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District heating and cooling: Review of technology and potential enhancements

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ABSTRACT

District energy systems are reviewed and possible future enhancements involving expanded thermal networks are considered. Various definitions, classifications and applications of district cooling and heating are discussed and elements of a district energy system are described. Also, the integration of combined heat and power (CHP) with district energy, permitting the cogeneration of electricity and heat, is examined from several points of view and for various locations and applications. One of the main advantages of district heating and cooling systems is their environmental benefits, which are explained in detail. The economics of a thermal network system, as a major factor in the justification for any project, is elaborated upon from industrial, governmental and societal perspectives. Furthermore, related regulations at government levels are suggested based on various investigations. The efficiency of district energy is discussed and exergy analysis, as an effective method for calculating the efficiency of a thermal network, is explained. Finally, other advantages of the district energy technology for communities are pointed out. This review of district heating and cooling considers technical, economic and environmental aspects and helps identify possibilities for future study on district energy systems.

1. Introduction

Humanity faces serious energy and environment problems at present. The environment is threatened, for instance, by increasing of greenhouse gas (GHG) emissions, which have contributed to concentrations in the atmosphere having already reached concerning levels in terms of their potential to cause climate change [5]. Air pollution, acid precipitation and stratospheric ozone depletion are other serious environmental concerns. The severity of climate change impacts is predicted to increase if significant action is not taken to reduce GHG emissions [5]. An important action to address energy and environmental challenges lies in the intelligent and efficient use of energy, including reducing/reusing energy waste and using low-carbon fuels. Rosen [68] describes methods to combat global warming through non-fossil fuel energy alternatives, and other approaches exist.

“Waste heat” is generated during electricity production and other industrial operations, despite it having significant energy content [80,78]. Much research have been carried out on uses for waste energy, including recycling [11,49,15], to reduce use of fossil fuels and other energy resources. Using low-temperature heat from renewable energy sources such as solar and geothermal energy, as well as industrial waste heat, in district heating has proven to be attractive [7,59,27,46,36,92]. Also, Lund et al. [47] point out that “low energy” buildings can be operated using industrial waste heat, waste incineration, power plant waste heat and geothermal energy in conjunction with a DE network. Incorporating TES can improve designs for such systems. Wetterlund and Soderstrom [86] state that DE system provide an efficient means for utilizing biomass and other fuels, while reducing the use of fossil fuels for heating.

Using waste heat increases efficiency and avoids emissions, helping to enhance the quality of the environment. Energy efficiency entails the use of less energy for a given process, such as occurs with energy saving appliances and equipment [60]. Industrial waste heat can be converted into useful energy forms [14]. GHG emissions resulting from energy consumption by end users can be reduced by energy conservation practices [60]. Sustainable district heating and cooling can have a significant effect on reducing GHG emissions and air pollution, as shown using US Department of Energy data by Patil et al. [60].

Fumo et al. [29] describe a technology to apply thermally activated components to recapture waste heat, which they consider a significant means of addressing global warming through smart use of fuel and higher energy efficiency. Fumo et al. [29] treat combined cooling, heating, and power (CCHP) as an integrated energy system that supplies recovered heat from a prime source and generates heating and cooling for buildings. They apply an environmental approach to CCHP to determine the emission operational

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strategy. Fumo and Charma [28] extend this work for CCHP via a primary energy consumption analysis.

In Canada, space heating and cooling, and water heating, generates 77% of greenhouse gas (GHG) emissions in the residential sector. A centralized local thermal energy system, which can produce hot and cold fluids, and then distribute them throughout the community, has significant potential to contribute to solving society's energy challenges. Having such a production and distribution system for heating and cooling not only provides hot water and hot and cold air for the community with reduced energy consumption, but also reduces GHG emissions. Furthermore, providing energy services with renewable energy via such a central system can be simpler and less expensive compared to utilizing renewable energy directly in each individual residential building.

This study is an overview of district energy system from technical, economic and environmental perspectives, directed at facilitating research into expanded thermal networks and their ultimate application. The work is part of a broader research program by the authors into the use of integrated thermal networks, based on expanded district heating and cooling systems, to meet the thermal requirements for various buildings and applications with greater efficiency and less environmental impact than traditional systems.

2. District energy systems

District energy systems have been used in Europe since the 14th century, with one geothermal district heating system in continuous operation in France (Chaudes-Aigues thermal station) since that time [45]. The US Naval Academy constructed the first district system on its Annapolis campus in 1853, and the commercial district heating system in New York was built in 1877 [51]. The first district energy system in Canada was built in Winnipeg's commercial core in 1924 [51].

Northern European countries are the main users in district energy systems. For instance, Sweden has installed a 40 TWh district heating system which supplied more than half of the heating capacity of the country in 2000 [30]. The percentage of district-heated homes is around 65% in Latvia and Lithuania. Due to use of district energy networks, the use of oil and hydroelectricity has dropped about 10% in Norway [61].

Less than 7% of the heating capacity in Canada is linked to district heating systems [55]. One reason for this low percentage is attributed to a low cost energy supply from hydroelectricity and fossil fuels, and another is the dispersion of small communities across the country's wide territory. Almost 80 district heating systems are operating in Canada, capable of generating 1730 MW of thermal energy, according to the Canadian District Energy Association [51]. Table 1 lists the thermal capacities of some Canadian district heating networks. The 2010 Winter Olympics in Vancouver are planned to receive heating services through a district heating network [83].

Five Canadian district heating networks use biomass as the source of energy: Charlottetown (Prince Edward Island), Chapais (Quebec), Ouje-Bougoumou Cree community (Quebec), William Lake (British Columbia) and Ajax (Ontario). Natural gas, propane, fuel oil and electricity are the energy sources for the other steam-based district heat systems in Canada [51,4].

Table 1
Major Canadian steam-based district heating networks. Source: Marinova et al. [51].

Name	Capacity (MW)
Toronto district heating system	276
Central heat distribution, Vancouver	232
University of Toronto	195
Cor. De Chauffage Urbain, Montreal	100

The historical development of DE in Canada indicates that there have been two major periods of growth for district energy in the country [13]. The first was in the 1970s when energy prices drastically increased. Not only was an expansion experienced in district heating but also in combined heat and power (CHP) plants for industrial process applications. The second significant growth period occurred in the late 1990s when the Canadian government encouraged the application of DE to foster sustainable energy and community planning. Table 2 depicts the growth in the number of district heating systems in Canada and the United States. Both countries have increased district heating networks in many sectors [51]. Some projects in the US are particularly significant, like the downtown district heating project in Montpellier, Vermont [84].

