“Potential for Combined Heat and Power and District Heating and Cooling from Waste-to-Energy Facilities in the U.S. – Learning from the Danish Experience”

Priscilla Ulloa

Advisor: Prof. Nickolas J. Themelis
Co-Advisor: Bettina Kamuk

Submitted in partial fulfillment of requirements for the degree of
Master of Science in Earth Resources Engineering

Department of Earth and Environmental Engineering
Fu Foundation of School of Engineering and Applied Science
Columbia University

Research sponsored by:
The Earth Engineering Center and the Henry Krumb School of Mines
May 2007

Executive Summary

In District Heating (DH), a large number of buildings are heated from a central source by conveying steam or hot water through a network of insulated pipes. Waste-to-Energy (WTE) signifies the controlled combustion of municipal solid wastes (MSW) to generate electrical and thermal energy in a power plant. Both technologies have been developed simultaneously and are used widely in Europe. In the United States, however, WTE is used for the generation of electricity. The advantages of district heating using WTE plants are: overall fuel conservation, by increasing the thermal efficiency of WTE, and overall reduction of carbon dioxide emissions to the atmosphere.

District heating in the United States is mainly based on the use of steam, such as the Con Edison Steam DH system in New York City and the Citizens Thermal Energy district heating and cooling system in Indianapolis. However, there are few U.S. hot water district heating systems presently, such as: Co-op City in Bronx, NY, and St. Paul, MN. The United States has an estimated 5,800 district heating and cooling systems, providing 320 million MWh of thermal energy.

Currently, 28 of the 88 U.S. WTE plants sell steam as an energy product. Twenty one of these WTEs co-generate approximately 470 MW of heat (1.6 million lbs of steam per hour) and 272 MW of electricity. Also, there are seven WTE plants that generate 273 MW of heat (929,000 lbs of steam per hour) exclusively.

Hot water district heating systems are used widespread in Europe and gaining in popularity in the U.S. because of: cogeneration of heat and power at the power plant is achieved with a higher thermal efficiency, hot water allows the transmission of heat over long distances, with relatively low heat loss, less than 10%, the central control system for the heat supply from the power plant is more economic, the interconnection of the space heating and hot water customers to the district network is simplified, less corrosion problems, and the hot water network may provide heat storage capacity.

Scandinavian countries have been very successful in promoting and increasing their hot water district heating networks. For example, Danish district heating supplies 60% of the heated floor, and 75% of the heat generation is generated in Combined Heat and Power (CHP) or cogeneration plants. In addition, European Parliament established the promotion of cogeneration based on useful heat demand in the internal energy market to increase energy efficiency to achieve a level of at least 80% of the annual overall efficiency in CHP plants. On the other hand, to increase the contribution of district heating in the U.S. and influence encouraging policies for cogeneration WTE industry and the International District Energy Association (IDEA) may establish an alliance. Presently, the U.S. Combined Heat and Power Association (USCHPA) and IDEA are promoting a CHP Investment Tax Credit bill in the lower house, which will provide a 10% investment for CHP plants up to 50 MW of electricity.

The objective of this study is (1) to examine the current situation of the district heating in the U.S. and (2) to present the technical and economic aspects of applying DH to existing WTE facilities located in Connecticut: the Wheelabrator Bridgeport, Covanta Preston,

and Covanta Hartford facilities. These facilities were chosen because of their location in the northeastern region, where energy prices and population density are relatively high and encourage such a project. The study presents the advantages and disadvantages of retrofitting these plants to co-generate heat and power and provide DH to their region. Hence, a preliminary evaluation was conducted of DH application at these three facilities.

Using a Canadian methodology, the minimal cost distribution heating network costs for Bridgeport were estimated at about $24 million for providing heat to a surrounding area of one square mile and the DH revenues at $6.8 million. The average diameter of Bridgeport piping network was estimated 49 cm (19.5 inches) and the total length of the network about 62 kms. However, the pipeline capital cost regarding the total length of the piping network, using the average pipeline cost per linear meter, results in a higher investment for Bridgeport (one square mile area). The capital cost may be at least $62 million, which is approximately three times higher than the cost of the piping network calculated by the Canadian methodology. Therefore, the Bridgeport DH system holds considerable promise and should be examined further by Wheelabrator Technologies.

The Preston DH network will be difficult to implement due to low density of housing units and heating demand. Although the mains would be of smaller diameter, 39 cm (15.4 inches), and less connecting piping would be required at Preston, the decrease in revenues, due to much lower heat requirement, indicates that the Bridgeport case was much more favorable. In addition, the Hartford WTE plant may be modified to provide both heat and power because Hartford city already have the infrastructure for district heating and cooling system. Indeed, one of the three DH system, the South End, is located relatively close to Hartford WTE, less than three kilometers. Consequently, Hartford WTE should consider increasing its overall efficiency and revenues by co-generating heat and electricity.

In conclusion, retrofitting a WTE plant to co-generate heat and electricity is always technically possible but it is necessary to consider some aspects such as: the ratio between the value of electricity and the value of heat, the ratio between the reduction of electrical output and the thermal output, and the capital and operational costs. U.S. WTE industry should consider retrofitting northeastern WTE facilities that are located in proximity to urban areas to augment the overall efficiency, economic and social benefit by providing heat to the community. Also, it may convince to U.S. citizens that combust MSW in a WTE plant has more environmental and social benefits than landfilling MSW.

Acknowledgements

First and foremost, I would like to thank Professor Nickolas J. Themelis for his invaluable support and guidance throughout my stay in the Department of Earth and Environmental Engineering. Furthermore, I feel privileged to have been able to work closely with him.

I would also like to thank my husband, Ricardo Montoya, for his advice and support through my graduate studies.

And, I am very grateful to my parents, Ernestina y Guido, for their encouragement to pursue my undergraduate and graduate studies.

I am gratefully acknowledging the support of the Waste-to-Energy Research and Technology Council (WTERT), the Earth Engineering Center and the Department of Earth and Environmental Engineering. Thanks are also due to Ms. Bettina Kamuk of Ramboll Denmark for arranging for visits of district heating systems in Denmark, and to Professor Stefano Consonni of Politecno di Milano, and Jennifer Haas, VP Sales & Marketing, Thermacor Process L.P., for providing valuable information.

Finally, I would like to recognize Paula Estevez, Georgia Columbus, Perinaz Bhada, Fabiola Brusciotti, Sandra Gualtero, Liliana Themelis, Shang-Hiu Lee, and Werner Sunk from Columbia University's Department of Earth and Environmental Engineering for their support in my graduate studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

District Heating (DH) is defined as the distribution of thermal energy from a central heat source to a large number of residential, by means of conveying steam or hot water through a network of insulated pipes. The central source may be an oil-fired, a Waste-to-Energy (WTE) plant, or the by-product steam of a utility. This approach, also called “cogeneration” or Combined Heat and Power (CHP), has a very high energy utilization efficiency that can reach 80%.

There are significant advantages to be gained from a cogeneration WTE plant. First, the energy efficiency can be increased by means of DH from 22% (electricity production only) to 80%. For example, Danish WTE facilities obtain an average of 0.6 MWh of electricity and 2 MWh of heat per metric tonne of MSW, thus tripling the amount of total energy obtained from MSW. Second, the high efficiency and low emission levels of WTE facilities make them environmentally friendly solutions, as compared to other technologies.

Currently, a conventional Waste-to-Energy plant in the U.S. losses over two thirds of the energy released from the controlled combustion of municipal solid wastes (MSW). This energy is rejected in the condenser in the form of low-temperature water that is not used effectively. Therefore, DH presents WTE facilities with the opportunity to increase thermal efficiency. However, there are some challenges that should be addressed. For example, it may be necessary to modify the steam turbine and provide equipment in the facility to recover heat in the form of hot water. Moreover, the thermal efficiency of electricity generation will be reduced somewhat when co-generating heat and power, though the total efficiency will increase. Also, it takes several years to build an extensive district heating system and requires long-term planning. Thirdly, district heating is capital-intensive and requires vision and commitment.

The purpose of this study is (1) to examine the current situation of the district heating in the U.S. and (2) to present the technical and economic aspects of applying DH to existing WTE plants in the United States. The study examines the retrofitting of three WTE facilities in Connecticut. These facilities were chosen because of their location in the northeastern region, where energy prices and population density are relatively high and encourage such a project. The study presents the advantages and disadvantages of retrofitting these plants to co-generate heat and power and provide DH to their region. Finally, the study provides a very preliminary cost analysis of implementing this technology.

2. District Heating and Cooling

2.1 Overview of District Heating

In a district heating (DH) system, energy is distributed to individual buildings or houses from a central plant by means of steam or hot or chilled water lines. Buildings or houses connected with the system extract energy from the transfer medium instead of generating energy on site. DH systems are adaptable to a wide variety of fuel types. This flexibility can benefit the consumers and a nation by providing thermal energy at stable and competitive prices while, at the same time, reducing dependence on scarce or imported fuels. DH is not a new technology. For instance, the first commercial applications in the United States date back as far as 1877. However, modern applications of the district heating concept have not been adopted readily, despite it being particularly well suited to the energy needs of many areas.

DH is best suited to those areas with high population density and in relatively cold climatic zones. In such areas, DH can maintain stable and competitive pricing. Since fossil fuels have become scarce and expensive, district heating deserve to be considered seriously, particularly in the high density eastern and central cities of United States [1].

2.2 The History of District Heating

Piped heating systems are a very old concept. Nearly two thousand years ago, piped systems were used by ancient Romans for heating dwellings as well as baths. In 1745, Sir William Cook demonstrated the potential of steam heat for buildings through a system of pipe coils in his home in Manchester, England. Three years later, Benjamin Franklin built an iron stove-type furnace in an underground chamber and used it to heat a series of row houses by running the flue in a brick and tiled fireproof enclosure beneath the floors. A water heating system was installed in a U.S. building in 1830 and, in 1844, the Eastern Hotel in Boston, Massachusetts, used steam for the first time as the medium for heating a large commercial building. With these advances, including the introduction in 1860 of the first cast iron radiator, a major industry sprang up manufacturing and installing steam and hot water heating system.

In 1877, Birdsill Holly, hydraulic engineer, pioneered the first commercial successful DH system. Using a boiler in his basement as the central heat source, he developed a loop steam distribution, radiation, condensation, and return for his own home. This was followed by increasingly distant extensions of the system to heat neighbors' homes up to 305 meters (1,000 ft) away. The distribution line was iron pipe, wrapped with asbestos, felt, and paper, and buried about 0.9 meters (3 ft) deep in a wooden box filled with sawdust. His initial efforts were so successful that he was able to raise the necessary capital to found the Holly Steam Combination Company in Lockport, New York. By 1879 Holly's company had nearly five kilometers (3 mi) of line in service, and by 1880 the steam service was extended to include several factories. By 1882, Holly had been issued 50 patents related to steam heat; he had developed a steam meter and his steam DH system was being used in cities across the U.S.

Within a decade, DH using steam transfer medium had expanded to ten cities in Pennsylvania and others such as Dubuque, Iowa, Denver, Colorado and New York City.

In 1879, while Thomas Edison was installing electric lines in New York City, the Steam Heating and Power Company of New York was founded. After that, a competing firm, the New York Steam Company was established. As many small electric utility companies evolved to meet the new and growing demand for electricity utilization, it became apparent that use of the exhaust steam from their power generation was obvious opportunity to add profits.

As efficiencies of scale began to be added to electrical generation, the DH industry endured. The advent of closed-cycle turbine generators lacking exhaust steam, and of larger, more efficient but less centrally located generating facilities limited the growth potential of the steam industry. Steam being a by-product of the generating process, which could be sold very inexpensively, had been a second profit center for power utilities. However, generation of steam separately from electricity greatly increased costs and therefore utilities were forced to raise rates. In 1909 about 150 DH systems existed in the United States. Many operated at low profit. The cost of converting from exhaust steam to live steam had been a shock to the industry. However, the management and profitability of DH systems improved dramatically through most of the first half of this century.

Since World War II, district heating in the United States has remained virtually static, as low-cost and "abundant" fossil fuels and electricity have surpassed many of the advantages of district heating. In contrast, European countries during the same period had significant success with hot water-based district heating such as Scandinavian countries, especially Denmark [1].

2.3 Benefits of District Heating and Cooling

There are several economic and environmental benefits to use district heating and cooling. The benefits include [1]:

a. Reduction of environmental pollution and improvement of air quality. DH replace small, uncontrolled source of air pollution with a fully controlled central source. Although air quality in the immediate vicinity of a central source may experience an increase in emissions, the net effect often will be a dramatic reduction in pollution concentration.

b. Conservation of scarce natural resources through using energy more efficiently, increasing conservation efforts, and maximizing the use of each Joule expended. Studies by the International District Energy Association (IDEA) suggest that new district heating and cooling systems, and implementation of CHP in existing district energy systems could reduce fuel consumption by 1.6 quads (1.6 x 10^{15} Btu), US energy usage was about 100 quads in 1996, and reduce carbon emissions by more than fifty million metric tonnes of carbon equivalent (MMTCE) by the year 2020 [2]. DH does this by utilizing waste heat which otherwise goes unused to displace consumption of oil and natural gas. Much greater fuel efficiency is achieved through cogeneration

c. Stabilization of energy costs and supplies. DH system central plants can use a variety of fuels, including local energy resources. These local energy resources such as solid waste, biomass, and wood are more stable in both supply and price than oil or natural gas, resulting 100% year round reliability.

d. Establishment of a base for future cooperative efforts in the field of energy planning and management. Cooperation among city governments, utilities, industry, building owners and citizens is crucial to almost any DH system installation. This cooperative structure can be used on a much broader scale.

e. Increase of space in buildings because no internal heating or cooling plant is needed in each building as well as reduce capital, operating and maintenance costs for building owners

2.4 Classification of District Heating and Cooling

District heating and cooling systems are typically classified by the thermal energy media used, as follows:

2.4.1. Steam Systems

a. Heat-only systems, where boiler capacity is committed to supply steam at the design pressure to the distribution network

b. Cogeneration or CHP systems, where steam used in the DH system is a by-product of the electric generation process

c. Supply or purchase systems, where steam above a base capacity generated by a WTE plant is supplemented from other boiler plants, depending on demand and availability

2.4.2. Hot Water Systems

a. Conventional hot water systems, where hot water is supplied from dedicated boilers or other heat sources at central locations in the system

b. Hybrid systems, where a steam system produces steam that is converted in a heat exchanger to hot water for a localized hot water network.

c. Cogeneration or CHP systems, where hot water is developed as a by-product of the electric generation process (e.g.: St. Paul and Co-Op City)

2.4.3. Chilled Water Systems

a. Chilled water is produced at a central plant by steam-driven equipment

b. Chilled water is produced at a central plant by electrically driven equipment

c. Chilled water is produced in the user’s building from the steam or hot water supplied by DH system [3].

2.5 District Cooling

As buildings become tighter and experience greater internal heat generation from computers, lights, and people, cooling capability is now often a 12-month requirement.

As a result, the heating market is declining relative to the cooling market in many urban areas, particularly in commercial office buildings.

This phenomenon has stimulated many district energy companies to expand into district cooling. Several district energy systems produce and circulate both hot and chilled water. On the chilling side, this value proposition eliminates on-site equipment ownership and operating costs and has many of the ease-of-use advantages of steam heating.

As shown in Figure 1, district cooling is still a modest factor in the overall energy market. However, it is growing rapidly. The installed cooling capacity in North American cities is 875,000 tons (11,000 GJ/h). Campuses, military bases and hospital complexes have 960,000 tons (12,100 GJ/h) installed now, and there are known plans to add 110,000 tons (1,400 GJ/h) in the next five years [4].

Figure 1. In-District Cooling captured a small share of the building cooling market, 1999

Many of the larger urban district cooling systems have been launched in just the last fifteen years. The number of chilled water systems in North America has been increasing. Some notable systems include Chicago, Toronto, Indianapolis, Denver, Baltimore, and Washington DC. Many of these systems were developed to augment existing steam systems, capture summer revenue and margins, and respond to market demands.

Many regulated and unregulated district energy companies have developed district cooling systems to supplement their base heating businesses. The business development and public policy attractions of district cooling include:

• A competitive cooling product that does not require an on-site chiller offered by steam systems to offset the cost disadvantage of steam turbine chillers.

• A low first cost, low maintenance option for cooling customers with the plug-and-play features of steam heat.

• Increased steam capacity utilization and, hence, lower average fixed costs for all customers.

• An alternative to high cost new electricity capacity to meet summer cooling loads

• A new revenue source to offset the declining need for heat in new buildings with high internal heat generation.

2.5.1 Chiller Technologies

There are several ways of using steam to remove heat from the air. The technologies vary in terms of heat-removal process, efficient capacity size or scale, capital cost per installed ton, and operating efficiency. The economics of these technologies also depend greatly on the spread between electricity prices and the primary fuel used to produce steam. The primary fuels used to operate chiller units are electricity, steam, and natural gas. There are mainly three chiller technologies as follows:

a. Centrifugal chillers

b. Steam turbine-driven chillers

c. Absorption chillers

To understand the differences among types of chillers, their most appropriate applications, and the underlying reasons for their relative efficiencies and costs. The leading chiller technologies are described briefly in the following section.

2.5.1.1 Centrifugal Chillers

All centrifugal chillers have a cooling circuit made up of a compressor, a condenser, an expansion chamber or valve, and an evaporator. Cooling is accomplished by compressing a cool, low-pressure refrigerant into a high temperature gas that is routed through a condenser coil to release its heat and condense into a liquid. The liquid refrigerant is then run through an expansion valve that produces a liquid that is circulated through an evaporator coil (heat exchanger), where it absorbs heat from the surrounding space and becomes a vapor that is then returned to be compressed and pumped through the circuit again. Figure 2 illustrates the basic circuit of a centrifugal chiller.

Centrifugal chillers require an energy source to power the compressors and pumps in the circuit. Centrifugal chillers are most frequently driven by natural gas, electricity, or steam. Natural gas engine-driven chillers use natural gas to fire an engine that runs the compressor. Electric centrifugal chillers use an electric motor to drive the compressor.

Figure 2. Centrifugal chiller circuit

2.5.1.2 Steam Turbine-driven Chillers

The steam turbine-driven chiller is very similar to the electric driven chiller, except that it uses a steam turbine to provide rotary power rather than an electric motor. High-pressure steam (9 bars) is used to spin a condensing turbine producing mechanical energy that drives a vapor compressor that is essentially the same as that used in an electric chiller.

