobothnia	Lapland	310	Kainuu	135
Paijat-Hame	Uusimaa	105	Tavastia Proper	80
Pirkanmaa	Southern Ostrobothnia	125	Satakunta	90
South Karelia	North Karelia	210	Southern Savonia	85
Tavastia Proper	Pirkanmaa	90	Finland Proper	95
Lapland	Northern Ostrobothnia	310	Sweden	130
North Karelia	Northern Savonia	130	Southern Savonia	165
Northern Savonia	North Karelia	130	Kainuu	180
Satakunta	Finland Proper	110	Pirkanmaa	90
Kainuu	Northern Ostrobothnia	135	Northern Savonia	180
Ostrobothnia	Central Ostrobothnia	105	Southern Ostrobothnia	65
Aland	Finland Proper	150		

Table A.5 Second table of distances between neighboring nodes

From	To	Distance (km)	To	Distance (km)
Central Finland	Southern Ostrobothnia	130	Pirkanmaa	135
Finland Proper	Uusimaa	125	Tavastia Proper	95
Southern Ostrobothnia	Ostrobothnia	65	Satakunta	145
Southern Savonia	North Karelia	165	Central Finland	140
Uusimaa	Paijat-Hame	105	Kymenlaakso	110
Central Ostrobothnia	Ostrobothnia	105	Southern Ostrobothnia	120
Kymenlaakso	Southern Savonia	120	South Karelia	85
North Ostrobothnia	Central Finland	250	Central Ostrobothnia	160
Paijat-Hame	Central Finland	155	Kymenlaakso	70
Pirkanmaa	Tavastia Proper	90	Central Finland	135
South Karelia	Kymenlaakso	85	Russia	45
Tavastia Proper	Uusimaa	70	Paijat-Hame	80
Lapland	Russia	135	Norway	150
North Karelia	South Karelia	210		
Northern Savonia	Southern Savonia	150		
Satakunta	Southern Ostrobothnia	145		

Table A.6 Third table of distances between nodes.

From	To	Distance (km)	To	Distance (km)
Central Finland	Paijat-Hame	155	Southern Savonia	140
Finland Proper	Sweden	255		
Southern Ostrobothnia	Pirkanmaa	125		
Southern Savonia	Northern Savonia	150		
Uusimaa	Estonia	100		

Table A.7 Set of solutions for high coal fuel costs and low natural gas and oil fuel costs. Values for each objective are included, along with the highlighted solution.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
2.883	*1.000*	*58.720*	*1.000*	*0.237*	*0.640*	*0.0055*	*0.676*	*1467.7*	*0.385*
3.048	0.933	60.347	0.923	0.123	0.849	0.0031	0.864	1533.5	0.231
3.227	0.860	62.301	0.830	0.040	1.000	0.0015	1.000	1631.9	0.000
3.394	0.793	63.450	0.776	0.200	0.709	0.0049	0.724	1405.0	0.533
3.745	0.650	66.247	0.644	0.270	0.580	0.0065	0.592	1357.5	0.644
4.058	0.524	68.991	0.514	0.334	0.464	0.0080	0.474	1321.6	0.729
4.584	0.310	73.422	0.304	0.438	0.276	0.0103	0.282	1273.1	0.843
4.790	0.227	74.717	0.242	0.482	0.194	0.0114	0.198	1234.6	0.933
5.350	0.000	79.835	0.000	0.589	0.000	0.0138	0.000	1206.0	1.000

Table A.8 Set of solutions for high coal fuel costs, medium natural gas fuel costs and low oil fuel costs. Values for each objective are included, along with the highlighted solution.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
5.112	1.000	75.603	0.198	0.649	0.000	0.0149	0.000	1259.6	0.887
5.188	*0.920*	*76.210*	*0.170*	*0.577*	*0.119*	*0.0135*	*0.110*	*1224.1*	*0.962*
5.223	0.883	70.266	0.448	0.522	0.210	0.0120	0.219	1316.3	0.767
5.241	0.863	77.153	0.126	0.562	0.143	0.0132	0.131	1212.7	0.986
5.298	0.802	66.855	0.608	0.440	0.345	0.0101	0.360	1355.8	0.683
5.298	0.802	66.855	0.608	0.440	0.345	0.0101	0.360	1355.8	0.683
5.353	0.743	79.835	0.000	0.589	0.099	0.0138	0.084	1206.0	1.000
5.379	0.716	63.872	0.747	0.365	0.469	0.0084	0.488	1395.0	0.600
5.472	0.617	58.472	1.000	0.237	0.679	0.0055	0.707	1514.5	0.347
5.472	0.617	58.472	1.000	0.237	0.679	0.0055	0.707	1514.5	0.347
5.632	0.446	59.988	0.929	0.110	0.889	0.0029	0.902	1525.8	0.323
5.817	0.248	62.170	0.827	0.044	0.997	0.0016	1.000	1629.0	0.104
6.050	0.000	64.780	0.705	0.042	1.000	0.0016	1.000	1678.3	0.000