District energy involves multi-building heating and cooling, in which heat and/or cold is distributed by circulating either hot water or low-pressure steam through underground piping [21]. District networks incorporate an underground system of piping from one or more central sources to industrial, commercial and residential users [79,51]. The heat delivered to buildings can also be used for air conditioning by adding a heat pump or absorption chiller (American Society of Heating, Refrigeration and Air Conditioning Engineers) [6]. District energy can provide efficiency, environmental and economic benefits to communities and energy consumers [56]. Difs et al. [18] state that DE systems usually exhibit lower environmental impacts compared to conventional systems; they also used the method for heating load analysis to demonstrate that increasing DE applications in industrial processes leads to increased resource energy efficiency.

The energy source for district heating systems can be fossil fuels or other energy sources, and mixed systems combining two or more energy sources, like natural gas, wood waste, municipal solid waste and industrial waste heat, can be feasible economically [74]. Persson and Werner [62] consider heat supplies for DE to include heat from CHP, waste-to-energy (WTE), biomass and geothermal energy plants, as well as industrial excess heat. This flexibility is one advantage of district energy systems. The thermal energy needed by the district grid is often supplied by a dedicated plant, but industrial waste energy can be an attractive alternative because it permits depreciation and maintenance costs for the power plant to be divided [81]. Fossil fuels used to be the primary energy sources of the heat supplied [39], but hybrid systems combining renewable or alternative energy technologies like solar collectors, heat pumps, polygeneration, seasonal heat storage and biomass systems have begun to be used as the energy source [63].

Table 2
Added floor surface area serviced by district heating in 2003 and 2006. Source: Marinova et al. [51].

Building type	Floor area (10^3 m^2)			
	2003		2006	
	US	Canada	US	Canada
Office and commercial	3600	3200	6700	3800
Industrial	2600		800	1300
Institutional	12,600	7500	4600	5300
Hotels	1600	1100	1800	1700
Residential	2200	1100	3400	300
Other	6200		200	300
Total	26,600	5400	17,500	12,400

3. Classifications

District energy systems are categorized based on different aspects. One grouping is derived from the heat transport fluid: low-pressure steam, hot water and hot air. Another classification is based on the thermal energy transported: heating, cooling, and cooling and heating. A further categorization of district heating system can be based on the type of heat resources: using a separate source of energy for heat or using recycled energy/heat. The most practical example of the latter type of thermal network is one using combined heat and power (CHP), as cogenerated heat from generating electricity can then be utilized for heating nearby buildings.

3.1. Energy classifications

District heating can also be classified based on energy source. For district heating, for example, energy sources can include fossil fuels, nuclear power, cogenerated heat, waste heat, and renewable thermal energy including solar thermal energy, heat from ground source heat pumps and biomass. Note that natural gas is a common energy source in present thermal networks because of its availability, price and relatively low emissions compared to other fossil fuels. Renewable technologies are expected to be increasingly used in future designs. Also note that electricity is often required by the thermal networks to drive chillers, to run ancillary equipment and sometimes for conversion to heat. This electricity can be provided via the electrical grid or by renewable energy (e.g., solar photovoltaic or wind energy). In the following subsections further explanations are provided about energy resources.

3.1.1. Renewable energy

Interest in new energy sources is increasing. The use of geothermal energy directly for district heating has increased notably; geothermal sites contribute 49% of the installed capacity of heating systems in Europe, 29% in Asia and 17% in the Americas [51]. Solar thermal energy has been used effectively in district heating [35]. They also note that solar technology performs with high reliability and low maintenance, and is flexible for optimizing the conventional boilers in the district heating systems. Use of geothermal district heating systems has increased by 10% over the past 30 years [48].

A potentially significant technology for the future is biomass gasification, which produces a wide range of potential feedstocks as well as downstream fuel production alternatives like methanol, synthetic natural gas (SNG) and Fischer–Tropsch diesel [86]. These authors also state that, since there is a significant surplus heat in biofuel production processes, a district heating (DH) system coupled with the plant can increase overall efficiency. The authors use the method for analysis of industrial energy systems as the optimization tool to show efficient policy instruments are crucial to obtaining an investment for a large-scale biomass gasification plant for a DH supplier. Capital costs require increased support, as investments in large-scale gasification plants involve large financial risks for DE suppliers. For this reason, DH companies are significantly dependent on supportive policies for success in the long term. Wood chips, wood waste, peat moss and natural biomass are also energy sources for district heating systems, and wood chips are used widely in Sweden in district heating plants [77]. Biomass applications have been examined in district heating and electricity generation [40], and biomass generates less expensive heat for district heating in comparison to fossil fuels like natural gas [26]. Biomass district heating systems can be more effective than conventional systems for reducing GHG emissions as well as community fuel consumption [56]. The authors note that the characteristics of such district energy systems are site specific.

Vallios et al. [82] in a extensive study demonstrate designs for biomass DE systems. They cover technical aspects including boiler, heat delivery network and heat exchanger design, as well as environmental and economical aspects.

Another possible energy source for a DE system is the ground source heat pump, which typically has a coefficient of performance (COP) of about 4. A ground source heat pump transfers heat into the ground in summer and extracts heat from the ground in the winter. Geothermal energy is an attractive replacement for fossil fuels for addressing environmental and energy issues while it is simple and safe [58]. The degree of adoption of geothermal energy depends on policy and other technology issues [25]. These authors performed a study on the future use of geothermal energy in Swedish DE systems, using an optimization procedure for dynamic energy systems; their results show that, since there are better incentives for CHP and waste incineration DE systems, the use of ground source heat pumps in DE systems will likely decrease in both short term and long term applications. They also investigate, for a short-term application, heat pumps competing with a biofuel heat-only boiler (HOB) which supplies forest fuels, a gas steam cycle CHP, a gas HOB and an oil HOB. Biofuel CHP is observed to be responsible for more new investments than geothermal energy in DE systems. Their work also confirms that waste incineration has less of an effect on future investments into ground source heat pumps, compared to biofuel CHP.

Zhai et al. [91] demonstrate, through an example of a hybrid solar heating, cooling and power generation system including parabolic solar collectors, that this type of solar collector is more efficient than conventional solar thermal collectors. The authors perform energy, exergy and economic analyses of that plant, which is discussed further in subsequent sections of this article.

3.1.2. Combined heat and power (CHP) plants

Cogeneration (or CHP) is the simultaneous generation of electricity and useable heat [74]. CHP is efficient because it avoids the large amounts of waste heat produced in typical power generation plants. Gustafsson et al. [33] explain for a CHP plant that fuel efficiency is more than 90% since most of the waste is recovered in a DE system. They state that higher fuel efficiency and more effective heat transfer capacity of the DE network reduces primary fuel consumption, these changes can lead to increases in consumers without establishing more heat plants. CHP generation is often economic and reduces both GHG emissions and fuel consumption in a community [41]. New technologies have enabled cogeneration to be cost effective, even in small-scale applications in communities or individual sites. The European Parliament [22] recognized CHP as a method to boost energy system efficiency and decrease CO_2 emissions. A well designed CHP system can increase the energy efficiency to over 80% [23]. For example, the gas engine-driven Gyorho cogeneration plant in Hungary has an efficiency of 81.5% based on fuel energy, i.e., 43.1% of the fuel energy is converted to electricity and 38.4% into heat for district heating [41]. A general cogeneration plant which produces simultaneously various forms of energy from a single source is illustrated in Fig. 1.