The steam turbine chiller is much more efficient than a single-stage absorption steam chiller and slightly more efficient than a two-stage steam absorption chiller. Additionally, the steam turbine chiller takes up less space than a steam absorption unit.

However, the steam turbine chiller is only about half as efficient as an electric chiller. Also, the steam unit costs about twice as much as comparable electric units due primarily to the cost of the turbine component.

2.5.1.3 Absorption Chillers

The absorption chillers, on average, have much lower cooling capacities than centrifugal units, averaging 831 tons per installation. The two primary types of absorption chillers – single-stage and two-stage – are described briefly below.

a. Single Stage Absorption Chillers

Absorption chiller technology is very different from centrifugal chiller technology. In the absorption cycle, the external energy source provides heat rather than rotary power. The absorption cycle takes place in a near vacuum and depends on that vacuum rather than adding pressure to the refrigerant. The heat source is generally steam, hot water, or natural gas. Steam absorption chillers use low-pressure (1 bar) steam as a heat source to evaporate water for use in a single-stage thermal compression cycle. Water is used as the refrigerant, and lithium bromide is used as the absorbent. Figure 3 illustrates the basic circuit of absorption chillers. The cycle is only able to work because water and lithium bromide have a tremendous chemical affinity for one another.

Figure 3. Single stage absorption chiller circuit

The single-stage absorption chiller cycle begins with a dilute solution of lithium bromide from the absorber. The lithium bromide is pumped through a pre-heater and then on to the generator where heat from steam or hot water causes the solution to boil. This action sends water vapor upward and leaves a concentrated solution of absorbent, which is finally channeled to the pre-heater where it is cooled by the weak solution making its way to the generator. The refrigerant vapor moves to the condenser, where its heat is extracted by cooling water tubes, causing it to condense and collect in the bottom of the condenser. The refrigerant, now a liquid, is then sprayed over the evaporator tubes. At the near complete vacuum conditions in the unit, the water boils at 4°C, producing vapor and dropping the temperature of the chilled water, which is then used to cool the building. The water vapor produced in the evaporator then travels to the absorber where it is sprayed with a strong lithium bromide solution that absorbs the refrigerant so completely and rapidly out of the chamber that it creates a near vacuum.

Single-stage absorption chillers are the least efficient chiller technology available and require the most physical space to install. A single-stage absorber requires about 8 kgs. of 1 bar steam per ton-hour of cooling. Steam condensate has to be cooled before discharging to the sewer, in many cases. However, single-stage absorption chillers can be used in conjunction with low-grade steam from solar, and other renewable sources. This ability to make use of low-grade steam and technical improvements has led to an increased interest in single-stage absorbers. In addition, since water is the refrigerant, absorption chillers do not require the use of environmentally hazardous chemical refrigerants, and because they use low-pressure steam, no operator is required.

b. Two Stage Absorption Chillers

The two-stage absorption chiller cycle is similar to the single-stage but achieves higher heat efficiency in the condenser by dividing the generator into high temperature and low temperature generators. Two-stage absorption units also use higher pressure steam. The efficiency of a two-stage absorption chiller is about 40-50% greater than a single-stage unit and comparable to that of a centrifugal chiller. A two-stage absorption unit typically uses 4.5 kgs. per ton-hour of 7-10 bar steam (about 50% less usage than a single-stage absorber).

Both single and two-stage absorption units are vulnerable to crystallization of the absorbent. Newer technology has greatly diminished this problem. Also, advanced control systems have made operating the units and achieving their potential efficiency much easier.

Absorption chillers suffer from both higher first costs and operating costs. However, due to the fact that electricity prices are usually high in summer this encourages the absorption chiller solutions. Table 1 summarizes cost data for different chiller technologies [4].

Table 1. Cost and operating parameters for chillers

COP: refers to the Coefficient of Performance, a measure of the ratio of input energy to heat energy removed from the space. BOP: Balance-of-plant: consists of the remaining systems, components, and structures that comprise a complete energy system that are not included in the prime mover and waste heat recovery (ex. gas turbine, steam turbine, HRSG, waste heat boiler, etc.) systems.

Table 2 summarizes the main technical characteristics of chillers available on the market [5]

Table 2. Technical characteristics chillers

3. District Heating in the United States

District heating in the United States is mainly based on the use of steam, such as the Con Edison Steam district heating system in New York City and the Citizens Thermal Energy district heating and cooling system in Indianapolis. However, there are few U.S. district heating systems presently that use hot water for transporting energy, such as those at Co-op City in Bronx, NY, and St. Paul, MN. The United States has an estimated 5,800 district energy systems, providing 320 million MWh (1.1 quadrillion Btu) of energy [2].

Three types of district heating systems have been developed in the United States. First, steam heating systems were developed beginning in the late nineteenth century to serve a variety of users and buildings located in urban areas, typically in the central business district. Many of these systems were owned and operated by local electric utilities.

Changes in power plant technology, size, and siting caused many urban systems to decline, in the late 1920s, as they lost their sources of nearby relatively cheap fuel. Urban systems continued to decline after World War II as low-priced oil and natural gas began to be used for heating and as larger and more efficient power plants were located further from the center of cities.

The second type is a non-profit system (usually municipally incorporated or owned) which serves many and varied urban users. Many have replaced older urban systems operated by investor-owned utilities, as in St. Paul, MN. In other cities, groups of users have combined to form non-profit cooperatives that run systems formerly operated by investor-owned utilities, as happened in Pittsburgh, Pennsylvania and in Rochester, New York.

The third type of system serves institutional users. These include university campuses, military bases, industrial parks, multifamily residences, prisons, and office, medical, and commercial complexes. Institutional systems serve a single user, or few buildings, or a complex of buildings. In contrast to the urban systems, institutional systems have grown significantly in the last two decades [3]. Over two thousand state institutional facilities in the U.S. use district heating and cooling systems.

Although, current district heating and cooling systems in the U.S. supply less than five percent of the nation’s heating and cooling load, there has been renewed interest in rejuvenating district heating [2]. This is because of the increase in fuel oil and natural gas (Figure 4) [3, 6].

Figure 4. Breakdown of natural gas price paid by residential consumers.

Presently, the average home spends about $1,500 annually on energy bills in the United States. Heating and cooling accounts for as much as half of a home’s energy use [7]. Indeed, 42% of an average family’s energy bills is spent to keep homes at a comfortable temperature (Figure 5) [8].

Figure 5. Percentage of average family’s energy bill

Currently, natural gas is the primary heating fuel in the U.S.; used by 52% of households in 1997. In contrast, the percentage of households mainly using fuel oil or kerosene for space heat is only 10%, 30% are using electricity and the remainder wood or liquefied petroleum gas (LPG) [9]. For example, in New York, more than four out of five households have access to natural gas and most households use gas for space and water heating [10]. There is a growing motivation to expand existing district heating systems whenever circumstances make such augmentation possible. In fact, an analysis for Argonne National Laboratory showed that thermal capacity for district heating in the United States is approximately 300,000 MW– that is a fifteen-fold increase from present district heating output. However, a joint effort between government and the private sector is required to expand the use of district heating in the future. This could be possible if the following initiatives are implemented:

a. Improved communication, coordination, and education among government and industry officials and potential customers concerning district heating

b. Development of a practical arrangement so public and private capital can be joined for district heating development

c. The U.S. government should encourage a public policy in DH and CHP because of high prices and scarce fossil fuels to save energy and resources.

For example, the Directive of the European Parliament and of the Council, 11 February 2004, established the promotion of cogeneration based on useful heat demand in the internal energy market. The purpose of this Directive is to increase energy efficiency and improve security of supply by creating a framework for promotion and development of high efficiency cogeneration of heat and power based on useful heat demand and primary energy savings in the internal energy market, taking into account the specific national circumstances especially concerning climatic and economic conditions. In order to increase the efficiency of the cogeneration units, such as for steam condensing extraction turbine, Member States establishes a level of at least 80% of the annual overall efficiency [11].

Presently, in the United States, the U.S. Combined Heat and Power Association (USCHPA) is working with the International District Energy Association (IDEA) and others to push forward a CHP Investment Tax Credit. This will provide a 10% investment tax credit for CHP facilities up to 50 MW of electricity [12].

3.1 New York City Steam District Heating System

The New York City district heating system of Con Edison Steam is the largest steam district heating system in the western world and has been operated continuously since 1882.

Con Edison Steam is a vertically integrated steam producer and distributor that sells steam and steam delivery to customers in Manhattan. The company also co-generates electricity at two facilities and purchases steam from the Brooklyn Navy Yard Cogeneration Partners (BNYCP) facility. The steam system provides primarily space and water heating, and powers approximately 625,000 tons of steam absorption and turbine chillers.

In recent years, the steam load has grown relatively slowly. For example, the 2004-2005 winter peak was 2850 MW (9.7 million lb steam/h). The company estimated that the 2005-2006 winter peak was 3000 MW (10.4 million lb steam/h). Currently, the cost of producing one thousand pounds of steam is $20.5, i.e. 7 cents per kWh of heat, the fuel cost is half of this. Table 3 summarizes significant characteristics of Con Edison Steam system [13].

Table 3. Characteristics of Con Edison steam system

3.1.1 Historical Evolution of the New York City Steam System

The original New York system had only five kilometers (3 mi) of main conduit, operated at about 5 bar (80 pounds per square inch or psig), and served only 62 customers in the downtown area. The steam system preceded Edison's Pearl Street Station that opened on September 4, 1882. The electric and steam systems were not fully wedded to become "Consolidated" Edison until the 1930s.

The steam system continued to grow both organizationally and through acquisition. In 1936, Con Edison purchased the New York Steam Company and its 105 km (65 miles) of main, six generating units, and rights to serve 2,500 buildings. This strengthened Con Edison's position in the midtown area.

The system now comprises over 160 km (100 miles) of main and service lines and serves over 1,800 buildings. Steam today is transmitted at 27 bar (400 psig) and is distributed at 10 bar (150 psig).

3.1.2 Steam Production and Cogeneration

Today, four stations in Manhattan and one each in Brooklyn and in Queens generate steam. Two of the plants at these four stations also produce electricity (Figure 6). Besides, 49% of Con Edison's 2004 steam output was produced in steam plants, 36 % was produced in cogeneration plants, and the remaining 15% was purchased from the BNYCP cogeneration facility.

The schematic of the steam production fleet below provides a conceptual picture. All of the plants shown are located in Manhattan except Ravenswood, Queens, and BNYCP and

Hudson Avenue, Brooklyn. It is important to note that three of these plants have the ability to burn both natural gas and oil.

Figure 6. Steam system schematic

Con Edison Steam controls the electric dispatch of East River Station. It produces both steam and electricity but it is controlled by Con Edison Electric, which calls on its electricity output during summer electricity peak period. Therefore, not all of the steam capability of this unit is available for marketing in the summer.

The Con Edison Steam fleet produces two products- steam and electricity -, and electricity thus accounts for only a portion of total energy output and underdetermined percentage of revenue. Con Edison Steam's cogeneration production capacity increased by a net 125 MW when the East River Repowering Project (ERRP) went on line in April 2005.

3.1.3 Steam Delivery System

The steam system currently comprises about 140 km (87 miles) of mains and 30 km (18 miles) of service lines from 96th street to downtown Manhattan (Figure 7). Short-term steam marketing and sales must be focused on locations on or near existing mains. This is due to the high cost to extend lines in the congested New York City subsurface. Indeed, Manhattan distribution and transmission line extensions cost about $2,000 and $4,000 per linear foot, respectively. Most of this line cost reflects the higher construction costs associated with steam lines, which must be insulated, set into channels and encased in four-foot-by-four-foot concrete jackets, in order to withstand traffic disturbances. In addition, the line extension cost reflects the difficulty of adding new lines to the dense network of pipes and conduits under the streets of New York City (Figure 8) [4].

Figure 7. Con Edison steam system, Manhattan

Figure 8. Underground interference to install pipelines

3.2 Hot Water District Heating System

Hot water systems are gaining in popularity in the U.S. because of the following advantages of using hot water as a heating medium compared with steam [3,14,15]:

1. Cogeneration of heat and power at the power plant is achieved with a higher thermal efficiency. In a hot water system, low pressure steam from turbine bleeds is used for heating the water supplied to the customers. In the steam system, the steam has to be extracted from the higher-pressure bleeds of the turbine to allow for required pressure drop in the piping network.

2. Hot water allows the transmission of heat over long distances, with relatively low heat loss, between 5 – 10%

3. The central control system for the heat supply from the power plant is more economic. For example, the relationship between supplied hot water temperature and ambient conditions can be more easily maintained.

4. The interconnection of the space heating and hot water customers to the district network is simplified.

5. In many steam district heating systems, the condensate is not returned to the power plant for a number of reasons (corrosion problems, collection problems, etc.). To replace the lost condensate in a steam system, high quality make-up water is required for the boilers, thus imposing a high cost penalty on steam systems.

6. Lower surface temperatures on the water radiators in the residential buildings provide better sanitary and safety conditions. In steam heating systems, organic dust is partially decomposed on high-temperature steam radiators, and as a result harmful substances may be released in the living space. Therefore, in many countries steam district heating systems are not permitted for use in residential buildings.

7. The hot water network inherently provides for large heat storage capacity that is proportional to the temperature increment above the water temperature required by the customers. This increment can be decreased easily at the power station during periods of low-load demand. Usually, the temperature of water in the return line is increased by bypassing water from the supply line. Such a possibility does not exist in the steam networks.

Nevertheless, some basic considerations apply for water systems:

a. Temperature: hot water systems are designed for maximum supply temperatures between 110-130 ºC (230-266 ºF) and return temperatures of 50 – 70 ºC (122 -158 ºF). The reasons for using lower temperatures are the smaller system sizes and the use of polyurethane insulation (with a temperature limitation of about 120 ºC).

b. Pressure: piping network pressure depends on the system’s size and operating temperature, and varies from 9 – 17 bar (130 - 250 psig) during the winter and 4 - 10 bar (60 - 150 psig) during summer.

c. Water velocity: the pipe diameter and water velocity of the network is usually determined by design work that considers piping cost, pumping power, and heat loss to provide the minimum annual cost of the system. Based on these data, the water velocities may range from 0.5 to 4 m/s (1.6 - 13 ft/s).

d. District Heating Standards: countries with hot water district heating have developed special standards to which the piping networks are manufactured and tested. Special consideration is given to pre-insulated, pre-fabricated, pipe-in-pipe type conduits. Finland, Denmark, Sweden, West Germany and the United Kingdom have set up special working groups within District Heating Associations.

e. Heat Carrier Pipe Materials: Metallic pipes available for district heating systems normally are made of steel, copper or copper alloys. The steel pipe is the most utilized in district heating systems. U.S. district heating systems usually use a thicker-walled pipe than comparable European systems. The thickness of the pipe depends on the network design in order to prevent groundwater from penetrating the external pipe surfaces.

f. Piping Installations: district heating pipes usually are installed underground and a variety of different designs are used to protect the insulation and pipe form groundwater damage which could deteriorate the insulating material [1].

As mentioned above, there are a few hot-water district heating systems in the United States, such as the district heating and cooling system in Co-Op City, Bronx, New York, and another system in St. Paul, Minnesota. Both systems also produce electricity using a cogeneration or CHP plant.

3.2.1 District Heating & Cooling Co-Op City

Co-Op City, the largest single residential development in the United States sits in the Northeast Bronx area of New York on the 134 hectares (330 acres) site of the short-lived Freedomland amusement park. This massive development with its 15,372 units in 35 high rise buildings, seven clusters of townhouses, eight parking structures, three shopping centers, an educational park, and a firehouse, was completed in 1971.

Originally, Co-Op City was provided with a steam DH system. In the 1990s it became clear that the steaming manholes and melted snow caused by miles of failing distribution pipe could no longer be ignored. Thermacor Process provided the pre-insulated piping for almost 43 km (27 mi) of cold and hot water piping. Some of the main pipes are up to 762 mm (30 inch) in diameter. In addition, pressure testable joint closures were developed (Figure 9), and adopted to ensure proper sealing of the pipes properly [16].

Currently, a combined cycle cogeneration plant is being built in Co-Op City that will consist of two Once Through Steam Generators (OTSGs) units. These units will recover waste heat from the exhaust of two 13 MW gas turbines, and produce steam for a steam turbine that will generate electricity for the Co-Op City housing cooperative. Also, steam generated by the OTSGs will be used for heating in the winter, and cooling in the summer time via absorption chillers. Excess electricity will be distributed to the New York power grid. The installation of these units was scheduled to be completed in the fall of 2006 [17].

Figure 9. Pressure testable joint closures

3.2.2 District Energy St. Paul

District Energy St. Paul Inc. is a private, non-profit, community-based corporation in downtown St. Paul. This is the largest hot water district heating system in North America and also has a large chilled water cooling system (District Cooling St Paul Inc.)

The district heating system of St. Paul currently provides heating service to more than 170 buildings and 300 single-family homes in 2.7 million m^2 (29 million ft^2) of building space, representing 80% of St. Paul’s central business district and adjacent areas.

The district heating system of St. Paul has been in operation since 1983.The district heating distribution system consists of 30 km (18.5 mi) of twin supply and return piping. It utilizes prefabricated steel pipes with polyurethane insulation encased in polyethylene jacket, and the diameter of those pipes varies from 19 – 712 mm (3/4 - 28 inches). The supply temperature is 88 – 120 ºC (190-250 ºF) and the return temperature is 60 –70 ºC (140-160 ºF).

The district cooling system of downtown St. Paul has been in operation since 1993. This system serves over 80 customers and building facilities ranging in size from 1,115 to over 60,400 m^2 (12,000 -650,000 ft^2), for a total of 1.6 million m^2 (17 million ft^2). In addition, the district cooling distribution system consists of 10 km (6.2 mi) of twin supply and return chilled water pipelines (up to 762 mm in diameter), circulating 3.5 million liters (915,000 gallons) of water. There are six electric and two steam-absorption chillers at the District Energy plant, one electric chiller at the Tenth and Sibley cooling plant, several satellite chillers, and 25 million-liter (6.7 million-gallon) chilled water storage systems.

The construction of a CHP plant located adjacent to District Energy St. Paul’s downtown facility was completed in spring 2003. The CHP plant produces heat and electricity making it more than twice as efficient as energy plants that only generate electricity. This plant produces 25 MW of electricity for the local utility and 65 MW of thermal energy.

It is interesting to note that this CHP plant is fueled by combusting 280,000 tons of wood waste annually, a plentiful and renewable local resource. A substantial portion of the wood waste comes from downed trees, tree trimmings and branches from around the Twin Cities area. Using this material has several benefits. First, by turning regional wood waste into a useful product, the system helps keep energy dollars in the local economy, instead of importing fossil fuels. Second, using wood waste helps solve the ongoing environmental challenge of wood waste disposal. However, the plant must use some coal and natural gas when there is a severe winter.