Table A.9 Set of solutions for high coal and natural gas fuel costs and low oil fuel costs. Values for each objective are included, along with the highlighted solution

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
5.180	1.000	77.385	0.209	0.687	0.000	0.0158	0.000	1296.0	0.809
5.229	0.983	78.618	0.157	0.681	0.009	0.0157	0.006	1235.1	0.938
5.326	0.949	79.629	0.115	0.625	0.096	0.0146	0.087	1218.6	0.973
5.357	*0.938*	*79.835*	*0.106*	*0.589*	*0.152*	*0.0138*	*0.138*	*1206.0*	*1.000*
5.516	0.883	78.256	0.173	0.453	0.362	0.0110	0.340	1378.5	0.635
5.581	0.860	73.350	0.378	0.595	0.142	0.0137	0.148	1332.2	0.733
5.846	0.767	82.381	0.000	0.301	0.598	0.0079	0.555	1517.5	0.340
6.025	0.705	68.862	0.565	0.493	0.301	0.0113	0.312	1379.9	0.632
6.246	0.627	79.694	0.112	0.233	0.704	0.0063	0.665	1552.8	0.266
6.548	0.522	64.389	0.753	0.389	0.462	0.0090	0.480	1435.8	0.513
6.866	0.410	62.005	0.852	0.331	0.553	0.0076	0.574	1459.6	0.463
6.875	0.407	77.740	0.194	0.150	0.833	0.0044	0.798	1625.7	0.111
7.420	0.217	58.472	1.000	0.237	0.697	0.0055	0.724	1514.5	0.347
7.424	0.215	67.136	0.638	0.082	0.939	0.0026	0.930	1631.0	0.100
8.040	0.000	64.780	0.736	0.042	1.000	0.0016	1.000	1678.3	0.000

Table A.10 Set of solutions for low oil and coal fuel costs and high natural gas fuel costs. Values for each objective are included, along with the highlighted solution.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
2.587	1.000	85.039	0.000	0.207	0.699	0.0060	0.638	1571.0	0.306
2.897	*0.934*	*83.416*	*0.061*	*0.263*	*0.597*	*0.0071*	*0.547*	*1480.9*	*0.477*
3.267	0.856	80.360	0.176	0.117	0.863	0.0039	0.810	1641.5	0.172
3.410	0.826	81.500	0.133	0.353	0.432	0.0089	0.398	1388.2	0.654
3.524	0.802	79.088	0.224	0.192	0.726	0.0054	0.685	1635.7	0.183
4.079	0.684	79.597	0.205	0.470	0.218	0.0113	0.204	1289.4	0.842
4.148	0.670	78.339	0.252	0.070	0.950	0.0027	0.906	1732.0	0.000
4.558	0.583	79.835	0.196	0.589	0.000	0.0138	0.000	1206.0	1.000
4.931	0.504	70.893	0.532	0.057	0.973	0.0022	0.949	1656.5	0.144
5.069	0.475	69.542	0.583	0.173	0.761	0.0046	0.750	1509.5	0.423
5.538	0.376	67.043	0.677	0.050	0.987	0.0019	0.975	1648.9	0.158
6.026	0.273	64.551	0.771	0.162	0.781	0.0042	0.788	1566.5	0.315
6.371	0.200	64.780	0.763	0.042	1.000	0.0016	1.000	1678.3	0.102
7.315	0.000	58.472	1.000	0.237	0.643	0.0055	0.680	1514.5	0.414