Cogeneration plants can be classified into the following categories [37]:

- Topping cycle: Electricity is generated in a turbine generator and high-pressure steam or exhaust gases are used for process heating or district heating. A general gas turbine cogeneration system, which is a type of topping cycle, is depicted in Fig. 2, along with a breakdown of the energy flows.
- Bottoming cycle: Steam from the cycle, which has already been used in another industrial process, passes through a low-pressure steam turbine to produce electricity.

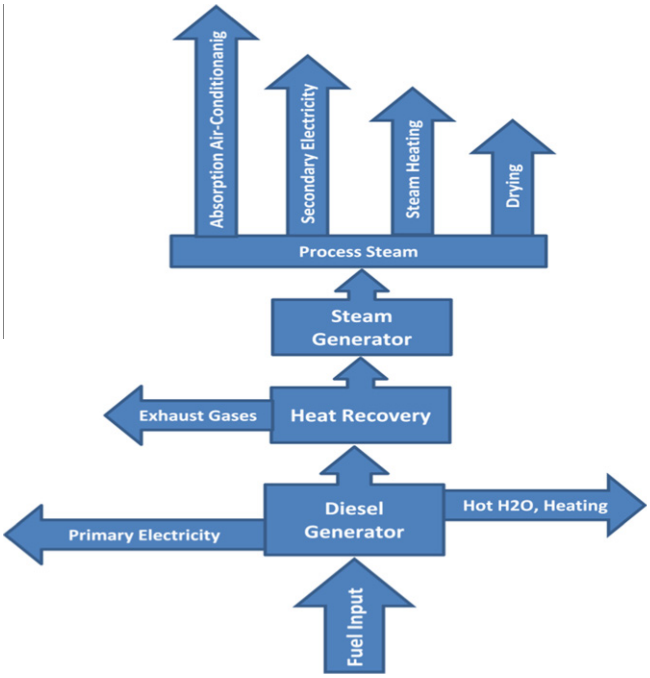

Fig. 1. Schematic of a general cogeneration plant, showing potential uses for the thermal product. Adapted from Hinrichs and Kleinbach [37].

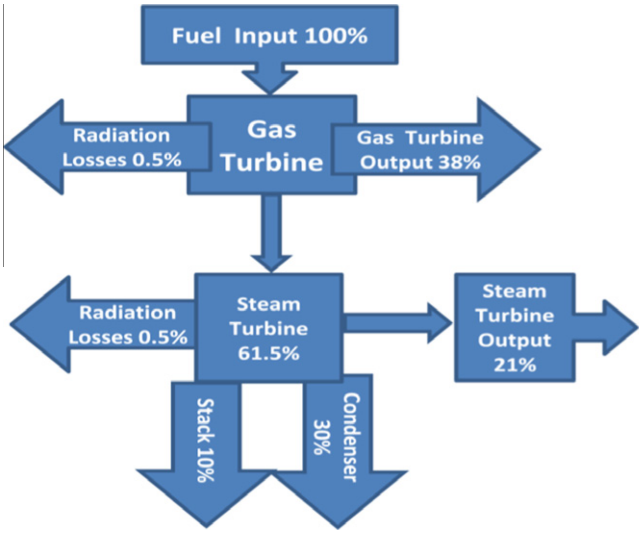

Fig. 2. Illustration of cogeneration using a combined cycle power plant, including a gas turbine and steam turbine, as well as a breakdown of energy flows. Adapted from Boyce [12].

Also, cogeneration systems can be categorized by type as follows [12]:

- Utility cogeneration: Such systems usually have large units with district energy systems, and are often partly funded and governed by the municipality.
- Industrial cogeneration: Paper mills, petrochemical plants, glass factories, textile mills and other industrial plants which are operated by private-sector entities are in this category.
- Desalination: Using hybrid cogeneration/desalination processes can reduce desalination costs. Desalination cogeneration facilities produce electricity and desalinated seawater and are usually large. Desalination processes are often a good fit for cogeneration, as electricity generators and the distillation unit's brine heater are both operated with high-pressure steam. Using steam for these two processes significantly reduces fuel consumption compared to separate operations. This type of cogenerations is used in the Middle East and North Africa, where desalination is common.

Cogeneration is often considered, where the primary requirement is heat [89]. Industries with high heat demands, such as paper industries, often install turbines or boilers on site to supply needed heat, sometimes involving tens of megawatts of thermal energy. Smaller buildings and offices which need heat for space heating in winter and to run chillers or air coolers in summer can operate with onsite cogeneration, often at the kilowatt level. Then, heat is treated as the main product and electricity can be used on site or sold to the local electricity utility.

Cogeneration has been used for more than a century [74]. Even before establishment of an extensive electrical network in the early 20th century, numerous industries applied cogeneration. Thomas Edison designed and built the first cogeneration plant in New York in 1882 [24]. In Europe after the Second World War, the heat of power plants was often used in district heating systems or industrial applications with less than 5% of the total generating capacity from local distributed generation [41]. Primary energy carriers are used to generate the secondary carriers, electricity and thermal energy, in cogeneration.

Gustafsson et al. [33] suggest that fuel efficiency can be increased by utilizing a large temperature difference in a DE network, since more energy is transferred per unit volume of distributed circulation fluid.

Several studies suggest that CHP and waste incineration will have major roles as sources of energy in DE future systems [76,43,42].

3.1.3. Waste heat

Werner [85] states the main idea of DE is recycling the waste heat. The operation of DH systems using waste heat is an efficient way to address government policies aimed at reducing fossil fuel use for space heating and corresponding CO_2 emissions [2]. It is reported that some industrial plants, which produce sufficiently large amounts of heat, supply it to nearby towns [51]. In Sweden in 2000, for instance, 3.5 TWh of heating, or about 9% of the total national heating capacity, was contributed by industry. Also, the OMV refinery in Vienna, Austria supplies heat for 19,000 homes and 400 industrial buildings [51]. Regional governments and industries are collaborating on different projects to promote district energy systems. Aspects of the regional collaboration of an integrated chemical pulp and paper plant in Sweden have been discussed [53], while the nature of co-operation among participants has been described in two cities in Sweden, Borlange and Falun, by considering the impact of the pulp and paper industry on district heating projects to reduce electricity costs in Sweden [30]. A system for supplying pharmaceutical waste heat for a district heating system was designed in Delft, Netherlands, while the economic, institutional and environmental feasibility of supplying low-level heat was studied, based on modeling done with the ASPEN Plus simulation software [2].