The CHP plant significantly reduces air pollution by displacing 80% of the coal and oil that would be burned every year. As a result, it reduces sulfur dioxide emissions by an estimated 600 tons per year and carbon dioxide emissions by 280,000 tons per year approximately. At the same time, 150 smokestacks and 50 cooling towers on downtown buildings have been eliminated, as well as 300 chimneys on nearby homes. Furthermore, the rates over past ten years have been very stable (Figure 10) [18].

In 2001, this CHP plant was cited as a “model of energy efficiency, diversity and affordability” by President George W. Bush [19].

Figure 10. 10-year combined rate summary District Energy St. Paul

4. Waste-to-Energy and District Heating in the United States

The district heating and cooling system in Nashville, Tennessee, was the first in the world to use municipal solid waste as source of energy to provide both district heating and cooling. The WTE plant began operations in February 1974 and was capable of burning 1,000 tons of waste per day. The resulting energy was used to generate steam that heated 29 buildings in downtown, or to produce chilled water to cool 24 buildings. However, despite several expansions and updates to improve operations and to increase its capacity during its 30-year life span, in 2001 this plant required a large expenditure to meet the MACT regulations of EPA for pollution standards. Moreover, a fire destroyed the tipping hall of this WTE plant in May 2002 [20]. Therefore, the authorities decided to close the plant, and modify the district energy system from a solid waste-fired system to a natural gas system by 2004.

In Baltimore, a privately owned system district provides heat to about 500 customers, including commercial and government buildings, hospitals, and schools. In 1986, the Baltimore Southwest Resource Recovery Facility, a 2,250 tons of waste per day mass-burn WTE facility, began to sell steam to the district heating system, thus making it the largest WTE facility in the United States to co-generate steam and electricity at that time.

The use of heat recovered from municipal waste combustion for district heating is still small in the U.S. However, with the increase in tipping fees and widespread concern about the environmental impacts of landfills, it is expected that waste heat recovery from solid waste combustion, linked to existing or proposed district heating systems, may become more widespread.

4.1 Waste-to-Energy as a Thermal System

A WTE plant supplying energy to a district heating system is made up of three principal components. The first is the thermal production plant, which provides the hot water or steam. The boilers burn solid waste along with fossil fuels or can be dedicated boilers that burn only solid waste.

The second component of the thermal energy system is the transmission and distribution network. This network conveys heat, in the form of steam, hot water, or chilled water, through pipes from the WTE plant to the customers.

The third component of the thermal energy system is the customers' in-building equipment. Steam or hot water supplied by the thermal system is directed into the building and circulated through the customer's equipment. In the case of hot water systems and newer steam systems, heat exchangers are used frequently, and many building space heating and domestic water heating systems are of hot water design. When chilled water is also distributed by the system, water-to-water heat exchangers are usually employed within the building. Heat exchangers isolate the user from the thermal system and preserve integrity of both system and customers. Energy loss in this approach is very low.

The transmission and distribution system transports thermal energy through a network of insulated pipes. The pipe loop carries energy in the form of steam or hot or chilled water to the end users. A separate pipe returns water with most of the energy removed to the production plant for reprocessing. Insulated pipes can be buried directly in the ground, placed in tunnels or above ground. A typical steam piping system normally services customers within two to three miles of the generating source. Hot water, on the other hand, can be piped over distances of up to 32 km (20 mi) with limited heat loss.

The use of hot water systems by district heating and cooling utilities in the United States is limited because most of the utilities' customers are in old areas and often in older buildings designed for steam. However, hot water distribution is more frequently used in institutional buildings such as university campuses, prisons, airports, malls, and military bases.

Where steam is provided and is already an essential part of a commercial zone, it may be impractical to convert to hot water distribution. However, when new areas are developed, a hot water system can be more appropriate. One way to develop hot water district heating is through the hybrid concept, where steam is transmitted for the distance necessary to meet existing customer commitments and is then fed into heat exchanger and pumping system for a hot water loop.

Hot water can also be produced in a WTE plant by placing a heat exchanger in the turbine exhaust to heat the system's water supply. In this system, the boiler water flowing through the turbine in the form of steam is kept separate from the water distributed for the thermal market loads and the cost for water treatment and energy loss is markedly reduced from the level experienced by steam systems where the condensate is not returned.

For chilled water systems, water is chilled to 1.7 to 4.5 ºC (35 - 40 ºF) and distributed to customers who use heat exchangers for space conditioning. Chilled water distribution is limited because large pipe systems are required and effective distances are less than for hot water distribution. WTE plants produce steam year-round, and there is little demand for heating in warm weather. Use of steam to drive chillers for air conditioning may contribute to the energy revenue steam and make the project more economically viable.

4.2 Environmental Benefits

A significant advantage of a DH system fueled by MSW is the potential for reducing environmental pollution. The environmental benefits are derived through system efficiency resulting from the WTE plants producing a higher ratio of units of useful energy to emissions. For example, the carbon dioxide savings from co-generating 1 MWh of electricity are approximately 500 kg., as compared to a separate production of heat and electricity in a conventional power plant [21].

Another benefit of DH is the potential for reduction of thermal discharges to lakes, and rivers. The rejection of waste heat from cooling towers will decrease, significantly during the winter months.

WTE technologies have incorporated air pollution control systems (APC) that minimize environmental impacts so that electricity produced by these plants has a lower environmental impact than that from coal-fired power plants. Obtaining thermal energy from WTEs, in addition to electricity, has obvious economic and environmental benefits.

In addition, combustion of wastes in WTEs reduces the amount of waste to be landfilled, 80% in terms of mass. And, it eliminates the danger of contaminating groundwater by leachate from landfills as well as avoids the contamination of land for future developments.

4.3 Financing

Both WTE facilities and DH systems are highly capital intensive. On the average, district heating operates with 80 % fixed cost and 20 % variable costs. This is exactly the opposite of the cost ratio for its gas competitors, indicating the sensitivity of the systems to interest rates and financing methods. For district heating, over a half of the capital costs are represented by the transmission and distribution network. Costs can be minimized by keeping the length of piping to a minimum. Thus, most systems are designed to serve high-use customers with specified areas. Existing U.S. steam systems serve between 1,000 and 3,500 customers.

It should be noted that most of district heating projects for urban areas in the U.S. have used long-term municipal bond, usually with bond rates at 7% over the assumed 30-year life of the project [22].

An important aspect of facility success is the need for systems to get customers to sign long-term, 20-year, take or pay commitments as is required by public policy in Denmark. This is difficult because the commitments may be considered a lien against property. Although the legal validity of these commitments has not been tested, this requirement unnecessarily complicates already difficult institutional arrangements and further extends the long development time [3].

4.4 Examples of Waste-to-Energy and District Heating in the United States

Currently, 28 of the 88 U.S. WTE plants sell steam as an energy product, according to the 2004 IWSA Directory of WTE plants. Twenty one of these WTEs co-generate approximately 470 MW of heat (1.6 million lb steam/h) and 272 MW of electricity (Table 4). Also, there are seven WTE plants that generate 273 MW of heat (929,000 lb steam/h), without producing electricity (Table 5) [23].

Table 4. Cogeneration U.S.WTE plants

Table 5. U.S.WTE plants providing steam

The author attended the 2006 Annual Conference of the International District Energy Association (IDEA), a nonprofit trade association that is promoting district heating and cooling. In this conference, there were two presentations that described two U.S. WTE plants providing steam to a district heating system, as described briefly below.

4.4.1. Indianapolis WTE

The Indianapolis WTE plant began commercial operation in 1988, serving approximately 815,000 residents of the City of Indianapolis, Indiana. The plant facilities are on a plot of 21 acres. The plant processes 2,175 tons per day of solid waste that produce over 1.3 MWh of heat (4,500 lb steam) per ton. Approximately, ten million pounds of steam are purchased by Citizens Thermal Energy daily. In fact, the Indianapolis WTE plant provides almost half of the steam needed for the downtown area (43.57%) [24]. This area includes nearly all downtown businesses, Indiana University, the Indianapolis campus of Purdue University, and Eli Lilly - the area's largest pharmaceutical manufacturer (Figure 11). The Indianapolis district heating area is the second largest in the U.S. [25]

The Citizens Thermal Energy district heating system was founded in 1893. It has 39 km (24 miles) of distribution piping and 640 manholes. Its capacity is approximately two million pounds of steam per hour, serving 240 customers. In addition, the Citizens Thermal Energy district cooling system produces 66,050 tons of chilled water since 1990. The district cooling system has 24 km (15 mi) of distribution piping and 150 manholes, serving 47 customers (62 buildings).

Figure 11. Steam and chilled water lines of Citizen Thermal Energy

4.4.2. Huntsville WTE

The Huntsville WTE plant began commercial operation in 1990. It is the only WTE plant in the state of Alabama. It is located on 20.5 acres adjacent to Redstone Arsenal. The Solid Waste Disposal Authority of the City of Huntsville owns the facility that is operated by Covanta [26].

The WTE plant processes 690 tons per day of municipal solid waste, commercial waste and limited amounts of dried sewage sludge. The plant consists of two, 345 tons per day, mass-burn, Martin-Stoker units. The boilers were designed for a 10,445 kJ/kg (4500 Btu/lb) of MSW. Each boiler is equipped with an auxiliary burner system capable of running at 50% efficiency on fuel oil, natural gas and landfill gas. In addition, the plant also has four fossil fuel boilers rated at 100,000 lb steam/h (two of them can run at 36% of rated capacity on landfill gas) providing complete redundancy. As a result, steam is available 100% of the time.

This plant has no electric generating capabilities produces nearly 180,000 pounds of steam per hour that is shipped via eleven kilometers (7 mi) of pipeline to the U.S. Army's Redstone Arsenal. The steam is delivered approximately at 205 ºC (400 ºF) and 15.5 bar (225 psi) and is used for heating and air conditioning, thus eliminating the Arsenal's dependence on its own steam production equipment.

The Solid Waste Disposal Authority of the City of Huntsville (SWDA) receives 100% of the total sales from the WTE facility's energy production sold to Redstone Arsenal. Approximately 52% of the SWDA income is derived from the sale of steam. The other 48% comes from tipping fees ($40/ton) and metals recovery. Most of steam piping is above ground -67%- and is in good condition. However, most vault piping is in poor condition as shown in Figure 12 [26, 27].

Figure 12. Above ground steam piping (left); vault piping (right)

4.5 Pre-Insulated Piping in the United States

In the U.S., there are some companies that fabricate pre-insulated pipes. One of them is Thermacor, with over 40 years experience in the industrial, commercial, and military piping markets, utilizes the latest in polyurethane foam, polyisocyanurate foam, and other high temperature insulation technology to manufacture pre-insulated, pre-fabricated piping systems specifically for individual project requirements. It produces pipes for high temperature systems, above 120 ºC (250 ºF), and for low temperature systems, up to 120 ºC.

One of the popular low temperature pipe systems is Ferro-Therm. It is a factory-fabricated, pre-insulated piping system that incorporates pressure testable components for the highest level of insulation protection. The system is ideal for below ground or above ground of hot and chilled water, low pressure steam, or condensate fluids. The system is designed with steel carrier pipe (type and grade specified as required), polyurethane foam insulation, and a high density polyethylene (HDPE) jacket (Figure 13).

The HDPE has proven to be the most reliable and structurally strong material available as standard jacketing material. The definitive standard in the European piping market, HDPE is emerging as the benchmark for jacketing material in the U.S. Over 90% of all pre-insulated piping systems in the world for below ground applications use HDPE jacket for protecting the insulation from moisture.

In addition, Ferro-Therm piping system insures the watertight integrity of the pre-insulated piping system by using pressure testable joint closures. It is a wrap around HDPE sleeve that is melted to the adjacent jacket via electric fusion wires embedded in the sleeve. Once the joint closure is properly installed, it is stronger than the jacket itself, and can be tested at 0.35 bar (5 psi) for five minutes to ensure watertight integrity. The pressure test guarantees that the joint was installed correctly, and its strength gives you the peace of mind that on higher temperature systems you are not solely relying on mastic backed heat shrink sleeves to hold your system together.

4.5.1 Leak Detection System

Today, piping system can incorporate a leak detection device that can be monitored throughout the life of the piping system. The name of this device is Electric Resistance Monitoring (ERM) system. This system is simple and easy to install that any manufacturer should incorporate in their system. In fact, the European market has been using ERM in their products for the past two decades.

Figure 13. Pre-insulated pipe, Ferro-Therm with ERM

The ERM system is a bare copper wire embedded within the insulating foam as shown in Figure 13. At field joints, the installing contractor has to crimp a short jumper cable to tie the adjacent pieces together. The installed piping system will then have a continuous copper wire embedded within the foam. Since the foam is not a conductor of electricity, there will be very high resistance between the wire and the metal pipe (100,000 ohms). This electrical resistance within the copper wire can be monitored with a simple analog Ohmmeter, purchased at any hardware store, to determine if there is a leak at any time. Alternatively, it can be supplied a commercially available panel to allow continuous monitoring. If water should at any time enter the foam insulation, the electrical resistance will drop drastically. Once this drop in resistance is detected, the location of the leak can be found by using a Time Domain Reflectometer (TDR) instrument.

Thermacor has spent the past ten years developing this product in the American market. Through the use of electro-fusion technology, a seam less HDPE-jacketed system can be created. As a result, the system will be watertight and the monitoring system will detect any leaks if they ever occur [28].

In addition, there is another type of leak detection more sophisticated than the previously mentioned. Its name is Pal-At. It is a sophisticated microprocessor system with multi-sending and remote monitoring capabilities. Its advanced technology provides dependable around the clock surveillance of all monitored areas. Pal-At operates similar to radar by sending out safe energy pulses, 2,000 times per second, on the sensor cable. The reflections generated by these energy pulses are specific to the condition of the installed sensor cable. These reflections are stored in memory as a reference map. The alarm unit continuously measures the cable reflections and compares them with the values of reference map stored in memory. Liquids in sufficient quantities to “wet” the sensor cable will alter the cable’s impedance at the leak detection. This alteration of impedance will change the energy reflected from the cable at this location. The monitoring unit’s microprocessor recognizes the change in energy reflection from the wet portion of cable and enters into alarm. A new reference map with the change can be stored in memory, to allow monitoring to continue.

The Pal-At located the point of origin of a leak within $\pm$ 1% of the distance from the last calibration point. In the alarm mode, the unit activates output relays to facilitate the control valves or remote alarms, while providing audio and visual alarms, including a digital display of the distance to the leak origin (Figure 14) [29].

Figure 14. Leak detection and location system (Pal-At)

5. Successful Cases of District Heating in the World

5.1 Danish District Heating

In the spring of 1902 Frederiksberg Municipality decided to build Denmark's first waste incineration or WTE plant (Figure 15). In 1903 it began to supply heat to a nearby hospital. The heat was produced in combination with electricity; therefore this was the first CHP plant. Nowadays, in Denmark most of heat is produced by CHP plants. Indeed, 75% of the total heat production is generated at CHP plants in the last years. The remaining is generated with heat-only boilers.

Figure 15. The first WTE and CHP plant in Denmark

Until the 1960's, there was a limited number of buildings supplied from district heating networks in Denmark and CHP production was very low. The breakthrough for the heat supply of the housing areas came when a number of Danish companies began to develop pre-insulated district heating pipes. The iron pipes were covered with a heat insulating layer of polyurethane finished by a dense non-corrodible jacket (Figure 16). The problem with this solution was how to obtain a completely tight assembly of the pipes. However, using a special technique where the joints were assembled with muffs that had been welded or screwed on, it proved a success as well. In addition, electrodes were built into the insulation layer of pipes, which made it possible to discover any intrusion of water and identify a leak. Consequently, the pipes could be repaired relatively easy.

Initially, the plastic jacket allowed only low temperature, with flow temperatures not exceeding about 90 ºC (195 ºF). However, the quality of this material was gradually improved and it became possible to supply new district heating schemes with high quality pipes at temperatures up to 120 ºC (250 ºF). Consequently, the cost of a network with pre-insulated pipes was much lower than the previous systems with concrete ducts. Furthermore, the low operation temperature made it possible to utilize the surplus heat from industrial enterprises, and from WTE plants for solid waste. The combination of these two facts resulted in a boom in the establishment of DH networks and WTE plants.

Figure 16. Pre-insulated pipes under installation

The fuel crisis in the 1970s accelerated the implementation of district heating. The situation called for the implementation of alternatives to oil and the introduction of new energy saving measures absolutely essential. Denmark relied almost 100% on imported oil for the generation of heat, and heat budgets multiplied within few months.

Therefore, the Danish government was obliged to devise methods for saving fuels in order to safeguard the interests of society and to reduce the consumer's heat bills. A number of initiatives were introduced:

a. Systematic planning of the heat supply in all cities and towns

b. Highest possible percentage of heat generated as CHP

c. Additional insulation of all buildings

d. Development of highly efficient pre-insulated DH pipe systems with low installation costs

e. Reduction of operating temperatures in DH systems and a variable flow in the pipelines to secure the most economical operation

Through a firm energy policy and close cooperation between central and local authorities and heat supply companies, it was possible to reduce the energy demand for space heating per capita by almost 50% from 1973 to 2003.

Today, DH supplies almost 60% of the heated floor area and the share is increasing. Moreover, if all of the DH pipes were laid end to end, they would stretch for 50,000 km. The total number of dwellings connected to district heating is close to 1.5 million [30, 31, 32]. Figure 17 shows the design and operation parameters for a large Danish heat transmission and distribution system.

Figure 17. Danish district heating system

5.1.1 Danish Waste-to-Energy

Currently, there are 29 WTE facilities in Denmark as shown in Table 6, with a total capacity of 477 metric tonnes per hour. All Danish WTE plants co-generate heat and power, and they obtain in average of 0.6 MWh of electricity and 2 MWh of heat per metric tonne of MSW. In 2003, they processed approximately 3.3 million metric tonnes of waste. According to the energy statistics of the Danish Energy Agency, the WTE facilities generated a total of 1.5 million MWh of electricity and 6.5 million MWh of heat approximately. As a result, the WTE facilities supplied around 3 % of the total Danish electricity production in 2003. The heat generated from waste made up around 40% of the total heat production from renewable energy sources. Furthermore, Danish WTE facilities supply 18 % of all heat for district heating [33, 34].