Table A.11 Set of solutions for a high natural gas fuel cost, a medium coal fuel cost and a low oil fuel cost. Values for each objective are included, along with the highlighted solutions.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
4.158	1.000	85.039	0.000	0.207	0.699	0.0060	0.638	1571.0	0.306
4.264	*0.967*	*83.416*	*0.061*	*0.263*	*0.597*	*0.0071*	*0.547*	*1480.9*	*0.477*
4.465	*0.904*	*81.500*	*0.133*	*0.353*	*0.432*	*0.0089*	*0.398*	*1388.2*	*0.654*
4.744	0.817	79.597	0.205	0.470	0.218	0.0113	0.204	1289.4	0.842
4.780	0.805	80.360	0.176	0.117	0.863	0.0039	0.810	1641.5	0.172
4.813	0.795	79.088	0.224	0.192	0.726	0.0054	0.685	1635.7	0.183
4.919	0.762	79.835	0.196	0.589	0.000	0.0138	0.000	1206.0	1.000
5.563	0.560	78.339	0.252	0.070	0.950	0.0027	0.906	1732.0	0.000
5.890	0.458	69.542	0.583	0.173	0.761	0.0046	0.750	1509.5	0.423
6.040	0.411	70.893	0.532	0.057	0.973	0.0022	0.949	1656.5	0.144
6.461	0.279	67.043	0.677	0.050	0.987	0.0019	0.975	1648.9	0.158
6.580	0.241	64.551	0.771	0.162	0.781	0.0042	0.788	1566.5	0.315
7.117	0.073	64.780	0.763	0.042	1.000	0.0016	1.000	1678.3	0.102
7.351	0.000	58.472	1.000	0.237	0.643	0.0055	0.680	1514.5	0.414

Table A.12 Set of solutions for medium natural gas and coal fuel costs and a low oil fuel cost. Values for each objective are included, along with the highlighted solution.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
4.068	1.000	85.039	0.000	0.207	0.699	0.0060	0.638	1571.0	0.306
4.174	*0.922*	*83.416*	*0.061*	*0.263*	*0.597*	*0.0071*	*0.547*	*1480.9*	*0.477*
4.212	0.894	80.360	0.176	0.117	0.863	0.0039	0.810	1641.5	0.172
4.308	0.823	79.088	0.224	0.192	0.726	0.0054	0.685	1635.7	0.183
4.374	0.775	81.500	0.133	0.353	0.432	0.0089	0.398	1388.2	0.654
4.549	0.646	78.339	0.252	0.070	0.950	0.0027	0.906	1732.0	0.000
4.653	0.570	79.597	0.205	0.470	0.218	0.0113	0.204	1289.4	0.842
4.669	0.559	70.893	0.532	0.057	0.973	0.0022	0.949	1656.5	0.144
4.718	0.522	69.542	0.583	0.173	0.761	0.0046	0.750	1509.5	0.423
4.827	0.442	67.043	0.677	0.050	0.987	0.0019	0.975	1648.9	0.158
4.916	0.376	79.835	0.196	0.589	0.000	0.0138	0.000	1206.0	1.000
5.001	0.314	64.551	0.771	0.162	0.781	0.0042	0.788	1566.5	0.315
5.144	0.209	64.780	0.763	0.042	1.000	0.0016	1.000	1678.3	0.102
5.428	0.000	58.472	1.000	0.237	0.643	0.0055	0.680	1514.5	0.414

Table A.13 Set of solutions for a medium natural gas fuel cost and low fuel costs for coal and oil. Values for each objective are included, along with the highlighted solutions.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
2.496	*1.000*	*85.039*	*0.000*	*0.207*	*0.699*	*0.0060*	*0.638*	*1571.0*	*0.306*
2.699	0.930	80.360	0.176	0.117	0.863	0.0039	0.810	1641.5	0.172
2.807	*0.893*	*83.416*	*0.061*	*0.263*	*0.597*	*0.0071*	*0.547*	*1480.9*	*0.477*
3.020	0.819	79.088	0.224	0.192	0.726	0.0054	0.685	1635.7	0.183
3.134	0.780	78.339	0.252	0.070	0.950	0.0027	0.906	1732.0	0.000
3.320	0.716	81.500	0.133	0.353	0.432	0.0089	0.398	1388.2	0.654
3.559	0.633	70.893	0.532	0.057	0.973	0.0022	0.949	1656.5	0.144
3.897	0.516	69.542	0.583	0.173	0.761	0.0046	0.750	1509.5	0.423
3.904	0.514	67.043	0.677	0.050	0.987	0.0019	0.975	1648.9	0.158
3.988	0.485	79.597	0.205	0.470	0.218	0.0113	0.204	1289.4	0.842
4.398	0.343	64.780	0.763	0.042	1.000	0.0016	1.000	1678.3	0.102
4.447	0.326	64.551	0.771	0.162	0.781	0.0042	0.788	1566.5	0.315
4.555	0.289	79.835	0.196	0.589	0.000	0.0138	0.000	1206.0	1.000
5.392	0.000	58.472	1.000	0.237	0.643	0.0055	0.680	1514.5	0.414