3.2. Density classifications

District energy systems can be categorized based on application and market served, by considering usage density [50]:

- Densely populated urban areas: In densely populated areas, a district energy system can serve a large number of customers for multiple purposes. Such networks are complicated and require significant financial investments.

- High-density building clusters: High-rise residential buildings, institutional buildings, shopping malls or high density mixed suburban developments are in this category.
- Industrial complexes: Having some similarities to the high-density building clusters, the industrial complex thermal requirements (steam, hot water, both) determines the type of the thermal networks and economics.
- Low-density residential areas: The district energy system for this type of area typically serves an area dominated by single or double residential units. Usually, the central source has a capacity of less than 10 MW.

Reihav and Werner [65] and Nilsson et al. [57] state that development of DE systems in low heat density areas involves higher distribution costs. Reihav and Werner [65] indicate that when the local distribution system has low investment costs and marginal costs for heat production, DE systems in sparse areas are may be viable. They demonstrate that for profitable DH systems in sparse areas, the heat density must be greater than 2 GJ/m and use of DH should be more than 50 GJ/house annually. They also conclude that DE systems in sparse areas in Sweden are more profitable since there is a notable carbon dioxide taxes on fuel oil, natural gas and electricity. Therefore, one method to foster the development of DE systems in sparse areas is to invoke policies on fossil fuel taxation. Nilsson et al. [57] also have investigated methods of increase the viability of sparse DH systems in the future, in part by considering the productivity effect under co-operation of technology and customer reaction as well as full-scale operation trials of the new methods. Their study suggests reductions in the laying depth of DE piping as a technological improvement and investment cost reduction measure. Generally, the profitability of sparse DH systems can be improved more by more efficient construction methods as well as improved customer communication, rather than the use of more efficient DH technology [64].

4. Subsystems

A general district energy system consists of three main subsystems: source of thermal energy (for heating, cooling or both), thermal distribution, and end users (consumers). The components for a typical district heating system can be categorized as shown below [56]. Note that a similar subsystem breakdown was reported, with thermal energy transportation divided into main transformation and distribution network [51].

- Thermal energy production plant: This plant generates heat in the form of steam or hot water to satisfy customers' heating needs. Thermal energy can be obtained from heat plants or cogeneration plants. Heating plants usually involve the combustion of a variety of fuels such as natural gas, oil, wood waste and peat, or reused thermal energy [50]. Other sources of energy for producing heat are geothermal resources, solar heaters, and heat pumps [17,50]. Cogeneration plants convert fuel into electricity and useful thermal energy simultaneously. In cogeneration plants, waste heat is either supplied for industrial applications or used for heating buildings in the vicinity through a district energy system [17].
- Thermal energy transportation and distribution piping network: Heat from thermal plants is transferred to consumers through a heat carrying fluid in supply pipes and after delivering the energy, returns to the source through return pipes [17]. The heat loss in a piping network is a critical element in designing a district energy system. Heat losses, mixed with customer loads, verify the size of the heat source [8,9,10,6,17].
- Consumers: The district heating system is designed for the final users load situations. This load consists of single family houses, multi family houses, large buildings, commercial buildings, institutional buildings, industrial buildings, offices, and hospitals.

5. Environment

One significant reason to pursue district energy is its environmental benefits. GHG emissions can be reduced with district energy in two ways [74]: facilitating the use of non-carbon energy forms for heating and cooling, and replacing less efficient equipment in individual buildings with a more efficient central heating system. Increasing efficiency and utilizing sustainable energy resources are important measures for reducing the environmental impacts of using energy. District energy can contribute to reducing climate change and other energy-related environmental concerns like air pollution, stratospheric ozone depletion and acid precipitation. Nonetheless, there are some concerns regarding district energy, e.g., some concerns about air quality are associated with emissions when biomass and waste are used in district energy plants [87].

Genchi et al. [31] use CO_2 payback time (CPT) to evaluate the environmental impact of a DE in Tokyo. CO_2 payback time is a useful measure for evaluating and understanding the net CO_2 emissions, and is expressed as follows:

$$\mathrm{CPT} = \frac{\mathrm{CO_2\ emissions\ during\ the\ initial\ construction\ phase}}{\mathrm{Annual\ CO_2\ emissions\ reduction\ by\ the\ introduction\ of\ new\ systems}} \tag{1}$$

Since district energy is sometimes linked with cogeneration, it is noted that generating electricity in such a manner and replacing grid electricity can reduce emissions of GHGs and other pollutants if grid electricity is generated from fossil fuel resources. For example, when grid electricity is produced by coil-fired electricity, the GHG emissions per kilowatt of power generated is higher compared to that for many other electricity sources.

Curti et al. [16] performed extensive modeling and optimization work for a DH system based on localized and delocalized heat pumps, CHP and gas boilers, utilizing an environmental approach.

6. Economics

Economics is a major factor in decision making and design. In a study of four types of district energy systems, thermal networks were shown to be financially beneficial for densely populated urban areas, high-density building clusters and industrial complexes [50]. For low-density residential areas, the economic advantages are less clear [50]. Based on European experiences, using district energy for single family residences can sometimes be economic [50]. The economics of district energy depend on three main factors [51]:

- the production cost of the thermal energy,
- the cost of the thermal energy distribution network, which depends on network size and thermal loads, and
- customer connection costs.

The customer connection cost can be reduced if the district heating system is designed and developed at the same time as a community is built; this cost is higher when the project is retrofitted in a fully developed site. The economics have been examined for a small town (population 2500) in Canada, where excess steam produced by a Kraft pulp mill is used for space heating [51]. The study revealed that the low density of the small town in the vicinity of the pulp mill needed to develop its surface and space heating capacity. It was determined that the thermal network and required equipment are not economically feasible for such a small population. District energy is more economically attractive for high heat demand buildings like large public buildings, commercial buildings, and high-density residential zones. In this case, it was found that a partial thermal network including half the town, a nonprofit management organization for the management of the district operation, a government rebate program to assist the district energy customers and an appropriate profit balance (between mill and district energy entities) could make the design of such a district heating system economically feasible.

Environmental externalities should be taken into consideration in economic models [38]. A model was suggested which considers economic and environmental factors on performance of a DH system with various configurations [16]. Data collected from a 300 km Bresica district energy system in Italy were used to carry out an economic comparison with a comparable domestic gas boiler system [52]. The results reveal that the thermal network system recovers in a few years through energy savings the costs needed to build the equipment and parts for the installation of the thermal network, and also yields environmental benefits.