Table 6. Waste-to-Energy facilities in Denmark

a. Nordforbrænding WTE plant

I/S Nordforbrænding is an inter-municipal waste management company located north of Copenhagen, the capital of Denmark, which serves approximately 180,000 inhabitants. Today, I/S Nordforbrænding WTE plant combusts solid waste from the six owner municipalities.

Currently, the Nordforbrænding WTE plant consists of four incinerator units with a total hourly capacity of 19 metric tonnes of waste. This plant has three producing units (three tonnes of waste per hour each unit) providing hot water, and one CHP unit (ten tonnes of waste per hour) providing electricity and hot water. The first three units were built in the late 1980s, whereas the last unit was added in 2000.

Table 7 shows that 110 thousand metric tonnes of waste were combusted, which produced approximately 275 GWh of heat and power in 2005, i.e. the energy recovery was approximately 2,500 kWh per tonne of combusted waste.

Table 7. Annual production Nordforbrænding WTE plant

Table 8 provides the electricity and heat production of each line in Nordforbrænding. It can be seen that the CHP line generates approximately 2,080 kWh of heat and 740 kWh of electricity per tonne of combusted waste, considering the capacity of the new line as 10 tonnes per hour.

Table 8. Electricity and heat per unit Nordforbrænding WTE plant

Nordforbrænding has taken over three different district heating distribution networks since 1998. Historically, these networks were owned and operated by the municipalities, and Nordforbrænding supplied the heat needed. Nordforbrænding took over the ownership and the operational responsibilities from the municipalities and has succeeded in trimming the administration of the networks, gaining the benefit of economies of scale.

Although the obvious choice would be to fully merge the three networks with respect to the administration, the *Danish Heat Supply Act* prevents this. The law requires that each of the three district heating distribution systems is administered in three separate systems on a non-profit basis. These three systems have been developed independently of each other. Consequently, they have different properties, such as investments per MWh sold, debts and technical standards.

Currently, approximately 100,000 metric tonnes of waste are incinerated, producing more than 200 GWh heat annually. This amount of heat represents half of the DH demanded by the six municipalities. Indeed, this WTE plant generates heat for 14,000 households which correspond to 33,000 residents. The length of the main pipe that distributes the hot water is 43 km, and the length of the transmission pipe is 30 km. The income of the Nordforbrænding WTE plant comes 60% from the heat sold to district heating, 35% from the tipping fee of waste and 5% from the electricity sold to the grid.

Figure 18 shows an outside view of a heat exchanger that is currently in operation in Nordforbrænding WTE plant. This heat exchanger is approximately two meters high (6.5 feet) and 1.8 meters wide (6 feet). The plant has four heat exchangers of this size providing hot water for 14,000 households [35].

Figure 18. Heat exchanger in Nordforbrænding WTE

b. Vestforbrænding WTE plant

I/S Vestforbrænding is an inter-municipal waste management company located west of the capital of Denmark, Copenhagen, and serving approximately 880,000 inhabitants and 46,000 businesses. It was founded in 1965. Today, I/S Vestforbrænding processes the waste generated by 29 municipalities.

I/S Vestforbrænding has the largest WTE plant in Denmark, and it co-generates heat and power by incinerating commercial and municipal solid waste. This plant mainly consists of four incinerator units, a waste reception area, a tipping floor, a flue gas cleaning area, and a stack. The total area of the plant is around 13 hectares including all incineration units, the parking lot, administration, tipping floor, etc.

Table 9 provides the capacity of each incinerator unit of I/S Vestforbrænding WTE plant, and the year in which each unit began its operation. It can be seen that the total hourly capacity is 84 metric tonnes. However, the four units are never simultaneously in use, which reduces the total capacity of the plant. Today, the two old units from 1970 are no longer part of the production. They can be used only in case of emergency.

Table 9. Capacity of each incinerator unit in Vestforbrænding

Note: Units 3 and 4 were removed in 2005. * Spare capacity.

Total annual capacity (including spare capacity) of the Vestforbrænding WTE plant is 650,000 metric tonnes of waste. However, the environmental approval stipulates combustion of a maximum of 500,000 tonnes, this results in a power output of 240 GWh and heat production of 1000 GWh annually, which corresponds to the annual power and heat consumption of approximately 60,000 houses. This represents 2,480 kWh per tonne of combusted waste. Taking into account the lower calorific value of waste the plant should generate 1,460 GWh - 2,920 kWh per tonne of waste input. As a result, and considering the lower calorific value, the efficiency of the Vestforbrænding WTE plant is 85%.

Finally, the power generated by the plant is sold to the EU power grid. The heat is sold to district heating consumers supplied from the district heating transmission and distribution networks owned by I/S Vestforbrænding. This system has been in operation without any breakdown since the plant was built. Surplus heat is transmitted to the integrated heat transmission system in the Copenhagen area.

In the future the I/S Vestforbrænding WTE plant will implement a heat pump system for condensation of the flue gas to enhance the efficiency of the plant. As a result, the electricity provided to the grid and the heat production will be of approximately 200 GWh and 1,300 GWh respectively. Thus, the total efficiency will be around 100% based on 1,460 GWh [36].

5.2 Korean District Heating

The Korea District Heating Corporation (KDHC) was founded in 1985. In 1987, KDHC began to provide heating service for Yeouido and Banpo districts of Seoul. In 1992, the KDHC was converted into a public corporation in accordance with the Community Energy Business Law. Since 1993, KDHC has supplied heat in the new satellite cities of the Seoul Metropolitan area. Moreover, KDHC is constructing medium and large CHP plants to increase the district heating service.

Figure 19 shows the district heating supply in South Korea. The red indicates the area supplied with heat. In contrast, the blue represents the area that other energy business groups occupy. Recently, many business groups have been participating in the competition of the district heating business.

Figure 19. District Heating supply in South Korea

KDHC's district heating system plays a key role in the South Korean energy industry, with a heat producing capacity of about 17,500 GWh (15,000 Tcal) and a heat supply pipeline over 3,000 km (1,800 mi) in 2005. The customers are about 1.4 million households (Figure 20).

CHP plants produce about 61% of the total heating production, peak-load boilers produce about 31% , and the remaining it is produced by combusting landfill gas and municipal solid waste.

District heating in South Korea use primarily heavy oil with 56% to generate heat, liquefied natural gas with 40%, and others such as landfill gas, municipal solid waste, and diesel fuel.

The users of the district heating are classified into residential, business and commercial, public users. Residential users constitute the majority of users with 89%.

The KDHC will build new CHP plants in new housing development areas such as Hwasung, Dongtan, Paju, and Seongnam Pankyo, which are the new cities of the Metropolitan Seoul. For example, Hwasung plant will produce 500 MW of electricity and 860 MWh (739 Gcal) of heat, providing heat to about 48,000 households in 2007.

In 2002, the energy-saving effect of KDHC’s district energy system reduced 53% of the fuel consumption in its service area – approximately 663,000 metric tonnes carbon dioxide – compared with conventional heating systems, resulting in 342 million dollars of avoided fuel costs. Additional environmental benefits of KDHC’s system included a 23% reduction of greenhouse gas emissions compared with conventional heating systems – approximately one million metric tonnes of sulfur oxide, nitrogen oxide and dust.

Figure 20. Development of District Heating in South Korea

The KDHC purpose is to enhance efficiency, to construct new facilities at a high standard with environmental friendly technologies, and also to be the first-rated energy provider with the best technology and, at the same time, to lead the energy industry in the 21st century. For example, KDHC is investing a total of 25 million dollars in harnessing waste incineration heat, landfill gases, food waste fermentation gases, geothermic energy, and others, to generate 1.5 GWh (1,318 Gcal) of heat annually. As a result, the KDHC will be the center of the eastern Asian energy network system [37].

6. Technical and Economic Aspects of a District Heating System in an Existing WTE Plant

In order to assess and plan a district heating system it involves a process with four distinct stages:

1. Preliminary evaluation
2. Detailed assessment
3. Design and implementation
4. Operation

At the completion of each stage, decisions are made related to the viability and desirability of a district heating project, and whether to proceed to the next stage. At each stage, more detailed information is required. This study will focus in the first stage "Preliminary Evaluation" due to insufficient amount of data. The preliminary evaluation consists in the evaluation of the community's energy needs and confirmation of technical and economic potential of the project (with $\pm$ 30% accuracy) [38].

To determine the feasibility of a DH system supplied from an existing WTE plant, the following major technical and cost components need to be considered:

1. Retrofitting a WTE plant
2. Piping distribution network
3. Customers' heating and domestic hot water system

This study will focus on retrofitting a WTE and piping distribution network because they are the most important technical and economic aspects of any DH system.

6.1 Retrofitting a WTE Plant

The best option for implementing a district heating system is at an existing WTE plant because it avoids the long delays associated of permitting a new WTE and increases the energy efficiency at the relatively low capital cost of about 60 $/kW of thermal energy [1, in 2005 dollars].

The economic criteria for establishing central station cogeneration by means of retrofitting existing WTE plants include:

1. Variation of climate and demand density by location
2. Thermal and electrical efficiencies of various electric generating units before and after retrofit for cogeneration
3. Density of residential, commercial, and institutional buildings in the area
4. Facility of building the required infrastructure for distribution and use of thermal energy to be provided by the WTE

As would be expected, studies have shown that a retrofit cogeneration plant is most economical in locations requiring high heating loads per unit surface area. The northeastern U.S. is more amenable to DH, from the point view of total load and load factor. However, it should be noted that it is needed to address some technical aspects about retrofitting a WTE plant. For example, in order to provide thermal energy, the WTE must sacrifice a certain percentage of the electricity production as shown in Figure 21 [39].

Figure 21. Efficiency of the cogeneration plant in comparison to an electricity-only power plant

Most of the existing WTE plants in the United States are of a single-purpose, condensing type, and are not designed for extraction of large amounts of steam as required for DH. For example, in a typical fossil-fueled power plant, the exhaust steam flow into the condenser constitutes about 60 – 65% of the throttle steam flow. For district heating purposes, a substantial part of this steam must be extracted from the turbine stages before it reaches the condenser [15].

The electricity lost because of cogeneration depends on the extracted steam flow rate, pressure and number of extractions. The ratio of the electricity lost to the heat supplied from the turbine depends on turbine design and may range 0.1 to 0.2 kWh of electricity per kWh of thermal energy obtained [40].

When considering the conversion of existing steam turbines to district heating operation, the possibility of extracting up to 15- 20% of the throttle steam flow from the crossover point of the turbine should be considered. An additional pressure control system may have to be installed at the crossover pipe to provide reliable operation of the turbine under district heating conditions.

It is important to note that the retrofitting of existing turbines to extract the required steam flow for DH is difficult and involves a significant redesign of the turbine and its control system. As a result, a substantial outage time may be necessary for modification. For example, three months outage time was required to install a piping and control system to extract steam from crossover of a 160-MW turbine.

In order to co-generate electricity and heat, the steam turbine must have bleeds that provide steam at an appropriate and controlled pressure. In some cases, this modification is not possible and as a result the installation of a new steam turbine is necessary. Turbines that are suitable to co-generate electricity and heat have been developed and are commercially available.

The European cogeneration turbines meet two principal requirements:

1. Providing suitable openings in the turbine cylinders for extraction of large amounts of low-pressure steam to the network heat exchangers.

2. Controlling concurrently and independently the electrical load and steam extraction for DH over a wide range of electrical and heat load demands.

The available heat that may be extracted from a turbine for DH purposes depends on the throttle steam parameters, extraction pressures and the number of extractions used for district heating. It has been recommended that for DH water supply temperatures between 93 and 121 ºC (200 -250 ºF), the following ratio of the heat extracted to electricity generated may be used for preliminary estimates [15]:

Medium backpressure turbines: 2.0 to 2.5 MWt/ MWe

Large turbines for fossil fuel : 1.4 to 1.6 MWt/ MWe

Retrofitting a WTE plant for cogeneration is always technically possible and the retrofit of WTE plants that provide hot water to a DH system to co-generation of heat plus electricity is widespread in Europe. In contrast, the retrofit of a WTE plant that provides electricity to grid to co-generate heat and electricity is not as common in Europe [41].

6.1.2 Estimate of capital cost of retrofitting WTE plant for DH service

The capital cost involved in retrofitting a WTE plant, so as to generate electricity and also hot water for the DH system, is impossible to estimate without specific information on the particular WTE, which was not available to the author. It will be relatively low if an existing turbine can be retrofitted and probably prohibitive if a new turbine is required, unless the retrofit is associated with the installation of additional WTE unit. However, on the basis of information provided in the literature, the retrofit cost will be a fraction of the DH distribution network.

6.2 Piping Distribution Network

The distribution network is comprised of pipes buried underground. Two sets of pipes: one to circulate the heated water to the consumers and the other to return the water back to the plant for reheating, are buried side by side in a trench. The network can take the form of a radial system or a looped system (Figure 22)

Figure 22. Forms of a distribution network

The radial system is cheaper than the looped system. However, the looped system offers greater reliability because water can be circulated from two directions. Thus, during shut downs for repairs, only customers between the two shutoff points will be affected.

The pipes are placed in trenches in the ground at a minimum depth of 600 mm. This is usually sufficient to withstand surface loads. It is not necessary to place the pipes below the frost line in cold climates because the constant circulation of water prohibits freezing and a high insulation value results in low heat loss. In cases where the ground does freeze to the depth of the pipes, insulation reduces heat loss to acceptable levels.

Depending on the scale of the system and temperature at which the water is circulated, the pipes can either be prefabricated steel or plastic. Prefabricated plastic pipes are used in situation in which the temperature of the water does not exceed 95 ºC. These pipes are cheaper and easier to install than steel pipes [42].

6.2.1. Cost Pipeline System

The main cost of a DH system is usually the installation of the pipeline network. The components making up the cost of a hot water pipeline vary widely. A typical cost distribution for installation in a open field is shown in Table 10:

Table 10. Components of cost piping system

It should be kept in mind that the size of the system has a considerable effect on the unit costs. By doubling the diameter of the pipe, other factors such as head remaining constant, the capacity increases six-fold. On the other hand, the cost approximately doubles so that the cost per unit delivered decreases 1/3 of the original [43].

However, the installation cost of the pipes is about five times the material price; it may be as high as ten times the cost of material based on site conditions according to a U.S. pipeline firm [28]. For example, the cost of a six inches steel pipe per foot, insulated with polyethylene foam, is about $83 (pipe itself) plus $412 for the installation. Thus, total cost is approximately $500 per foot installed, plus 15% of this cost for engineering, i.e. $575 per foot.

The cost of the distribution network was estimated using the guideline provided by Natural Resources Canada [38]. This determines the capital cost and the cost per megawatt hour of installed pipes for a hot water DH system in one square mile area in the vicinity of the Wheelabrator Bridgeport, Covanta Energy Preston, and Covanta Energy Hartford WTE facilities. This was done in six steps:

1. Selection of service area and determination of floor area served

2. Assessment of peak heating demand

3. Assessment of the minimal cost for installing pipe network

4. Adjustment of piping cost for ground conditions

5. Assessment of total energy demand

6. Assessment of revenues from DH systems

6.3 Bridgeport WTE

The Bridgeport WTE plant of Wheelabrator Technologies is located in the city of Bridgeport, Connecticut. This city has a population of 140 thousand people according to Census 2000, and a density population of 3,367 inhabitants per square kilometer (8,720 inhabitants per square mile) [44]. There are some similarities between Bridgeport and a very successful DH hot water system powered by a cogeneration WTE plant in Brescia, Italy (WTERT 2006 Industry Award). Brescia has nearly 200 thousand inhabitants and a population density of about 2,000 inhabitants per square kilometer. The Brescia WTE provides to the city of Brescia electricity (200 GWh/y) and heat (350 GWh/y) that amounts to a quarter of the city's energy needs [45].

The Bridgeport WTE plant processes up to 700,000 tons/yr of MSW from 14 Connecticut townships and provides electricity to an estimated 40,000 households. It generates 67 MW of electricity, of which 60 MW feed the grid and 7 MW are used internally. The current tipping fee is $72.50 per ton of MSW. This plant is only three kilometers (2 mi) away from the center of downtown area [46, 47]. Thus, a DH system may be feasible in Bridgeport. First of all, it is necessary to estimate the size of the heat load to determine the cost of the retrofitting. Also, it is important to consider the amount of electricity that may be sacrificed by conversion to cogeneration.

6.3.1. Bridgeport Distribution Network

1. Selection of service area and determination of floor area served

The service area refers to the area of the community to be served by the DH system. It may consist of the entire community or only a particular district. The selection of a service area affects the amount of energy required and the degree to which fossil fuel, usually fuel oil or natural gas, can be replaced with more environmentally friendly or lower cost sources of energy. It may not be cost effective to serve an area that is too large, while an area that is too small may not be cost effective.

Floor space density has been proven a good tool to select a suitable service area, although it is difficult to generalize about the best areas of a community in which to implement DH. In high floor space density areas, the heat load served per meter of pipe is usually high and the installation expensive. This is because of existing underground infrastructure and traffic disruptions. On the other hand, in lower floor density areas, the heat load per meter of pipe is usually smaller and the installation costs are lower. Generally, areas of high density are good candidates for the first phase of a DH system. Downtown areas and business districts are the areas with the highest density. As the service area extends farther from the center, density decreases. Residential areas of suburbs usually have the lowest density.

For these calculations, density is referred as the floor area per unit of total surface of the service area. This value varies from 0.3 to 3. The most accurate way to evaluate the density is to calculate the floor area from municipal records and the total surface from a map and then take their ratio. For a preliminary assessment, the average density of the chosen area can be based on the reference examples provided in the Natural Resources Canada Brochure [38].

The author selected a service area of 2.6 million square meters surround the Bridgeport WTE plant - one square mile - for this preliminary study (Figure 23). The estimated density of the area - assuming residential area, mix of two-story buildings and single-family homes in Bridgeport- was 0.5 square meter of floor area per square meter of total surface area. Therefore, the floor area was calculated to be:

Floor area = 2.6 million m^2 * 0.5 floor area/total surface of the area = **1.3 million m^2**

Figure 23. Overview of service area surrounds Bridgeport WTE

2. Assessment of peak heating demand

The average peak heating demand is the maximum power needed to keep the temperature of the buildings and houses of a service area at 18 ºC (65 ºF) and to heat the domestic hot water. This value depends on two factors: design outdoor temperature and domestic hot water consumption. Estimation of these two factors requires a detailed assessment for a particular DH project. For simplicity, the Bridgeport value was assumed to be that provided for the average peak heating demand of Toronto (Table 1 of the Natural Resources Canada Brochure [38]). Accordingly, the average peak heating demand was assumed to be 75 watts per square meter.