Table A.14 Set of solutions for high fuel costs. Values for each objective are included, along with the highlighted solution.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
7.125	1.000	74.762	0.366	0.068	0.953	0.0027	0.910	1625.7	0.062
7.373	0.983	72.487	0.454	0.063	0.963	0.0024	0.930	1617.2	0.081
7.584	0.969	70.569	0.529	0.058	0.972	0.0022	0.947	1618.9	0.077
7.661	0.963	69.574	0.568	0.062	0.964	0.0023	0.941	1624.2	0.065
8.068	0.936	66.829	0.675	0.048	0.990	0.0018	0.981	1620.4	0.074
8.206	*0.926*	*63.794*	*0.793*	*0.058*	*0.973*	*0.0020*	*0.970*	*1575.8*	*0.173*
8.291	0.920	64.513	0.765	0.043	1.000	0.0016	1.000	1653.3	0.000
8.686	0.893	61.201	0.894	0.060	0.968	0.0019	0.975	1628.0	0.057
8.887	0.880	79.544	0.179	0.145	0.813	0.0045	0.763	1567.9	0.191
9.506	0.837	60.842	0.908	0.087	0.920	0.0024	0.932	1606.1	0.106
10.918	0.741	84.152	0.000	0.233	0.652	0.0065	0.596	1514.1	0.311
11.708	0.687	59.904	0.944	0.158	0.790	0.0039	0.813	1553.0	0.224
12.831	0.610	83.582	0.022	0.296	0.537	0.0078	0.491	1452.3	0.449
13.176	0.587	58.790	0.988	0.205	0.702	0.0048	0.735	1503.7	0.334
14.172	0.519	58.472	1.000	0.237	0.644	0.0055	0.681	1514.5	0.310
15.028	0.460	82.575	0.061	0.367	0.406	0.0093	0.372	1385.5	0.599
16.960	0.328	81.427	0.106	0.430	0.291	0.0105	0.267	1333.7	0.714
19.965	0.123	80.010	0.161	0.529	0.110	0.0126	0.102	1246.4	0.910
21.769	0.000	79.835	0.168	0.589	0.000	0.0138	0.000	1206.0	1.000

Table A.15 Set of solutions for medium fuel costs. Values for each objective are included, along with the highlighted solution.

COST		CO2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
4.483	1.000	74.762	0.366	0.068	0.953	0.0027	0.910	1625.7	0.062
4.666	0.985	72.487	0.454	0.063	0.963	0.0024	0.930	1617.2	0.081
4.824	0.973	70.569	0.529	0.058	0.972	0.0022	0.947	1618.9	0.077
4.909	0.966	69.574	0.568	0.062	0.964	0.0023	0.941	1624.2	0.065
5.179	0.945	66.829	0.675	0.048	0.990	0.0018	0.981	1620.4	0.074
5.347	0.931	64.513	0.765	0.043	1.000	0.0016	1.000	1653.3	0.000
5.360	*0.930*	*63.794*	*0.793*	*0.058*	*0.973*	*0.0020*	*0.970*	*1575.8*	*0.173*
5.748	0.899	61.201	0.894	0.060	0.968	0.0019	0.975	1628.0	0.057
6.001	0.879	79.545	0.179	0.145	0.813	0.0045	0.763	1567.9	0.191
6.447	0.844	60.842	0.908	0.087	0.920	0.0024	0.932	1606.1	0.106
7.757	0.739	84.152	0.000	0.233	0.652	0.0065	0.596	1514.1	0.311
8.328	0.694	59.904	0.944	0.158	0.790	0.0039	0.813	1553.0	0.224
9.391	0.609	83.582	0.022	0.296	0.537	0.0078	0.491	1452.3	0.449
9.589	0.594	58.790	0.988	0.205	0.702	0.0048	0.735	1503.7	0.334
10.438	0.526	58.472	1.000	0.237	0.644	0.0055	0.681	1514.5	0.310
11.270	0.460	82.575	0.061	0.367	0.406	0.0093	0.372	1385.5	0.599
12.927	0.328	81.427	0.106	0.430	0.291	0.0105	0.267	1333.7	0.714
15.505	0.123	80.010	0.161	0.529	0.110	0.0126	0.102	1246.4	0.910
17.049	0.000	79.835	0.168	0.589	0.000	0.0138	0.000	1206.0	1.000

Table A.16 Set of solutions for low fuel costs. Values for each objective are included, along with the highlighted solution.