On the cost of delivering heat from the generation station to customers, factors such as plant efficiency, temperatures of supply and return fluids, and heat losses affect prices [90]. Methods for decreasing distribution network costs have been reported, such as the use of a network for air conditioning and dynamic energy storage jointly with demand-side management to cover peak demand periods [51]. The Jyvaskyla district heating system in Finland was tested for the possibility of eliminating the use of expensive fuels during the morning peak hours [88]. Higher electricity and/or lower investment costs have been shown to make cogeneration more beneficial for small district heating networks in Nordic countries, which have long winters [40]. Persson and Werner [62] have comprehensive studied heat delivery costs, explaining that heat distribution cost includes annual payback of original network investment cost plus operational costs to cover temperature and pressure losses during heat delivery. They find that DH is profitable when the total costs are lower than those for other means of local heat production, suggesting that, when the distribution cost is high, a lower cost of recycled heat can compensate for the total cost of the DH.

More broadly, Persson and Werner [62] divide the total costs to four categories:

- Heat delivery capital cost. This cost includes the network construction cost, which is often more than half of the total delivery cost.
- Heat delivery heat loss cost which, to some extent, is dependent on heat delivery capital cost since low heat densities have higher heat losses. This term also relates to the price of recycled heat in DH.
- Heat delivery pressure loss cost: The cost of the pressure loss during heat distribution needs to be recovered.
- Service and maintenance cost: This cost is typical of most systems.

The focus of much recent research has been on distribution costs, and the results of this research may impact the future of DE. According to Persson and Werner [62] the capital costs for DH heat delivery in dense areas like cities are low, and in such low density areas the local heat producer may operate a DH system. Persson and Werner claim, in examining possible future applications of DH and future competitors in the DH market, that the future architecture of cities should be carefully planned.

Reihav and Werner [65] apply evaluate the net present value (NPV) (currency/house) of an investment (I) in a DH delivery system as follows:

$$NPV = \left(PQ - \frac{C_{prod}}{(1-h)}Q - C_{serv\&maint}\right)NF - I$$

Here, P denotes unit price to the customer (currency/GJ), Q denotes the DH annual heat delivery to the consumer (GJ/house), C_{prod} is marginal heat production cost (currency/GJ), h denotes annual heat loss (GJ/year), $C_{serv\&maint}$ expresses annual service and maintenance costs (currency/house), and NF denotes the net present value factor, which is dependent on the interest rate and the period.

Zhai et al. [91] perform a cost analysis, as part of feasibility study of a solar DE system, using a life cycle approach in which they consider total cost to include construction costs (capital costs for equipment and insulation), operational costs (operation, fuel and maintenance), and demolition costs at the end of the DE system's life. Zhai et al. [91] calculate dynamic payback period (PP) of the investment utilizing the equation which was introduced by Kong et al. [44]:

$$PF = \frac{\ln\left[\left(1 - \frac{iC_{IC}}{C_{power}+C_{cool}+C_{heat}+C_{hotwater}-C_{fuel}-C_{OM}}\right)^{-1}\right]}{\ln(1+i)} \tag{2}$$

Here, i denotes interest rate, IC the initial capital (currency), C_{power} the cost of power (currency), C_{cool} he cost of cooling (currency), C_{heat} the cost of heating (currency), $C_{hotwater}$ the hotwater cost (currency), C_{fuel} the fuel cost (currency), and C_{OM} operation and management cost (currency).

6.1. Regulation

The market economics of district energy systems have been investigated. The energy markets are becoming less constrained, and district heating markets helped natural gas and electricity markets become more liberalized. This observation is attributable to the rules of the monopolized market of district heating distribution. A thermal network is used in local distribution systems, where customers are tied to one heating supplier, while natural gas and electricity markets are different. International transmission grids, which link producers and consumers, support natural gas and electricity markets. The lack of linkages between heating (and cooling) markets and distribution areas is similar to a natural monopoly, which is characterized through a set of heating customers supplied by a sole producer. This situation makes it difficult or perhaps impossible for the market to increase production efficiency due to market competition. Monopolies in district heating permit profits but at a cost to consumers, who have to be connected to the district heating system. Hence, it has been suggested that appropriate regulation of district energy systems is required.

Agrell and Bogetoft [1] state that the effect of government action (on such parameters as fuel choice, plant size and network configuration) is three times more important than managerial performance. With a certain fuel technology, plant size, and organized side tasks, the local plant manager has a limited authority regarding total variable cost. As the plant size is small on average and purchases are not organized, the plant operates as a price taker on the national fuel market. Replacing fuels for certain biofuel configurations is possible, although feasibility has been shown to be not possible for all fuels in the Danish market. The maintenance and administrative costs for the plant are also limited. Agrell and Bogetoft also state that the local government has a significant role in the economic feasibility of the district heating system to guarantee financing and the sustainability of the thermal network. Marinova et al. [51] also believe government regulations have a significant impact, even more than managerial performance, on district heating system advantages. Munksgaard et al. [54] state that supplying cost-of-service pricing helps eliminate the potential monopoly abuse of the district heating market.

As mentioned in Section 3, government regulations can have a significant impact on growth of DE systems, especially in sparse areas, where local heating is often more profitable. Taxation of fossil fuels makes DE more attractive financially. Sweden is an example of DE growth due to support via governmental regulations. Numerous studies have been reported of Swedish DE [62,3,33,86,18,57,65,25,34]. Other countries may customize Swedish guidelines for to promote their DE systems in the future.

7. Efficiency

Although efficiency is normally regarded as a technical term, the efficiency of a district energy system can be defined in terms of engineering or economics. Both efficiencies are important factors in designing a district energy system. The economic efficiency is explained in the next paragraph and exergy as an efficient method to estimate the engineering efficiency is clarified in Section 7.1.

Munksgaard et al. [54] evaluated databases used by Agrell and Bogetoft [1] to show the robustness of efficiencies and rank order of district heating plants based on the choice of model design. The rank order and the efficiency of each plant are highly dependent on the model originally used [54]. Organizers should be cautious with the choice of regulation model and the purpose for the regulation. The authors' analysis indicated that by considering a short run model, the regulation model will either improve technical efficiency or cost efficiency, but not both simultaneously. Moreover, a short term model concept to design the regulation system falls short of achieving long term efficiency goals, such as a lower level of CO_2, and opportunities for cogeneration of heat and electricity can be missed. Similarly, when a regulation system is based on a long term model, short term objectives are not considered and consequently financial difficulties for heating plants may not be taken into account. The selection of the proper scale of operation is important for the Data Envelopment Analysis (DEA) for district heating systems. The design of a rebate program based on DEA should contain reasonable goals.

7.1. Efficiency and exergy

Exergy analysis is a useful tool, which provides meaningful efficiencies for engineering systems and identifies the locations and causes of inefficiencies [66,69,70,21]. Exergy analysis also helps determine the appropriate energy management of an engineering system. Exergy was applied to assess and increase the efficiency for the proposed design for cogeneration-based district heating in Edmonton [19,20,67,71–75]. The authors concluded that, for a cogeneration-based district energy system that produces heating, cooling and electricity, exergy analysis provides important information about system performance and efficiency.