The peak demand is the maximum power required to supply sufficient energy to the service area. Multiplying the floor area estimated in the first step by the average peak heating demand, it results in the following power demand:

Peak demand= 1.3×10^6 m^2 * 75 W/m^2 = 97×10^6 W = **97 MW**

Kalhammer [48] determined that for district heating to be economical, a concentration of DH consumers is required with a minimum heat load density of 60 – 90 MW per square mile. On this basis, the above DH system for Bridgeport would be economically feasible.

3. Assessment of the minimal cost for installing pipe network

Hot water DH has the advantage of being able to use pre-insulated pipes. These pipes offer considerable savings to piping installation, as compared with the old method of wrapping pipes in mineral wool, in concrete casing or in tunnels. Typically, pre-insulated DH pipes are steel pipes with polyurethane foam insulation and a high density polyethylene casing. For system operating at temperatures less than 95ºC (203 ºF), the most economical option is the use of flexible plastic pipes for building connections.

The cost of DH pipes depends on their diameter. In turn, this depends on demand, temperature difference between supply and return pipe, and the relationship between velocity and pressure. For the service area of this study, the peak demand and the density of the floor area are 97 MW and 0.5 respectively. Using Graph C of the Natural Resource Canada Brochure [38], and extrapolating to the assumed Bridgeport DH, the minimal cost for installation of the piping system was estimated $11.7 million.

4. Adjustment of piping cost for ground conditions

The estimated minimal cost for pipe installation should be adjusted for ground conditions that can affect excavation and ground restoration costs. The ground conditions are divided in four categories:

Condition 1: loam, sandy, nearly free from roots, boulders, or other obstructions.

Condition 2: ordinary clay soils with few roots, rocks or other obstructions.

Condition 3: fairly hard or tough clays, or ordinary clay with some loose rock or shale.

Condition 4: mixture of clay and loose rocks, soft shale and hard and tough clays, difficult excavation requiring elaborate restoration (e.g. downtown areas).

These conditions will affect the cost of installation, with Condition 4 being the most difficult and Condition 1 the easiest. Other factors, such as the level of ground water table and bedrock, will also affect the excavation costs. In order to be very conservative, the worst scenario of Condition 4 was assumed. As a result, the adjusted distribution cost was estimated to be twice the minimal cost, i.e., nearly **$24 million**.

An economic analysis for investment of the distribution network was calculated assuming municipal ownership with 100% debt financing with bond rates at 7% and a 30-year life. The resulting annual cost for the piping network was estimated $1.9 million.

5. Assessment of total energy demand

The peak demand and equivalent load utilization period are necessary to determine the total energy demand. During a normal heating season, the energy generating facilities supply a certain amount of energy to the network. The "equivalent full load hours" is defined as the time required to generate this amount of energy, if the generating facilities were to operate continuously a peak load. The equivalent full load hours depends upon the heat demand profile of the service area or "load duration" curve.

An accurate calculation of the equivalent full load hours is quite involved. For simplicity, this study assumed the value associated with Toronto of 2,175 hours per year [38]. The resulting total energy demand, for the previously estimated peak demand of 97 MW, is:

Total energy demand= 97 MW * 2,175 h/y= 211,000 MWh/y = **211 GWh/y**

Therefore, the total distribution cost was estimated to be $110/MWh of thermal energy, regarding the distribution cost and the total energy demand.

6. Assessment of revenues from DH system

The revenues that the Bridgeport WTE may derive from the DH retrofit was estimated using the average annual bill for Southern Connecticut Gas residential customers who use natural gas for heating. This was approximately $ 2,000 according to the Department of Public Utility Control [49].Taking into account the average density of housing units [44], assuming that every housing unit will be connected to the DH system, indicates that the economic benefit may be as high as seven million dollars annually:

Number of housing units per square mile	= 3,398 housing units/ mi^2
Average heating bill annually	= $2,000 /housing unit/yr
Economic benefit	= 3,398 * $2,000
Economic benefit	= **$6,796,000 /yr**

6.3.2 Diameter of the Piping Network

To estimate the diameter is needed to have the flow rate and the water velocity in the pipe. The hot water flow rate was calculated taking into account the heat flow rate, "Q", as follows:

Q = 97 MW = 97 MW * 3,600,000 kJ/h/MW = **349,200,000 kJ/h**

To calculate the hot water flow rate, "F" (L/s), as follows [50]:

$F = Q / (15{,}050 * \Delta T)$

Where:

Q = Heat flow rate , kJ/h

Δ T = supply temperature –return temperature, ºC

Hot water Danish DH system used 120 º C as supply temperature and 70 º C as return temperature. Therefore, the hot water flow rate is:

F = 349,200,000/ (15,050 * (120 – 70))

F = 464 L/s

F= 0.464 m^3/s

The hot water flow rate, F, is associated with the water velocity, *v*, and the cross sectional area of the pipe, A, as follows [51]:

F = *v* * A

A = F/*v*

The typical water velocity range for a hot water DH system is between 0.5 to 4 m/s (1.6 - 13 ft/s) [1]. However, an upper limit of 2.4 m/s (8 ft/s) is usually considered safe in a hot water DH system to avoid noise generation [22, 50]. Therefore, the diameter of the piping network, d_p, was estimated as follows:

A = 0.464 / 2.4 = 0.19 m^2

$d_p = (4*A/ \prod)^{0.5} = (4* 0.19/ 3.1416)^{0.5}$

d_p = 0.49 m = **19.5 inches**

6.3.3. Length of the Piping Network

To estimate the total length of the piping network is necessary to make some assumptions:

- The service area is divided in a same number of blocks per side
- Each block has the same area
- The dimension of one block is 100 m x 100 m
- The streets in the service area are perpendicular

With these assumptions, it was estimated the number of streets inside of the service area, and therefore the length of the piping network, as follows:

Number of blocks per side of the service area:

b = 1600 m/ 100 m = 16

Number of blocks per side inside of the service area:

b’= 16 -2 = 14

Number of streets inside of the service area:

s = 14 * 2 = 28

Length of the pipes under the streets inside of the service area:

L’’ = 28 * 1600 m= 44,800 m

Equivalent length (elbows, valves, etc) = 44,800*0.2 = 8,960 m

Length of the perimeter of the service area (including elbows, valves, etc) = 7,759 m

Therefore, the total length of the piping network, L_t, was estimated about 62 km (Figure 24), as follows:

L_t = 44,800 + 8,960 + 7,759

L_t = 61,519 m = 184,557 ft

Figure 24. Illustration of the area to calculate the length of the pipeline

6.3.4 Cost of the Piping Network using the Length of the Pipeline

Table 11 shows a comparison among different distribution pipeline extensions cost taking into account the total length of the pipeline for the service area of Bridgeport WTE plant (one square mile). The distribution cost using the total length pipeline is much higher at least three times than the previous distribution cost calculated using the Natural Resources Canada brochure (see 6.3.1). This may be due to an overestimation of the total length pipeline, and also the cost per meter of pipe varies with the diameter of the pipe. Generally, a hot water DH system has pipes with diameters from 19 to 762 mm (¾ to 30 inches) in the piping network.

Table 11. Distribution cost using the total length pipeline

Note:

[1] European hot water distribution pipeline extensions cost about $1,000 per linear meter (Source: Bettina Kamuk, Project Director, Rambøll)

[2] American steam distribution pipeline extensions cost at least $700 per linear foot (Source: Dominick Chirico, P.E. Facilities Management, Columbia University)

[3] Manhattan steam distribution pipeline extensions cost about $2,000 per linear foot [4]

6.4 Preston WTE

The Southeastern Connecticut Resource Recovery Facility, operated by Covanta, is located in Preston, CT. The town has a population of 4,688 people according to Census 2000, and a density population of 59 inhabitants per square kilometer (151 inhabitants per square mile) [52]. The Preston WTE plant has two lines, processes up to 147,000 tons/yr of MSW from numerous communities in Southeastern Connecticut, and generates 17 MW of electricity [23, 25]. Presently, Covanta is planning to add a third line. Therefore, the Preston WTE plant may be modified to provide both heat and electricity if it is shown to be economically and technically feasible. Figure 25 shows the location and overview of the surrounding area of the Preston WTE facility.

Figure 25. Overview of service area surrounds Preston WTE

6.4.1 Preston Distribution Network

1. Selection of service area and determination of floor area served

Again, a service area of 2.6 million square meters (1 square mile) in the vicinity of the Preston WTE plant was selected for this preliminary study. The estimated density of the area assuming residential area, single-family homes in Preston, is 0.3 square meter of floor area per square meter of total surface area. Therefore, the floor area is:

Floor area = 2.6 million m^2 * 0.3 floor area/total surface of the area = **0.8 million m^2**

2. Assessment of peak heating demand

The peak demand is the maximum power required to supply sufficient energy to the service area. Considering the floor area found in the first step and the average peak heating demand results the peak demand:

Peak demand= 0.8×10^6 m^2 * 75 W/m^2 = 58×10^6 W = **58 MW**

This value is at the low end limit of 60 MW per square mile, which is preferable for a district heating project [48].

3. Assessment of total energy demand

For this case, the peak demand is 58 MW (from step 2), and the estimated equivalent full load utilization period is about 2,175 hours per year. Hence, the resulting total energy demand is:

Total energy demand= 58 MW * 2,175 h/y= 127,000 MWh/y = **127 GWh/y**

The capital cost of the Preston piping network was not estimated because the heat and the total energy demand are low. This is due to the fact that Preston is a small town and residential area almost exclusively in comparison to Bridgeport city.

4. Assessment of revenues from DH system
The additional annual revenues to the Preston WTE from the sale of heat are calculated, similarly to the Bridgeport WTE, to be $3.8 million annually. This is considerably lower

(45%) than the $6.8 million estimated for the same area of one square mile in Bridgeport, CT.

6.4.2 Diameter of the Piping Network

Again, the hot water flow rate was calculated taking into account the heat flow rate, “Q”, as follows:

Q = 58 MW = 58 MW * 3,600,000 kJ/h/MW = **208,800,000 kJ/h**

To calculate the hot water flow rate, “F” (L/s), as follows [50]:

$F = Q / (15{,}050 * \Delta T)$

$F = 208{,}800{,}000 / (15{,}050 * (120 - 70))$

F = 278 L/s

F= 0.278 m³/s

The hot water flow rate, F, is associated with the water velocity, *v*, and the cross sectional area of the pipe, A, as follows [51]:

$A = F/v$

The diameter of the piping network, d_p, was estimated, considering 2.4 m/s as hot water velocity, as follows:

$A = 0.278 / 2.4 = 0.12\ m^2$

$d_p = (4*A/ \prod)^{0.5} = 0.39\ m =$ **15.4 inches**

The length of the pipeline for Preston’s service area will be the same as Bridgeport’s service area taking the same assumptions. Because of that it was not estimated again the total length of the piping network.

6.5 Hartford WTE

Hartford is the capital of the State of Connecticut. The city has a population of 121,578 people according to Census 2000, and a density population of 2,712 inhabitants per square kilometer (7,025 inhabitants per square mile). It is the third largest city in the state, after Bridgeport and New Haven. Greater Hartford is also the largest metro area in Connecticut and 44th in the country (2004 census estimate) with a population of 1,184,241 [53].

The Mid-Connecticut Resource Recovery Facility, owned by Covanta, is located in Hartford, CT. The Hartford WTE plant has three lines, processes approximately 2,000 tons of refuse derived fuel (RDF) per day or 624,000 tons per year, and generates 68.5 MW of electricity [23, 25]. The facility is also designed to burn coal when solid waste is unavailable. Figure 26 shows the location and overview of the surrounding area of the Hartford WTE facility.

Figure 26. Overview of service area surrounds Hartford WTE

6.5.1. Hartford District Heating

In 1950's, the Hartford Gas company had just connected to interstate pipelines, which made gas readily available year-round. Connecting to those pipelines brought tremendous gas capacity that stood unused in the summer. As a result, the president of Hartford Gas, William Jebb, considered developing a gas-based district energy system, where gas could be used to produce chilled water to cool downtown buildings in the summer and steam to heat downtown buildings in the winter. With customers like Constitution Plaza and Travelers Insurance willing to use such a system, the concept went ahead.

In 1960's, the district heating and cooling system was used as a key infrastructure component to help attract new buildings to downtown. Travelers Insurance Company offered its steam plant as an interim facility to serve adjacent development, while the Hartford Steam Company's plant was being built down the road. Nowadays, the development in Hartford has focused on residential buildings, with a boom in apartment and condominium construction.

In 1962, the Hartford Steam Company was the first in the world to commercially own and operate a combined district heating and cooling system. The Hartford Steam Company's plant is located at 60 Columbus Boulevard, which is the heart of system operation.

Presently, the Hartford Steam Company has three district heating and cooling systems serving three different areas in Hartford: Downtown, the Capitol area and the South End. The three systems have the option to use multiple fuels, including electricity, fuel oil or natural gas, whichever is the most cost-effective [54]. These three systems are briefly described below:

1. Capitol area system

It began operation in 1987 and now serves 16 buildings. The largest building on the system is the 25 Sigourney Street State office building, which receives both heating and cooling service. Area generally bounded on the north by Farmington Avenue, the south by Russ Street, the west by Laurel Street, and the east by West Street. Also, the Capitol area district heating and cooling system is interconnected to the downtown system for enhanced service reliability (Figure 27).

Figure 27. Capitol area DH system customers

2. Downtown system

It began operation in 1962 and now serves 47 buildings. Largest building on the system is City Place I building, which receives both heating and cooling service. Area generally bounded on the north by I-84, the south by Charter Oak Avenue, the west by Bushnell Park and the east by I-91 (Figure 28).

Figure 28. Downtown DH system customers

3. South End system

It began operation in 1999 and now serves eight buildings. Largest building on the system is the Hartford Hospital building, which receives heating and cooling and electric power service. Area generally bounded on the northwest by Jefferson Street, the southwest by Broad Street, and the east by Maple Avenue (Figure 29). The South End system is connected to a cogeneration plant, which further increases energy efficiency.

Figure 29. South End DH system customers

It was assumed that the same density floor area and capital cost for DH Bridgeport because Bridgeport and Hartford have similarly conditions, such as the population and housing unit density. The diameter and length of the pipeline for Hartford's service area will be the same as Bridgeport's service area. Because of that it was not estimated again the diameter, length, and the cost of the piping network. However, the additional annual revenues to the Hartford WTE from the sale of heat are calculated, similarly to the Bridgeport WTE, considering 1,130 housing units per square kilometer (2,927 per square mile), to be $5.9 million annually. This is slightly lower (13%) than the $6.8 million estimated for the same area of one square mile in Bridgeport, CT.

On the other hand, the Hartford WTE plant may be modified to provide both heat and electricity because Hartford city already have the infrastructure for district heating and cooling system. In addition, the South End system is located less than three kilometers away from the Hartford WTE to Hartford Hospital. Therefore, Hartford WTE should take advantage of that and increase its overall efficiency and revenues by co-generating heat and electricity.

It should be noted that all estimations done are preliminary values. In fact, calculating flow rates and pressures in a piping network with branches, pumps, and heat exchangers is difficult without the aid of a computer. Nowadays, computer-aided design methods usually incorporate methods for hydraulic analysis as well as for calculating heat losses and delivered water temperature at each consumer. Calculations are usually carried out in an iterative fashion, starting with constant supply and return temperatures throughout the network. After initial estimations of the design flow rates and heat losses are determined, refined estimations of the actual supply temperature at each consumer are computed. Flow rates at each consumer are then adjusted that the load is met with reduced supply temperature, and then the calculations are repeated [55].

6.6 Other Methods to Estimate the Pipe Diameter

6.6.1 Optimal Pipe Diameter of a Single Pipe Segment

To find the optimal diameter for a single pair of supply and return pipes, it is needed to consider the costs involved and minimize their sum with respect to the pipe diameter. The cost minimization is done for the life cycle of the system using a net present value approach. Some types of heat distribution systems may have a salvage value, while others will, in fact, have a disposal cost associated with the end of their useful lifetime. Since these will be mild functions of the pipe diameter, they will not significantly affect the optimal pipe diameter [56]. With these limitations in mind, the objective function becomes:

Min. $C_t = C_{hl} + C_{pe} + C_{pp} + C_{m\&r}$

where:

C_t = total system owning and operating cost ($)

C_{hl} = cost of heat losses ($)

C_{pe} = cost of pumping energy ($)

C_{pp} = capital costs of pipes and pumps ($)

$C_{m\&r}$ = cost of maintenance and repair ($).

Each of the costs in the above equation are examined briefly (more details [56]).

1. Cost of Heat Losses

The basic form of the heat loss cost is

$C_{hl} = PVF_h \int C_h Q_{hl} dt$

where:

PVF_h = present value factor for heat (dimensionless)

C_h = cost of heat ($/Wh)

$Q_h l$ = rate of heat loss (W)

t = time of year (hr [0 <= t <= 8760])

2. Cost of Pumping

The pumping cost is associated with the electrical energy input to drive the pumps. The portion of this energy that results in frictional heating of the fluid in the pipes is recovered as heat. In general, the value of the heat recovered will be less than the value of the electrical energy input to drive the pumps. It can be significant, however, and therefore it has been included here.

Thus, the pumping cost can be estimated as follows:

$C_{pe} = PVF_e \int C_e PP_a \, dt - PVF_h \int C_h PP_f \, dt$

where:

PVF_e = present value factor for electrical energy (dimensionless)

C_e = cost of electricity ($/Wh)

PP_a =actual pumping power required, including pump and pump driver inefficiencies (W)

PP_f =frictional pumping power, exclusive of pump and pump driver inefficiencies (W)

The first integral term represents the total cost of electrical energy input to drive the pumps. The second integral term is the value of heat recovered in frictional heating of the fluid.

3. Cost of Pipes and Pumps

In general, for the entire system the pump capital costs can be estimated as follows:

$C_{pumps} = A_1 n_p + A_2 (m_d/\rho_d) \Delta P_d$

where:

A_1 = empirical constant ($/pump)

A_2 = empirical constant ($/W)

m_d = mass flow rate (kg/s)

ρ_d = fluid density at design conditions (kg/m^3)

n_p = number of pumps

ΔP_d = total pressure drop (supply and return) at design flow rate (N/m^2)

The most significant cost to be considered is the capital cost of the piping system. For the capital cost of the supply and return piping including installation can be estimated as follows:

$C_{pipes} = (A_3 + A_4 d) L$

where:

A3 = empirical constant ($/m)

A4 = empirical constant ($/m^2)

L = pipe length (m)

d = pipe diameter (m)

Therefore, the cost of pipes and pumps is:

$C_{pp} = C_{pipes} + C_{pumps}$

4. Cost of Maintenance and Repair

The cost of maintenance and repair can be estimated as follows:

$C_{m\&r} = PVF_{m\&r}\ A_{m\&r}\ C_{pp}$

where:

$A_{m\&r}$ = annual maintenance and repair rate as a fraction of initial capital cost (dimensionless)

$PVF_{m\&r}$ = present value factor for maintenance and repair costs (dimensionless)

Finally, if each of the component cost is defined in function of the diameter of the pipe "d" the total cost "C_t" can be minimized with respect to "d" by using mathematical software.