COST		CO_2 Emissions		SOx Emissions		PM10 Emissions		Exergetic Efficiency Parameter	
$/s	Value	kg/s	Value	kg/s	Value	kg/s	Value	MW	Value
1.671	1.000	74.762	0.366	0.068	0.952	0.0027	0.909	1625.7	0.111
1.729	0.980	69.430	0.573	0.054	0.979	0.0021	0.960	1675.2	0.007
1.739	*0.976*	*63.794*	*0.793*	*0.058*	*0.972*	*0.0020*	*0.968*	*1575.8*	*0.217*
1.753	0.972	64.780	0.754	0.042	1.000	0.0016	1.000	1678.3	0.000
1.948	0.904	60.842	0.908	0.087	0.919	0.0024	0.930	1606.1	0.153
2.067	0.862	79.544	0.179	0.145	0.812	0.0045	0.762	1567.9	0.234
2.359	0.761	59.904	0.944	0.158	0.789	0.0039	0.812	1553.0	0.265
2.516	0.707	84.152	0.000	0.233	0.652	0.0065	0.596	1514.1	0.348
2.817	0.602	58.472	1.000	0.237	0.643	0.0055	0.680	1514.5	0.347
2.876	0.582	83.582	0.022	0.296	0.537	0.0078	0.490	1452.3	0.479
3.286	0.439	82.575	0.061	0.367	0.406	0.0093	0.371	1385.5	0.620
3.644	0.315	81.427	0.106	0.430	0.291	0.0105	0.267	1333.7	0.730
4.207	0.120	80.010	0.161	0.529	0.110	0.0126	0.102	1246.4	0.914
4.551	0.000	79.835	0.168	0.589	0.000	0.0138	0.000	1206.0	1.000

Appendix B

NAME:____________________

In this survey, you are asked to compare the relative importance of criteria two at a time. First, the economic, technological and environmental criteria are compared. There are five criteria (within the economic, technological and environmental) considered in this model: 1 economic criterion, 1 technological criterion and 3 environmental criteria. Next, the emissions SO_x, CO_2 and particulate matter (PM_{10}) are compared. The ratios of importance you choose should reflect your willingness to trade off the criteria under examination. The following scale is suggested for ratio judgment (ratio of criterion X to criterion Y):

1/4	Criterion X is extremely less important than criterion Y
1/2	Criterion X is moderately less important than criterion Y
1/1.5	Criterion X is slightly less important than criterion Y
1	the two criteria are equally important
1.5	Criterion X is slightly more important than criterion Y
2	Criterion X is moderately more important than criterion Y
4	Criterion X is extremely more important than criterion Y

Any values between 1/4 and 4 may be used to convey your willingness to trade off criteria. Please fill out Table 1 below assuming that the rows are the X criterion and the columns are the Y criterion. Note the following information given regarding how the economic, technological and environmental aspects are incorporated into the model.

- Economic-The criterion considered in this model is the fuel cost minimization. The fuels in this model are coal, natural gas and fuel oil.
- Technological-The criterion considered in this model is the fuel exergy minimization. This criterion takes into account the amount of fuel consumed on an exergetic basis.
- Environmental-This criterion considers the minimization of three pollutants separately: CO_2, SO_x and PM_{10}.

Table 1. Comparison of economic, technological and environmental criteria

	Economic	**Technological**	**Environmental**
Economic	1		
Technological		1	
Environmental			1

Note that the diagonal row (top left, middle, bottom right) values should be 1 since the same criterion is being compared. Also, fill out Table 2. Again, the rows are the X criterion and the columns are the Y criterion.

Table 2. Comparison of emissions: CO_2, SO_x, PM_{10}

	CO_2	**SO_x**	**PM_{10}**
CO_2	1		
SO_x		1	
PM_{10}			1

Example for entry: For Table 1, if you believe that the technological aspect is extremely more important than the economic aspect, then you will put a 4 in row 2, column 1. Furthermore, if you believe that the economic aspect is moderately less important than the environmental aspect then you will put a 1/2 in row 1, column 3.

Also, note that the values that you fill into the tables above the 1s diagonal should be inverses of the values below the 1s diagonal. So, if row 2, column 1 has as value of 4, then it would only make sense for row 1 column 2 to have a value of 1/4.