Zhai et al. [91] also perform an exergy analysis on a hybrid solar heating, cooling and power generation system. They customized the exergy equation for each point on the thermodynamic cycle of the DE plant, and calculate the exergy efficiency (ψ) of the DE based on the original definition of efficiency, as follows:

$$\psi = \frac{\dot{W}_E + \dot{E}x_{cool}}{\dot{E}x_s + \dot{E}x_G} \quad \text{(in summer)}$$

$$\psi = \frac{\dot{W}_E + \dot{E}x_{heat} + \dot{E}x_{hotwater}}{\dot{E}x_s + \dot{E}x_G} \quad \text{(in winter)}$$

Here, $\dot{W}_E$ denotes power rate (W), $\dot{E}x_{cool}$ exergy rate of cooling (W), $\dot{E}x_{heat}$ exergy rate of heating (W), $\dot{E}x_{hotwater}$ exergy rate of hot water (W), $\dot{E}x_s$ exergy rate of solar energy (W), and $\dot{E}x_G$ exergy rate of natural gas (W).

Gong et al. [32] optimize cooling and heating based on exergy analysis. They customize exergy balances for the heating and cooling and then use an optimization tool. Ozenger et al. [58] also applied exergy analysis on a geothermal DH system to show the impact of reference state on the performance of the DH system.

8. Advantages and disadvantages of district energy

District energy systems offer a variety of benefits for the local community and society in general and, more specifically, for building owners and tenants [50]. According to MacRae [50], some of the major issues of modern Canadian society, such as energy supply, fuel prices and air and water quality can be resolved by the development of district energy systems. Some benefits of the district energy system follow:

- For society: flexibility in choosing heat sources (permitting more cost effective operation), independence of a sole heat source, reduced fuel consumption, enhanced environmental quality, emissions reductions (due to higher efficiency and lower fuel consumption), and reduced CFC utilization via district cooling.
- For communities: enhanced community energy management and employment, increased opportunities to use local energy resources, greater ability for controlling environmental emissions, retention of energy capital in the local economy, and reduced fuel costs.
- For building owners and tenants: reduced heating costs, reduced operation cost and complexity, safer operation, reduced space requirements, improved comfort, and increased reliability.
- Some drawbacks exist for the district energy systems, including the following [50].
- Knowledge of know-how and technical skills for district energy system is limited.
- District energy demands a substantial front-end investment, often requiring extensive negotiations with investors for funding.
- Finding appropriate sites for district energy systems, so as to have the source of heat near users, can be challenging, especially in populated areas.

When fossil fuel taxation is not applicable, especially in sparse areas, DE systems may not be competitive with local heating systems financially. In such instance, DE systems require government support to be viable.

Another disadvantage of district energy is the potential monopoly provided to the owner of the thermal network, as a non-competitive market is usually not beneficial for consumers. Appropriate government regulations avoid this problem, as noted in earlier (Section 6.1).

9. Enhancement of district energy

District energy systems can assist in addressing energy requirements for heating and cooling and environmental concerns like GHG emissions. However, there are additional possibilities for the application of thermal networks, which are the subject of ongoing investigations by the authors. One possibility is to expand district energy to integrated thermal networks, in a manner analogous to how electricity networks are becoming more integrated. Such integration could allow multiple producers of thermal energy to supply the network, e.g., consumers who have heat generation capacity could sell excess heat via supplying it to the thermal grid. Suppliers of the heat could be industrial facilities with excess heat, cogeneration plants, governmental institutions, or possibly individual home owners. The idea of producing and selling thermal energy via a local thermal network management is similar to the idea producing and selling electricity. Such an approach is likely feasible thermodynamically, and the economic feasibility depends on many challenging factors, including governmental regulatory approval.

Allowing entities connected to a thermal network to generate thermal energy may facilitate greater use of renewable energy (e.g., solar thermal, geothermal, biomass), by providing a market for excess thermal energy. The types of renewable energy sources (biomass, solar, wind, and geothermal) that are relevant depends on the location, availability and application, but such factors may be addressed more readily using thermal networks. The authors are investigating the potential advantages of different forms of renewable energy in the context of integrated thermal networks, so that a comparison of the different sources of energy can be performed and the most advantageous options determined for thermal networks and applications. This information facilitates the work of system designers and helps investors in decision making.

10. Conclusions

District energy systems have been reviewed and potential enhancements and extensions discussed. District energy systems can be classified by circulating fluid, thermal application (heating or cooling or heating and cooling together), network size (populated areas, high-density building clusters, industrial complexes, low-density residential areas, etc.), and energy source. District energy systems are flexible in terms of the sources they can accommodate of heating and cooling media, and can thus contribute to reducing fossil fuel use. District energy is efficient and can be environmentally beneficial and cost effective in appropriate applications. District energy systems tend to be more economic for higher density and more populated regions, and governments can facilitate greater utilization of the technology through appropriate regulations and incentives. Despite the successes of district energy around the world, potential enhancements to attain greater benefits are possible. Potential future enhancements of the technology include expanding district energy systems to larger integrated thermal networks, which can facilitate better integration of energy systems, increased utilization of renewable energy sources and increased system efficiency. Research is being carried out by the authors into the potential for expanding district energy to integrated larger thermal networks.