6.6.2. Pipe Diameter of a Single Pipe Segment based on Rule of Thumb

Most systems are designed based on rules of thumb that have evolved from practice at the first stage. Although such rules of thumb may prove rule of thumb adequate in some cases, they lack the flexibility to account for varying conditions. Because these rules of thumb are based on designs proven to be functional, they cannot profess to yield least life cycle cost designs. For example, a common design rule of thumb used in Europe for hot water systems is: that the pressure loss in the piping not exceeds 100 Pa/m [56].

To apply the European rule of thumb it is necessary to calculate the pressure loss which would result at maximum flow conditions using increasing pipe size until we find a size that satisfies the rule of thumb. This calculation is done using the following equation:

$\Delta P_d = a\ \varepsilon^b\ (4/\pi)^{2+c}\ A_5\ m_d^{2+c}\ L\ d^{-(5+b+c)}$

where:

$A_5 = ((\rho^{-1}\mu^{-c})_{d,s} + (\rho^{-1}\mu^{-c})_{d,r})/2$, $m^{3+c}\ s^c/kg^{1+c}$

(s and r subscripts denote supply and return conditions, respectively)

a, b, c = coefficients determined by curve fitting of the type of pipe, dimensionless

ε = the absolute roughness of the piping, m

ρ = fluid density , kg/m^3

μ = dynamic viscosity, Pa-s

m_d = design mass flow rate, kg/s

L = pipe length, m

7. Conclusion

Waste-to-Energy technology and district heating and cooling systems are complementary solutions for several reasons. First, waste that is used locally as the fuel to power the WTE plant avoids methane and other emissions at distant landfills and also reduces the use of non-renewable fossil fuels. Second, a district heating and cooling system provides a centralized and efficient way to supply heating and cooling to a residential and/or commercial area, thereby increasing the thermal efficiency of the WTE substantially and also avoiding the uncontrolled emissions of thousands of residential and commercial boilers.

There are numerous conditions for proposing district heating in the U.S. using WTE plants, especially in the northern regions. First, northeastern cities are densely populated, have cold winters, and large heating expenditures in the cold months of the year. Second, the technologies for retrofitting a WTE plant and building a district heating are available and proven within the U.S. Third, there is an ample supply of MSW to fuel new WTE plants, or expansions of existing WTEs.

Scandinavian countries have been very successful in promoting and constantly increasing their hot water district heating networks. For example, Danish district heating supplies 60% of the heated floor, and 75% of the heat generation is generated in cogeneration plants. In addition, European Parliament launched the promotion of cogeneration based on useful heat demand in the internal energy market to increase energy efficiency to achieve a level of at least 80% of the annual overall efficiency in CHP plants. In contrast, there is a lack of energy policies relating to district heating and increasing energy efficiency of coal and MSW-fired power plants in the U.S. One option may be an alliance between the WTE industry and IDEA with the objective of increasing the contribution of district heating in the U.S. and influencing favorable policies for cogeneration. Currently, USCHPA and IDEA are promoting a CHP Investment Tax Credit, which will provide a 10% investment for CHP plants up to 50 MW of electricity.

This preliminary analysis showed that the DH system at Bridgeport holds considerable promise and should be examined further by Wheelabrator Technologies. The average diameter of Bridgeport piping network was estimated 49 cm (19.5 inches). The Preston DH network will be difficult to implement due to low density of housing units and heating demand. Although the mains would be of smaller diameter, 39 cm (15.4 inches), and less connecting piping would be required at Preston, the decrease in revenues, due to much lower heat requirement, indicates that the Bridgeport case was much more favorable. In addition, the Hartford WTE plant may be modified to provide both heat and electricity because Hartford city already have the infrastructure for district heating and cooling system. In addition, the South End district heating system is located very close to Hartford WTE, less than three kilometers. Therefore, Hartford WTE should consider seriously increasing its overall efficiency and revenues by co-generating heat and electricity.

In addition, the pipeline capital cost regarding the total length of the piping network, using the average pipeline cost per linear meter, results in a higher investment for Bridgeport (one square mile area). The capital cost may be at least $62 million, which is approximately three times higher than the cost of the piping network calculated by the Canadian procedure- $24 million.

Finally, retrofitting a WTE plant to co-generate heat and electricity is always technically possible but it is necessary to consider some factors such as: the ratio between the value of electricity and the value of heat, the ratio between the reduction of electrical output and the thermal output, and the capital and operational costs. U.S. WTE industry should consider retrofitting northeastern WTE facilities that are close to urban areas to enhance the overall efficiency, economic and social benefit by providing heat to the community. Also, it may persuade more U.S. citizens to be in favor of WTE industry.

8. References

[1] “District Heating Handbook”, fourth edition, 1983, published by The International District Heating Association (IDEA)

[2] U.S. EPA, “Combined Heat and Power”, Climate Change Technologies, January 2000, http://yosemite.epa.gov/OAR/globalwarming.nsf/UniqueKeyLookup/SHSU5BPLD4/$File/combinedheatandpower.pdf#search=%22district%20heating%20facts%20United%20States%22

[3] Brooks C., “District Heating Systems Fueled by Municipal Waste a Winning Combination”, in a report: “Waste-to-Energy and District Heating: a Handbook for Municipal Officials”, U.S. Department of Housing and Urban Development, September 1986

[4] Steam Business Development Task Force, CCN Management Counsel, and Thornton Energy Associates, “Steam Business Development Plan for Consolidated Edison Steam System”, report, August, 2005, http://www.nycedc.com/enewsletter/documents/SteamBusinessPlanFinal082605.pdf

[5] Delbes J. and Vadrot A., The District Cooling Handbook, Second Edition, 1999, published by European marketing Group District Heating and Cooling in cooperation with ELYO, Euroheat and PPG-Preinsulated Pipe Group

[6] EIA, Residential Natural Gas Prices: What Consumers Should Know, http://www.eia.doe.gov/oil_gas/natural_gas/analysis_publications/natbro/gasprices.htm

[7] U.S. EPA, “A Guide to Energy- Efficient Heating and Cooling”, May 2005, http://www.energystar.gov/ia/products/heat_cool/GUIDE_2COLOR.pdf#search=%22U.S.%20energy%20is%20used%20for%20heating%20and%20cooling%22

[8] EIA, Energy Facts: Residential/Commercial http://www.eia.doe.gov/kids/energyfacts/saving/efficiency/savingenergy.html

[9] EIA, Changes in Energy Usage: Main Heating Fuels http://www.eia.doe.gov/emeu/recs/recs97/decade.html

[10] EIA, New York Household Electricity Consumption in 2001: HVAC and Water Heating, http://www.eia.doe.gov/emeu/reps/enduse/er01_ny.html

[11] European Parliament and the Council, 11 February 2004, Directive 2004/8/EC

[12] USCHPA Advocacy Day, April 16-17, 2007, Summary of Legislative Priorities; http://uschpa.admgt.com/Advocacy_Day_Overview_for_Members.pdf

[13] Personal communication provided by Fernando Perez, Con Edison Steam, New York.

[14] Wade D., P.E. President - RDA Engineering Inc., “District Heating Conversion from Steam to Hot Water at the Savannah Regional Hospital”, presented at the International

District Energy Association- IDEA, 86th Annual Conference, Indianapolis, Indiana, June 3-6, 1995, www.rdaeng.com/PDFs/SAVAN.PDF

[15] Oliker, I, and Phillip, J., "Technical and Economic Aspects of District Heating Systems supplied from Cogeneration Power Plants", Proceedings of the American Power Conference, Vol. 40, pp. 314-327, 1978.

[16] Thermacor News, "Story Time: Co-Op City", www.thermacor.com

[17] IST News, "IST completes sale of two units in New York", February 24, 2006, http://otsg.com/section/view/?fnode=56

[18] Clean Energy Resource Teams, "Case Study: District Energy St. Paul - CHP District Energy Fueled by Biomass", Minnesota Project, 2003, http://www.cleanenergyresourceteams.org/metro/CS-District%20Energy%20St.%20Paul.pdf#search=%22st%20paul%20district%20energy%22

[19] District Energy St. Paul website: http://www.districtenergy.com/

[20] Gershman H., Gershman, Brickner & Bratton, "The Nashville District Energy System", presented at the International District Energy Association- IDEA, 97th Annual Conference, Nashville, Tennessee, June 11-14, 2006, http://www.districtenergy.org/06AnnConfProceedings/06AnnConfProceedings.htm

[21] Järvenpää, T., Koivisto, H., Mäkelä, T. and Salonsaari-Posti, A., "Cogeneration in Finland: District Heating and Industrial Perspectives", Helsinki, Finland; http://www.worldenergy.org/wec-geis/publications/default/tech_papers/17th_congress/1_2_17.asp

[22] Oliker, I., "District Heating System for Jamestown, New York ", Official Proceedings of the Annual Conference of the International District Heating Association, Vol. 74, pp. 225-233, 1984

[23] The Integrated Waste Services Association- IWSA, Directory WTE plants, http://www.WTE.org/docs/IWSA%202004%20Directory.pdf]

[24] Toombs D., General Manager, Citizens Thermal Energy, "Citizens Thermal Energy Provides District Heating & Cooling to Indianapolis", presented at the International District Energy Association- IDEA, 97th Annual Conference, Nashville, Tennessee, June 11-14, 2006, http://www.districtenergy.org/06AnnConfProceedings/06AnnConfProceedings.htm

[25] Covanta website, Facilities, http://www.covantaholding.com/ourFacilites.shtml

[26] Solid Waste Disposal Authority Hunstville website, http://www.swdahsv.org/wtoe.html

[27] Griffin T., Hinson J. and Holliday D., RMF Engineering, Inc, "The Army and NASA Move Forward with Waste To Energy District Heating and CHP", presented at the International District Energy Association- IDEA, 97th Annual Conference, Nashville,

Tennessee, June 11-14, 2006, http://www.districtenergy.org/06AnnConfProceedings/06AnnConfProceedings.htm

[28] Personal Communication with Jennifer Haas, VP Sales & Marketing, Thermacor Process, LP

[29] Perma-Pipe website, Leak Detection PAL-AT, http://www.permapipe.com/product_catalog_listing.asp?product=24

[30] Odgaard O. and Jorgensen M., (Editors), "Heat Supply in Denmark 2005- Who What Where and Why", published by The Danish Energy Authority, ISBN Electronic Version: 87-7844-498-5, January 2005, www.seas.columbia.edu/earth/WTErt/sofos/DEA_Heat_supply_in_denmark.pdf

[31] Danish Board of District Heating-DBDH-website, "The Danish District Heating History", http://www.dbdh.dk

[32] "A Comparison of Distributed CHP/DH with Large Scale CHP/DH", International Energy Agency – District Heating and Cooling Project Annex VII, Report 8DHC-05.01, Appendix B: Report on Experience in Denmark, published by Netherlands Agency for Energy and the Environment]

[33] Kamuk B., "A Neglected Resource: Using the WTE for District Heating", presented at North American Waste to Energy Conference –NAWTEC; 14th Annual Conference, Tampa, Florida, May 1-3, 2006

[34] RenoSam & Ramboll, "The Most Efficient Waste Management in Europe: Waste-to-Energy in Denmark", Report, 2006

[35] Ulloa P., Field trip to Nordforbraending WTE plant, May 26th, 2006. http://www.seas.columbia.edu/earth/wtert/sofos/Ulloa_field_trip_Nordforbraending.pdf

[36] Ulloa P., Field trip to Vestforbraending WTE plant, May 24th, 2006. www.seas.columbia.edu/earth/WTErt/sofos/Ulloa_Field_trip_Vestforbraending_2006_Priscilla.pdf

[37] Young Nam Kim, CEO of Korea District Heating Corporation, Presentation "The Status and Vision of District Energy", presented at the International District Energy Association- IDEA, 97th Annual Conference, Nashville, Tennessee, June 11-14, 2006, http://www.districtenergy.org/06AnnConfProceedings/06AnnConfProceedings.htm

[38] Natural Resources Canada, "District Energy Economic Assessment of Distribution Networks" (brochure developed by CETC)

[39] Meador, R., Writer, S., Michigan, A., "Cogeneration and District Heating: An Energy-Efficiency Partnership", 1981, Publisher Ann Arbor Science

[40] Oliker, I., and Muhlhauser, H., "Technical and Economic Aspects of Coal-Fired District Heating Power Plants in the United States", Proceedings of the American Power Conference Vol. 42, pp. 351-357, 1980.

[41] Personal communication with Professor Stefano Consonni

[42] Schweig, G., "Feasibility of Wood Fuelled District Heating in a Remote Community, M.S. Thesis, Department of Forestry, University of Toronto, 1997

[43] Stephenson, D., (1976), "Pipeline Design for Water Engineers", Elsevier

[44] Wikipedia, Demographics of Bridgeport, Connecticut; http://en.wikipedia.org/wiki/Bridgeport,_Connecticut

[45] Bonomo, A., "Cofiring of Biomass with Municipal Solid Waste and Sludge in Brescia Waste to Energy Plant", Workshop: European Experience in Biomass Cofiring, Grenoble, September 13th -14th , 2000.

[46] Ulloa P., Field trip to WTE Bridgeport, October 2006.

[47] Wheelabrator Bridgeport WTE facility website http://www.wheelabratortechnologies.com/WTI/CEP/bridgeport.asp

[48] Baker, D.K., and Sherif, S.A., "Heat Transfer Optimization of a District Heating System using Search Methods", International Journal of Energy Research, Vol. 21, pp. 233-252, 1997.

[49] Department of Public Utility Control, Oil Research Report, Average Energy Bills and Taxes, McCarthy Kevin, Principal Analyst, October 10th 2006; http://www.cga.ct.gov/2006/rpt/2006-R-0602.htm

[50] Hansen, E., "Hydronic System Design and Operation: a Guide to Heating and Cooling with Water", Chapter 2, 3 and 4, McGraw-Hill, 1985, ISBN: 0-07-026065-6.

[51] Themelis, N.J., "Transport and Chemical Rate Phenomena", Chapter 9: Applications of the Overall Energy Balance, pp. 93-95 (pdf file can be downloaded at www.seas.columbia.edu/earth/WTErt/sofos/transport_themelis.pdf)

[52] Wikipedia, Demographics of Preston, Connecticut; http://en.wikipedia.org/wiki/Preston,_Connecticut

[53] Wikipedia, Demographics of Hartford, Connecticut, http://en.wikipedia.org/wiki/Hartford,_Connecticut

[54] Hartford Steam District Heating and Cooling, CT,

http://www.hartfordsteam.com

[55] "2004 ASHRAE Handbook-HVAC Systems and Equipment", Chapter 11.

[56] Phetteplace, G., CRREL Report 95-17, Optimal Design of Piping Systems for District Heating, August 1995, http://www.crrel.usace.army.mil/library/crrelreports/CR95_17.pdf

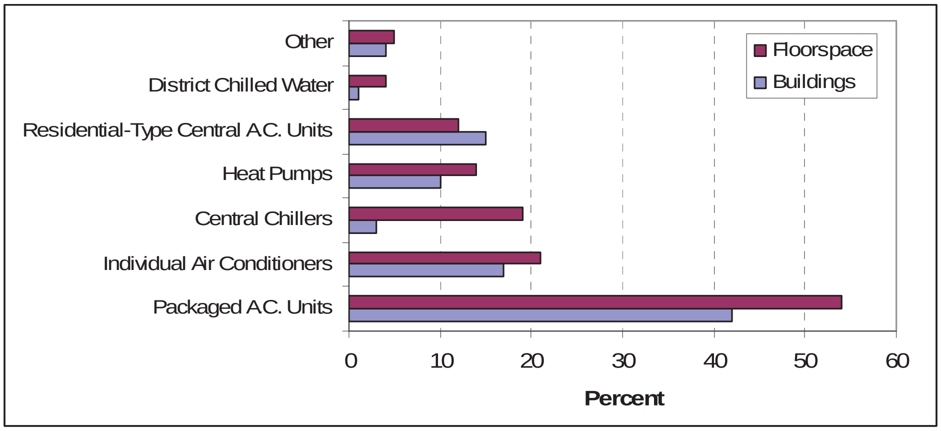

Other
District Chilled Water
Residential-Type Central A.C. Units
Heat Pumps
Central Chillers
Individual Air Conditioners
Packaged A.C. Units
Floorspace
Buildings
0
10
20
30
40
50
60
Percent

Fig 1

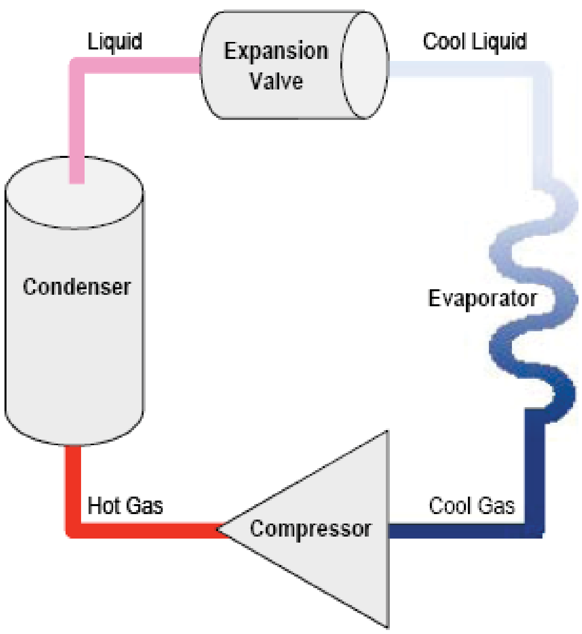

Liquid
Expansion Valve
Cool Liquid
Condenser
Evaporator
Hot Gas
Compressor
Cool Gas