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References

[1] Agrell PJ, Bogetoft P. Economic and environmental efficiency of district heating plants. Energy Policy 2005;33:1351–62.
[2] Ajah AN, Patil AC, Herder PM, Grievink J. Integrated conceptual design of a robust and reliable waste heating system. Appl Thermal Eng 2007;27:158–1164.
[3] Amiri S, Moshfegh B. Possibilities and consequences of deregulation of the European electricity market for connection of heat sparse area to district heating systems. Appl Energy 2010;87:2401–10.
[4] Arkay KE, Blais C. The district energy options in Canada. Ottawa: Natural Resources Canada; 1999.
[5] Arroyo V. Agenda for climate action. Arlington, VA: Pew Centre on Global Climate Change; 2006.
[6] ASHRAE. HVAC applications. American society of heating, refrigeration and air-conditioning engineers; 1999.
[7] Bloomquist RG. Geothermal space heating. Geothermal 2003;32(4-6):513–26.
[8] Bohm B. Simple methods for determining the heat loss from district heating pipes under normal operating conditions. Report, Laboratory of Heating and Air Conditioning, Technical University of Denmark; 1990.
[9] Bohm B. Determination of heat losses from district heating networks. Report 3.15 E. 25, UNICHAL Congress, Budapest; 1991.
[10] Bohm B, Borgestorm M. A comparison of different methods for in situ determination of heat losses from district heating pipes. Report, Technical University of Denmark; 1996.
[11] Bonilla JJ, Blanco JM, Lpezt L, Salat JM. Technological recovery potential of waste heat in the industry of the Basque Country. Appl Thermal Eng 1997;17:283–8.
[12] Boyce MP. Handbook for cogeneration and combined cycle power plants. New York: American Society of Mechanical Engineers; 2002. pp. 25 and 32.
[13] Canadian District Energy Association (CDEA). District energy: a national survey report. Report, Natural Resources Canada; 2009.
[14] Casten TR, Ayers RU. Recycling energy: growing income while mitigating climate change. Report, recycled energy development, Westmont, IL. <http://www.recycled-energy.com/_documents/articles/tc_energy_climate_change.doc>; October 18, 2005 [accessed 27.01.10].
[15] Chinese D, Meneghetti A, Nardin G. Waste-to-energy based greenhouse heating: exploring viability conditions through optimization models. Renew Energy 2005;30:573–1586.
[16] Curti V, Von Spakovsky MR, Favrat D. An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I: methodology. Int J Thermal Sci 2000;39:48–53.
[17] Diamant RME, Kut D. District heating and cooling for energy conservation. New York: Wiley; 1981.
[18] Difs K, Danestig M, Trygg L. Increased use of district heating in industrial processes: impact on heat load duration. Appl Energy 2009;86:2327–34.
[19] Dincer I. The role of exergy in energy policy making. Energy policy 2002;30:137–49.
[20] Dincer I, Hussain MM, Al-Zaharnah I. Energy and exergy use in industrial sector of Saudi Arabia. IMech E – Part A: J Power Energy 2003;217:481–92.
[21] Dincer I, Rosen MA. Exergy: energy, environment and sustainable development. Oxford, UK: Elsevier; 2007.
[22] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending. Directive 92/42/EEC.
[23] DOE. Combined Heat and Power: a federal manager's resources guide. Final report, US Department of Energy Federal Management Program, Washington, DC; 2000.
[24] DOE. Cogeneration or combined heat and power, office of energy efficiency and renewable energy. US Department of Energy, Washington, DC; 2003.
[25] Erikson M, Vamling L. Future use of heat pumps in Swedish district heating systems: short- and long-term impact of policy instrument and planned investments. Appl Energy 2007;84:1240–57.
[26] Erikson O, Finnveden G, Ekvall T, Bjorklund A. Life cycle assessment of fuels for district heating: a comparison of waste incineration, biomass – and natural gas combustion. Energy Policy 2007;35:1346–62.
[27] Faninger G. Combined solar biomass district heating in Austria. Solar Energy 2000;69:425–35.
[28] Fumo N, Charma LM. Analysis of combined cooling, heating, and power systems based on source primary energy consumption. Appl Energy 2010;86:2023–30.
[29] Fumo N, Mago PJ, Charma LM. Emission operational strategy for combined cooling, heating, and power systems. Appl Energy 2009;86:2344–50.
[30] Gebremedhin A. The role of a paper mill in a merged district heating system. Appl Thermal Eng 2003;23:769–78.
[31] Genchi Y, Kikegawa Y, Inaba A. CO_2 payback-time assessment of a regional-scale heating and cooling system using a ground source heat-pump in a high energy-consumption area in Tokyo. Appl Energy 2002;71:147–60.
[32] Gong G, Zeng W, Chang S, He J, Li K. Scheme-selection optimization of cooling and heating sources based on exergy analysis. Appl Thermal Eng 2007;27:942–50.
[33] Gustafsson J, Delsing J, Deventer J. Improved district heating substation efficiency with a new control strategy. Appl Energy 2010;87:1996–2004.
[34] Gustafsson L, Karlsson A. Heating detached house in urban areas. Energy 2003;28(8):851–75.
[35] Heller A. Solar energy – a realistic option for district heating. Euroheat Power 2001;30(1–2):46–8.
[36] Hepbasli A, Canakci C. Geothermal district heating applications in Turkey: a case study of Izmir–Balcova. Energy Convers Manage 2003;44(8):1285–301.
[37] Hinrichs RA, Kleinbach M. Energy, its use and the environment. Brook Cole; 2002. pp. 377–8.
[38] Holmgren H, Amiri S. Internalizing external costs of electricity and heat production in a municipal energy system. Energy Policy 2007;35:5241–53.
[39] Holmgren K. Role of a district-heating network as a user of waste-heat supply from various sources – the case of Goteborg. Appl Energy 2006;83:1351–67.
[40] Keppo I, Savola T. Economic appraisal of small bio fuel fired CHP plants. Energy Manage 2007;48:1212–21.

[41] Klimstra J. Five years of operational experience – the Gyorho cogeneration plant. Wartsila Tech J 2008;00:4–8.
[42] Knutsson D. Simulating conditions for combined heat and power in the Swedish district heating sector. Report for Department of Energy and Environment, Chalmers University of Technology, Goteborg, Sweden; 2005.
[43] Knutsson D, Sahlin J, Werner S, Ekvall T, Aklgren EO. HEATSPOT: a simulation tool for national district heating analyses. Energy 2006;31:278–93.
[44] Kong XQ, Wang RZ, Hauang XH. Energy efficiency and economic feasibility of CCHP driven by stirling engine. Energy Convers Manage 2004;45:1433–42.
[45] Lemale J, Jaudin F. La geothermie, une energie d'avenir, une realite en Ile de France [Geothermal heating, an energy of the future, a reality in Ile-de-France], IAURIF, Paris; 1999.
[46] Lottner V, Schulz ME, Hahne E. Solar assisted district heating plants: status of the German programme solarthermie-2000. Solar Energy 2000;69:449–59.
[47] Lund H, Moller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;32:1381–90.
[48] Lund JW. Geothermal taping focus: tapping the earth's natural heat. Refocus 2006;7:48–51.
[49] Lunghi P, Burzacce R. Energy recovery from industrial waste of a confectionery plant by means of BIGFC plant. Energy 2004;29:260–1.
[50] MacRae M. Realizing the benefits of community integrated energy system. Canadian Energy Research Institute; June 1992. pp. 41–3, 70–1, and 73–8.
[51] Marinova M, Beaudry C, Taoussi A, Trepanier M, Paris J. Economic assessment of rural district heating by bio-steam supplied by a paper mill in Canada. Bull Sci, Technol Soc 2008;28(2):159–73.
[52] Marletta L, Sicurella F. Environmental and energy costs of district heating network. In: Brebbia CA, Zannetti P, editors. Development and application of computer techniques to environmental studies. United Kingdom: WIT Press; 2002. p. 35–44.
[53] Moshfegh B, Klugman S, Karlsson M. An integrated chemical pulp and paper mill: energy audit and perspectives on regional cooperation. In: Proceedings of ECOS 2006: 19th international conference on efficiency, cost, optimization, simulation and environmental impact of energy system, Athens, Greece; 2006. pp. 637–44.
[54] Munksgaard J, Pade LL, Fristrup P. Efficiency gains in Danish district heating. Is there anything to learn from benchmarking? Energy Policy 2005;33:1986–97.
[55] Natural Resources Canada. Energy use data handbook, 1990 and 1998 to 2004 – Comprehensive energy use database. Report, Ottawa; 2005.
[56] Nijjar SJ, Fung AS, Hughes L, Taherian H. District heating system design for rural Nova Scotia communities using building simulation and energy usage databases. Trans Can Soc Mech Eng 2009;33(1):51–64.
[57] Nilsson SF, Reihav C, Lygnerud K, Werner S. Sparse district-heating in Sweden. Appl Energy 2008;85:555–64.
[58] Ozenger L, Hepbasli A, Dincer I. Effect of reference sate on the performance of energy and exergy evaluation of geothermal district heating systems: Balcova example. Build Environ 2006;41:699–709.
[59] Ozenger L, Hepbasli A, Dincer I. Energy and Exergy analysis of geothermal district heating system: an application. Build Environ 2005;40(10):1309–22.
[60] Patil A, Ajah A, Herder P. Recycling industrial waste heat for sustainable district heating: a multi-actor perspective. Int J Environ Technol Manage 2009;10(3/4):412–26.
[61] Pavlas M, Stehlik P, Oral J, Sikula J. Integrating renewable sources of energy into an existing combined heat and power system. Energy 2006;31:2499–511.
[62] Persson W, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76.
[63] Philibert C. The present and future use of solar thermal energy as a primary source of energy. Paris: International Energy Agency; 2005.
[64] Pohl H, Klingmann M. Sparse district-heating overview 3: technology choices. Varmegles 2006, paper 24c. Stockholm, Sweden; 2006 [in Swedish].
[65] Reihav C, Werner S. Profitability of sparse district heating. Appl Energy 2008;85:867–77.
[66] Rosen MA, Dincer I. On exergy and environmental impact. Int J Energy Res 1997;21:643–54.
[67] Rosen MA. Second law analysis: approaches and implications. Int J Energy Res 1999;23:415–29.
[68] Rosen MA. Combating global warming via non-fossil fuel energy options. Int J Global Warming 2009;1:2–28.
[69] Rosen MA, Dincer I. Exergy analysis of waste emissions. Int J Energy Res 1999;13:1153–63.
[70] Rosen MA, Dincer I. The intimate connection between exergy and the environment. In: Bejan A, Mamut E, editors. Thermodynamic optimization of complex energy systems. The Netherlands: Kluwer Academic; 1999. p. 221–30.
[71] Rosen MA, Dincer I. Thermodynamic analysis of power plants: an application to a coal fired electrical generating station. IMechE – Part A: J Power Energy 2003;217:2743–61.
[72] Rosen MA, Le MN. Efficiency measures for process integrating combined heat and power and district cooling. In: Thermodynamics and the design, analysis and improvement of energy systems, vol. AES 35. New York: ASME; 1995. pp. 423–34.
[73] Rosen MA, Le MN. Thermodynamic assessment of the components comprising an integrated system for cogeneration and district heating and cooling. In: Proc ASME Adv Energy Syst Div, vol. AES 38. New York: ASME; 1998. p. 3–11.
[74] Rosen MA, Le MN, Dincer I. Efficiency analysis of a cogeneration and district energy system. Appl Thermal Eng 2005;25:147–59.
[75] Rosen MA, Leong WH, Le MN. Modeling and analysis of building systems that integrate cogeneration and district heating and cooling. In: Proceedings of Canadian conference on building energy simulation; 13–14 June, 2001. p. 187–94.
[76] Sahlin J, Knutsson D, Ekvall T. Effects of planned expansion of waste incineration in the Swedish district heating systems. Resour Conser Recyc 2004;41:279–92.
[77] Sjostrom M. Biofuels and market power – the case of Swedish district heating plants. Report, Department of Economics, Umea University, Umea, Sweden; 2004.
[78] Sotoudeh M. Participatory methods: a tool for improvement of innovative environmental technology. Int J Environ Technol Manage 2003;3:336–48.
[79] Summerton J. District heating comes to town: the social shaping of an energy system. Linkoping Stud Art Sci 1992;80:220–319.
[80] TEAM, 2001. District heating and cooling to save energy. section in "Innovation for sustainability: TEAM progress report on climate change solutions 1998–2001", Technology early action measurement (TEAM), report <www.team.gc.ca/english/publications/team_199801/nation.asp#districts>; 2001.
[81] Trygg L, Gebremedhin A, Karlsson BG. Resource-effective systems achieved through changes in energy supply and industrial use: the Volvo–Skovde case. Appl Energy 2006;83:801–18.
[82] Vallios I, Tsoutsos T, Papadakis G. Design of biomass district heating systems. Biomass Bioenergy 2009;33:659–78.
[83] Vancouver 2010 Organization Committee. "Sustainabilty/Take the Heat", report. <www.vancouver2010.com/more-2010-information/sustainability/sustainability-stories/taking-the-heat_120764jl.html>; [Retrieved 28.01.10].
[84] Veolia Energy. Montpellier district energy CHP. Scoping report, modified. <www.montpelier-vt.org/upload/groups/327/files/montpelier_district_energy_chp_scoping_report2.pdf.>; 1 December, 2009 [accessed 28.01.10].
[85] Werner S. District heating and cooling. Encyclo Energy 2004;1:841–8.
[86] Wetterlund E, Soderstrom M. Biomass gasification in direct heating systems: the effect of economic energy policy. Appl Energy 2010;87:2914–22.
[87] Wierzbicka A, Lillieblad L, Pagels J, Strand M, Gudmondsson A, Gharibi A. Particle emissions from district heating units operating on three commonly used biofuels. Atmos Environ 2005;39:139–50.
[88] Wigbels M, Bohm B, Sipila K. Dynamic heat storage and demand side management strategies. Euroheat Power – Engl Ed 2005;11:58–61.
[89] Wood J. Local energy: distributed generation of heat and power. London, United Kingdom: The Institute of Engineering and Technology; 2008. p. 32.
[90] Zebik A, Sitku G. Heat exchanger connection in substations – a tool of decreasing return temperature in district heating networks. Energy Eng 2001;98:20–31.
[91] Zhai H, Dai YJ, Wu JY, Wang RZ. Energy and exergy analyses on a novel hybrid solar heating, cooling, and power generation system for remote areas. Appl Energy 2009;86:1395–404.
[92] Zinco H, Bjarklev J, Bjurstrom H, Borgstrom M, Bohm B, Koskelainen L, et al. Quantitative heat loss determination by means of infrared thermography – the tx model. Report, IEA district heating – annex 4 – network supervision, international energy agency. <www.iea-dhc.org/reports/final/AIV4.pdf>; June 1996.