Fig 2

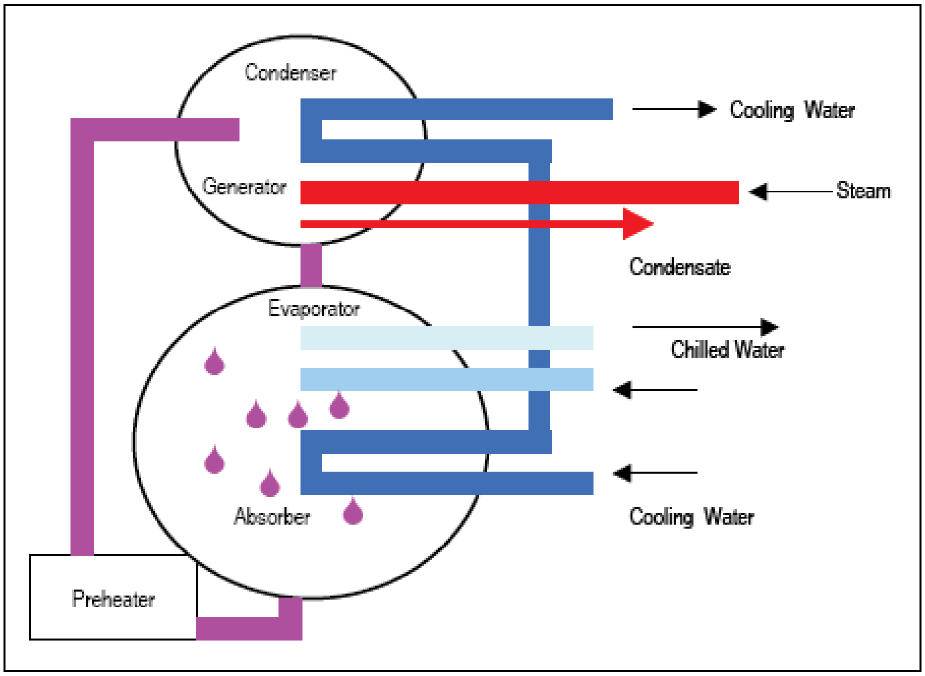

Condenser
Cooling Water
Generator
Steam
Condensate
Evaporator
Chilled Water
Absorber
Cooling Water
Preheater

Fig 3

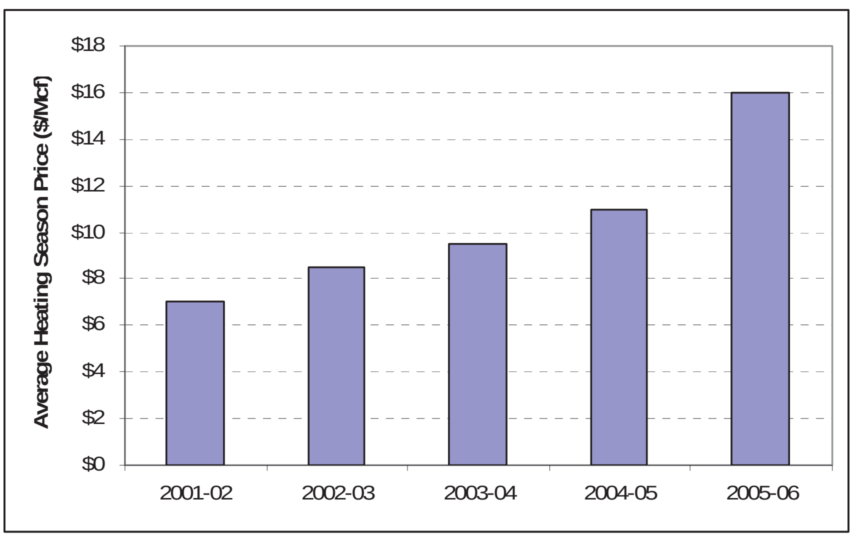

Average Heating Season Price ($/Mcf)
$18
$16
$14
$12
$10
$8
$6
$4
$2
$0
2001-02
2002-03
2003-04
2004-05
2005-06

Fig.4

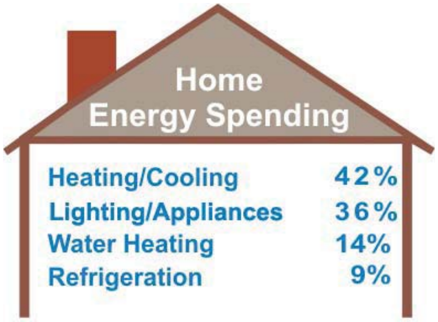

Home
Energy Spending
Heating/Cooling 42%
Lighting/Appliances 36%
Water Heating 14%
Refrigeration 9%

Fig.5

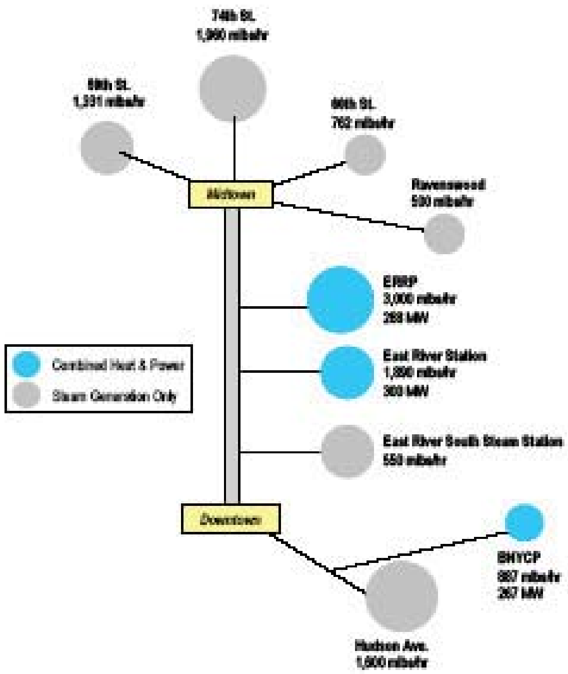

74th St.
Midtown
Ravenswood
ERRP
East River Station
East River South Steam Station
Combined Heat & Power
Steam Generation Only
Downtown
BNYCP
Hudson Ave.

Fig.6

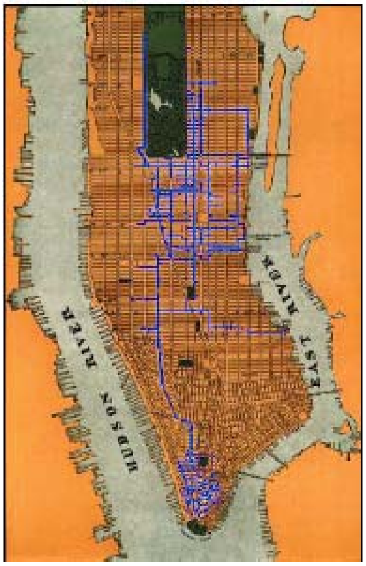
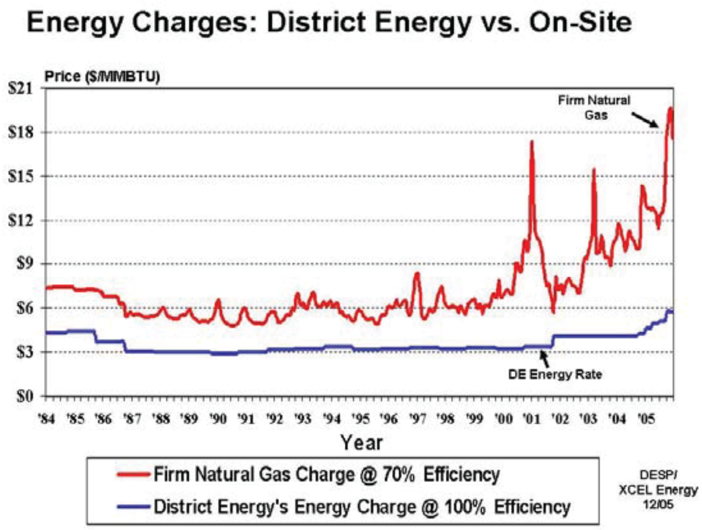


Fig. 7

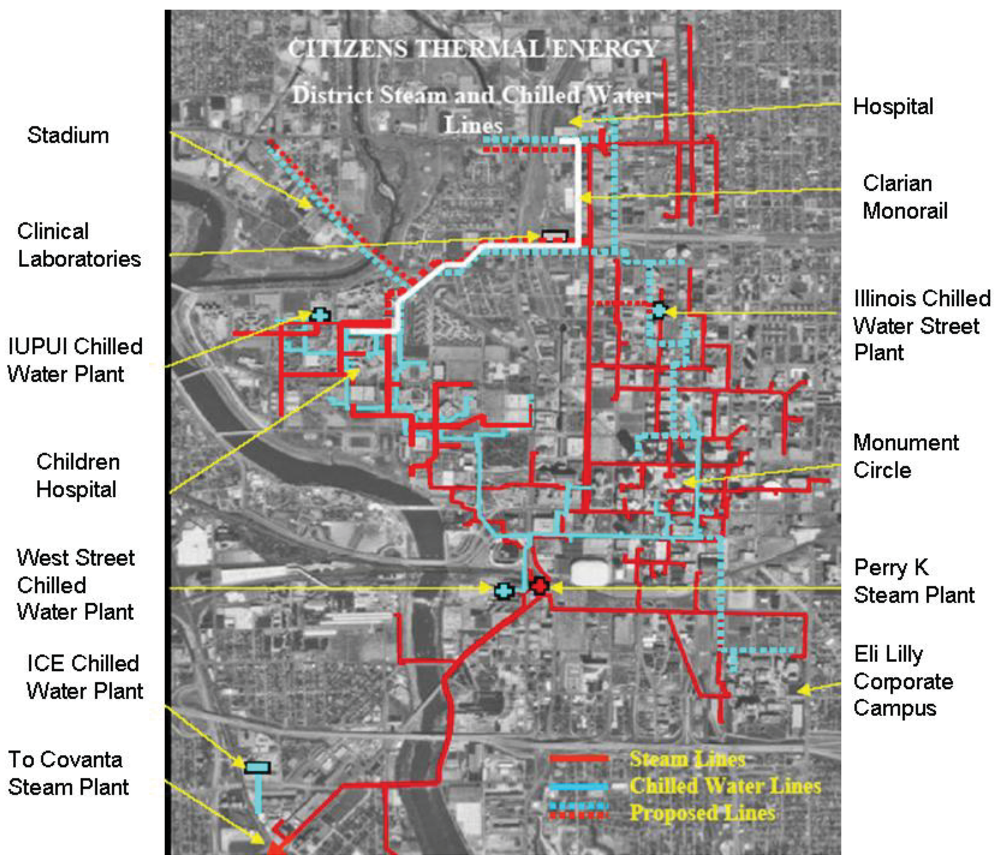

Fig. 8


Fig.9



Energy Charges: District Energy vs. On-Site
Price ($/MMBTU)
$21
$18
$15
$12
$9
$6
$3
$0
Firm Natural Gas
DE Energy Rate
'84 '85 '86 '87 '88 '89 '90 '91 '92 '93 '94 '95 '96 '97 '98 '99 '00 '01 '02 '03 '04 '05
Year
Firm Natural Gas Charge @ 70% Efficiency
District Energy's Energy Charge @ 100% Efficiency
DESP/
XCEL Energy
12/05

Fig 10



CITIZENS THERMAL ENERGY
District Steam and Chilled Water Lines
Stadium
Clinical Laboratories
IUPUI Chilled Water Plant
Children Hospital
West Street Chilled Water Plant
ICE Chilled Water Plant
To Covanta Steam Plant
Hospital
Clarian Monorail
Illinois Chilled Water Street Plant
Monument Circle
Perry K Steam Plant
Eli Lilly Corporate Campus
Steam Lines
Chilled Water Lines
Proposed Lines

Fig.11

Fig.12

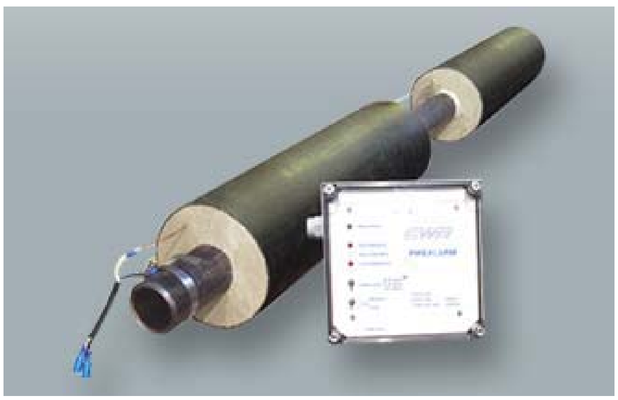


Fig.13

Fig.14

Fig.15

Fig. 16

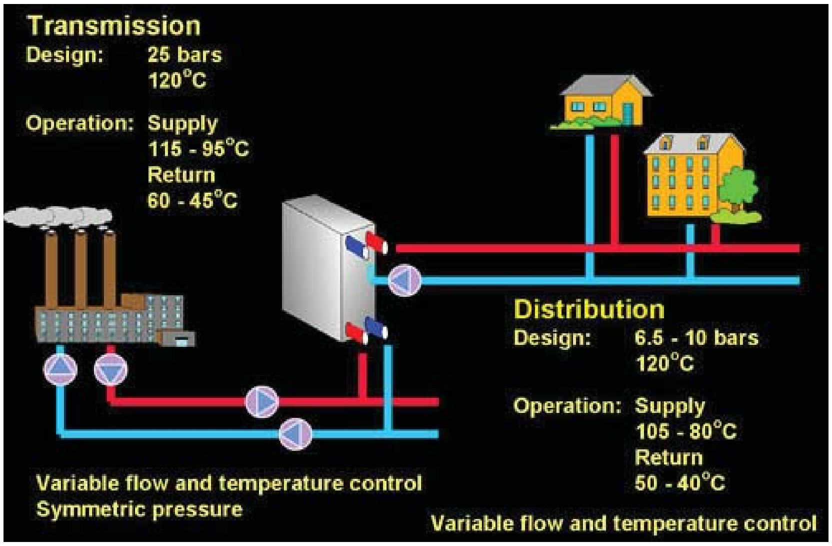

Transmission
Design: 25 bars
120°C
Operation: Supply
115 - 95°C
Return
60 - 45°C
Distribution
Design: 6.5 - 10 bars
120°C
Operation: Supply
105 - 80°C
Return
50 - 40°C
Variable flow and temperature control
Symmetric pressure
Variable flow and temperature control

Fig.17

Fig. 18

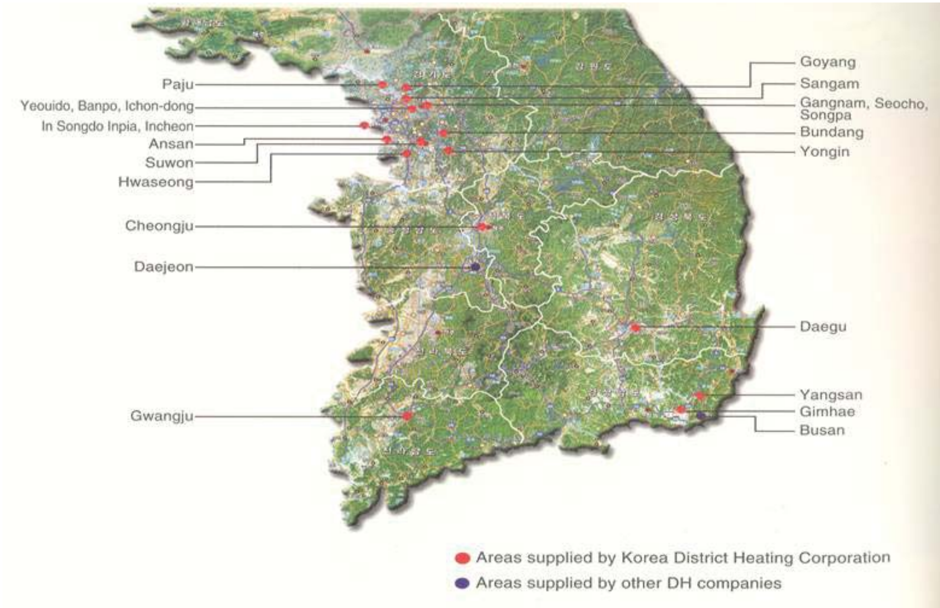

Goyang
Sangam
Gangnam, Seocho, Songpa
Bundang
Yongin
Paju
Yeouido, Banpo, Ichon-dong
In Songdo Inpia, Incheon
Ansan
Suwon
Hwaseong
Cheongju
Daejeon
Daegu
Yangsan
Gimhae
Busan
Gwangju
Areas supplied by Korea District Heating Corporation
Areas supplied by other DH companies

Fig.19

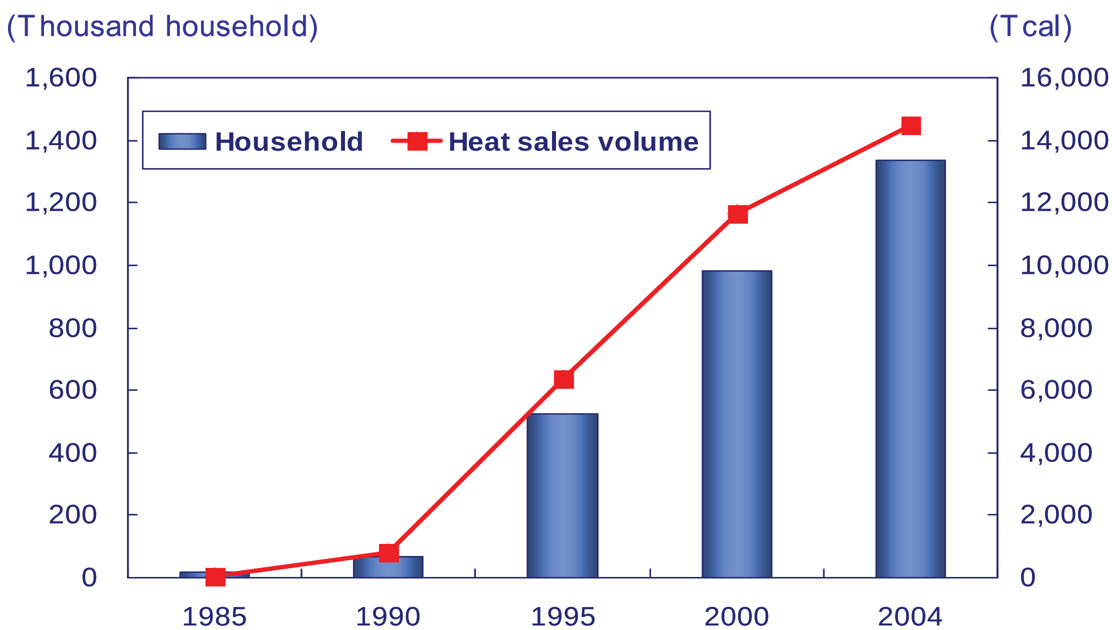

(Thousand household)
(Tcal)
1,600
1,400
1,200
1,000
800
600
400
200
0
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Household
Heat sales volume
1985
1990
1995
2000
2004

Fig. 20

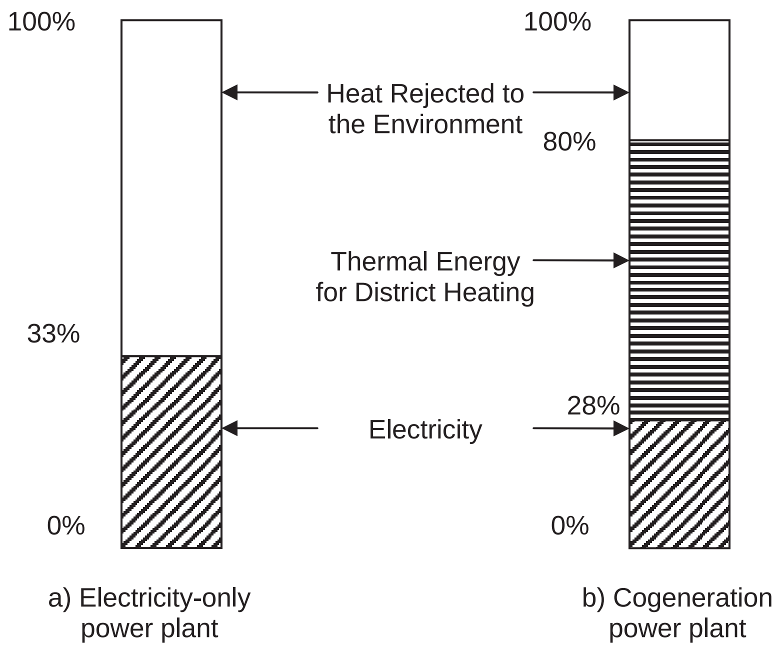

100%
33%
0%
Heat Rejected to
the Environment
Thermal Energy
for District Heating
Electricity
100%
80%
28%
0%
a) Electricity-only
power plant
b) Cogeneration
power plant

Fig 21

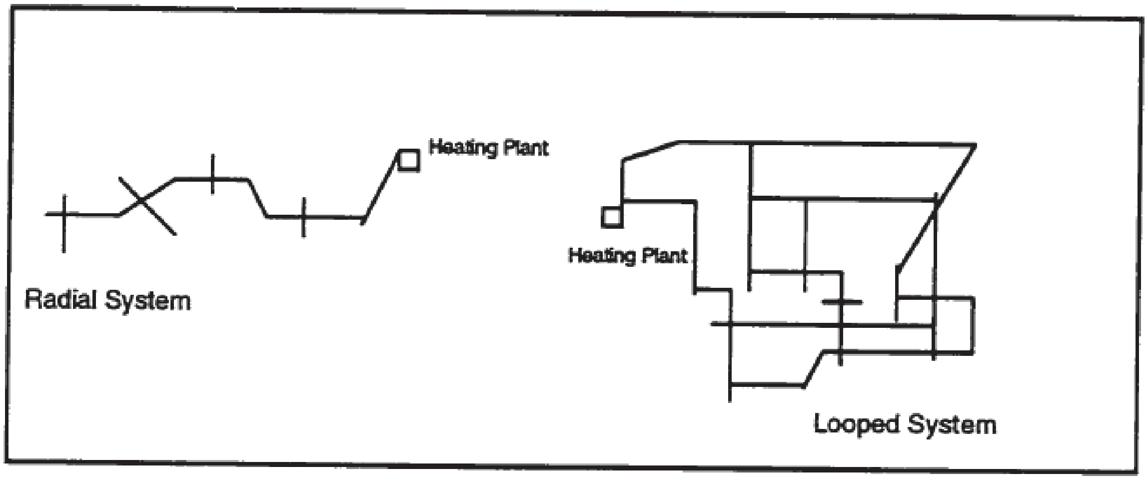

Heating Plant
Radial System
Heating Plant
Looped System

Fig 22


Bridgeport WTE
© 2007 Europa Technologies
Google

Fig. 23

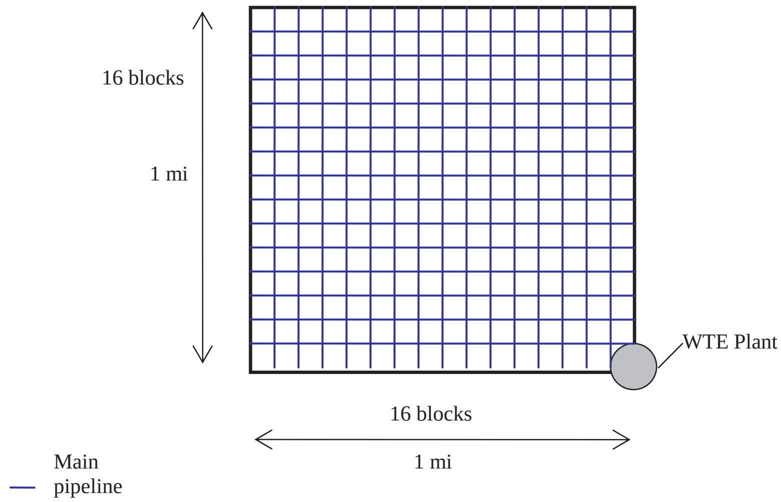

16 blocks
1 mi
WTE Plant
16 blocks
1 mi
Main
pipeline

Fig. 24


Preston WTE
©2007 Europa Technologies
Google

Fig 25

Fig 26

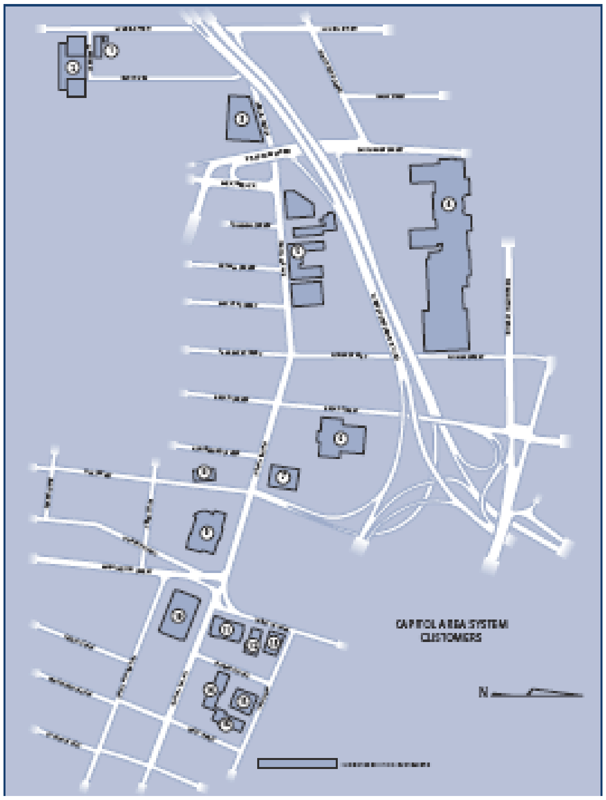


Fig 27

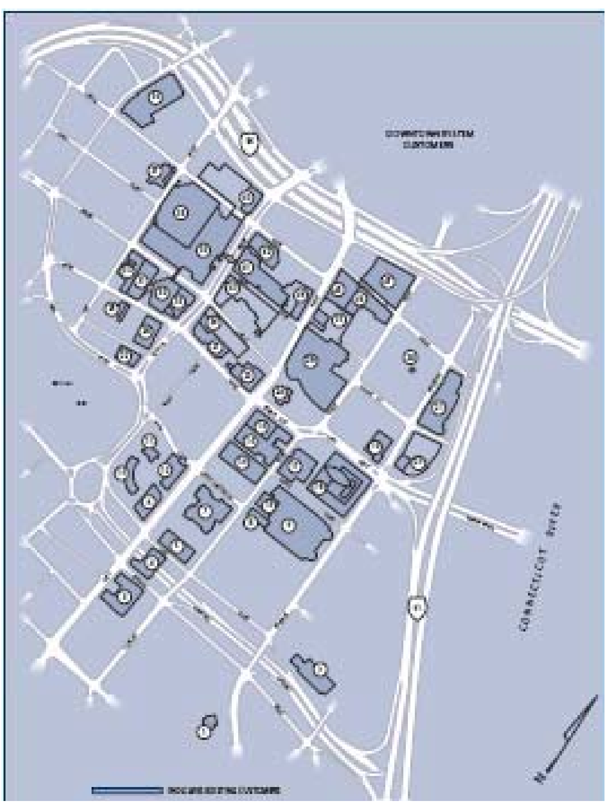


Fig 28

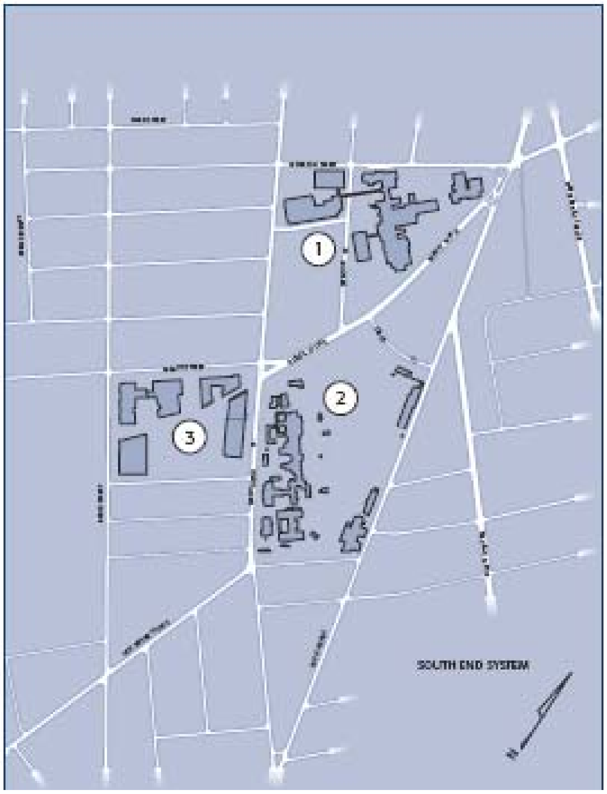


Fig 29

TABLES

Table 1

Chiller (COP)	Tonnage Range	Cost/Ton				Operating Cost/Ton-hr	Manufacturer
		Chiller	Turbine	BOP/ Install	Total		
Single-stage steam-fired absorption (0.6-0.9)	100-1,500 500-1,350 100-700	$300	n/a	$700	$1,000	$0.27-$0.30	York Trane Carrier
Two-stage steam-fired absorption (1.0-1.3)	300-675 100-1,660	$625	n/a	$675	$1,300	$0.17-$0.21	York, Carrier Trane
Steam-turbine driven centrifugal (1.6-1.9)	700- 5,000	$250	$585	$725	$1,560	$0.17-$0.21	York, Carrier
Gas-engine driven centrifugal (1.9)	350 – 1,800	$700	n/a	$700	$1,400	$0.15	York, Trane
Two-stage direct fired absorption (1.0)	100- 1,500 100- 1,100				$1,200	$0.21	Carrier Trane
Variable speed, electric-drive centrifugal (10)	200- 5,000	$350		$550	$900	$0.10- $0.13	York
Electric centrifugal (6-7)	200- 3,000 200- 8,500	$250		$550	$800	$0.11	Trane York, Carrier

Table 2

Parameter	Compression Chiller	Absorption Chillers	
	Centrifugal Chiller	Single-stage	Two-stage
Primary Energy	Rotation work	Hot water, low grade steam 65 C< T< 100 C	Steam or fire T > 170 C
Fluids	R 134a, HCFC, NH_3	H_2O with LiBr	H_2O with LiBr
Range (MW)	0.5 to 25	0.1 to 5.8	0.1 to 5.3
Surface on ground (m^2/ kW)	0.006 to 0.016	0.01 to 0.03	0.01 to 0.03
Weight on ground (kg/ kW)	5.2 to 9.1	8.5 to 22	8.5 to 22

Table 3

Parameter	Unit	Value
Steam Sales	Million pounds	26,877
Steam Sendout	Million pounds	30,890
Maximum Hour Load	Million pounds/hr	10.49
Load Factor	%	27.4%
System Capacity	Million pounds/hr	12.86
Electricity Capacity	Megawatts	692.7
Air conditioning Capacity	Megawatts	375
Heating Floorspace	square feet	359,926,976
Cooling Floorspace	square feet	218,849,050
Total floor area heating&cooling	square feet	578,776,026
Customers	number	1,811
Commercial and residential establishments in Manhattan	number	100,000
Generation Stations	number	7
Unit Production Costs	US dollars/thousand pounds	20.5
10 year rate of steam sales growth	%	-10.4%
Type of Pipe		single
Main lines	miles	87
Services lines	miles	18
Total length of mains and services	miles	105
Steam Manholes	number	3,000
Maximum Diameter of the pipe	in	36
Minimum Diameter of the pipe	in	2
Cost of pipeline installed	$US/ linear ft of pipe installed	2,000 - 4,000
Percentage of the steam that comes from CHP plants	%	36.1%
The summer peak sendout	Million pounds/hour	6.35
The winter peak sendout	Million pounds/hour	8.4
Percentage of distribution losses	%	13%
Natural Gas consumed	cubic feet/year	10,880,617,000
Oil consumed	barrel/year	3,036,274
Steam air conditioning load	tons	625,000
The average heating load for a NYC building	MMBTU/ft2/hr	0.02
Turbine Chillers	number	135
Absorption Chillers	number	235
Both systems	number	4
Total Steam Chillers	number	366

Table 4

Name WTE	State	Design Capacity (TPD)	Cogeneration	
			Steam (lbs/hr)	Electricity (MW)
Eielson Airforce Base	Alaska	10	2,775	0.2
Montenay Savannah Operations	Georgia	502	130,000	6
Harford County WTE	Maryland	360	100,000	1.2
Pioneer Valley Resource Recovery	Massachusetts	408	96,000	9.4
Greater Detroit Resource Recovery	Michigan	3,300	15,000	65
Jackson County Resource Recovery	Michigan	200	49,200	3.7
Kent County	Michigan	625	76,000	8
Olmsted WTE	Minnesota	200	60,000	4
Perham Resource Recovery	Minnesota	116	37,000	2.5
Pope-Douglas Waste Recovery	Minnesota	80	35,000	0.4
Dutchess County RRF (Poughkeepsie)	New York	450	50,000	10.5
Niagara Falls Resource Recovery	New York	2,250	350,000	50
Oswego County Energy Recovery	New York	200	50,000	4
W.B. Hall Resource Recovery	Oklahoma	1,125	240,000	16.8
Harrisburg WTE	Pennsylvania	800	50,000	23
Montenay Charleston RRI	South Carolina	600	50,000	13
Sunner County Resource Authority	Tennessee	200	54,000	0.5
Davis Energy Recovery	Utah	420	104,000	1.4
Harrisonburg Resource Recovery	Virginia	200	43,000	2.5
Southeastern Public Service Authority	Virginia	2,000	25,000	50
Barron County WTE & Recycling	Wisconsin	100	19,000	0.265
Total			**1,635,975**	**272**

Table 5

Name WTE	State	Design Capacity (TPD)	Steam (lbs/hr)
Hunstville WTE	Alabama	690	180,000
Indianapolis Resource Recovery	Indiana	2,362	558,000
Pittsfield Resource Recovery	Massachusetts	360	66,000
Fergus Fall Resource Recovery	Minnesota	94	22,000
Polk County Resource Recovery	Minnesota	80	22,000
Red Wing Waste Recovery	Minnesota	72	15,000
Hampton-NASA Steam Plant	Virginia	240	66,000
Total			**929,000**

Table 6

Plant	Owner	No. of Lines	Total Capacity (t/h)
Aalborg	I/S Reno-Nord	2	31
Aars	Aars kommune	2	8.5
Aarhus	Århus kommunale Værker	3	31.2
Esbjerg	L 90	1	24
Frederikshavn	Elsam A/S	1	5
Glostrup	I/S Vestforbrænding	4	83
Grenå	Grenå kommune	1	2.5
Haderslev	Elsam A/S	2	9
Hammel	Hammel Fjernvarme A.m.b.a.	2	6
Herning	EG. Jylland	1	5
Hjørring	AVV I/S	2	12
Hobro	I/S Fælles Forbrænding	2	6.9
Holstebro	Elsam A/S	2	18
Horsens	Elsam A/S	2	10
Hørsholm	I/S Nordforbrænding	4	19
København	I/S Amagerforbrænding	4	48
Kolding	TAS I/S	1	9.2
Næstved	I/S FASAN	3	17
Nykøbing F	I/S REFA	3	17
Odense	Elsam A/S, Fynsværket	3	32
Rønne	I/S BOFA	1	2.5
Roskilde	I/S KARA	3	34
Skagen	Skagen kommune	1	2
Skanderborg	I/S RENO SYD	2	9.5
Slagelse	I/S KAVO	2	10
Sønderborg	Sønderborg Kraftvarmeværk I/S	1	8
Svendborg	Svendborg kommune	1	6
Thisted	I/S Thyra	1	6.4
Vejen	Elsam A/S	1	4.3
TOTAL			477

Table 7

Product	Unit	Quantity
Waste		
Waste combusted	tonnes	110,000
Bottom ash	tonnes	17,000
Residues from flue gas cleaning	tonnes	3,000
Energy		
District Heating	GWh	225
Electricity	GWh	50
District Cooling	GWh	3

Table 8

Unit	Electricity (MWh)	Heat (MWh)
Combined heat and power (1 line of 10 t/h)	7.4	20.8
Heat production (3 lines of 3 t/h)	-	21

Table 9

Units	Start-up Year	Capacity (tonnes/hr)
1-2*	1970	2 x 12
5	1999	26
6	2005	34
Total		**84**

Table 10

Component	Percentage
Supply of pipe	55%
Excavation	20%
Laying and jointing	5%
Fittings and specials	5%
Engineering and survey costs	5%
Others (coating, structures, administrative costs, etc.)	10%
Total	100%

Table 11

Distribution Cost per length of pipe	At $1,000 per meter pipe[1]	At $2,100 per meter of pipe[2]	At $6,000 per meter of pipe[3]
Total Cost for 61,519 m of pipeline (184,557 ft)	$61,519,000	$129,189,648	$369,113,280