Chapter

Review on District Cooling and Its Application in Energy Systems

Sana Sayadi, Jan Akander, Abolfazl Hayati and Mathias Cehlin

Abstract

This chapter investigates the implementation of district cooling systems by exploring several research studies reported in the literature. The topics addressed include typologies and design parameters, benefits and limitations, applications of the system, and the technology readiness level. District cooling systems are generally regarded as cost-efficient and environmentally friendly solutions. One might think that district cooling is only a solution for areas with a very warm climate. However, based on the reported results of the surveyed studies, the number of operating district cooling systems has increased over the years, with the Scandinavian countries taking the lead in this market within European countries. Implementation of these systems concluded reduction in primary energy and electricity use, they also proved to be an environmentally efficient way.

Keywords: district heating and cooling system, district cooling, free cooling, energy systems, energy efficiency

1. Introduction

With the increase in population and urbanization, energy use also has grown rapidly worldwide. Energy use in the building sector (commercial and residential buildings) has increased between 20 and 40% in developed countries [1]. Several researchers have worked on moderating the use of fossil fuels by introducing alternative energy sources such as industrial waste heat, biogas and biomass, nuclear energy, geothermal and solar energy, groundwater [2–5]. The European Union is responsible for 33% of the total CO_2 emission [2]. Based on the European Green Deal, the European Commission has provided an action plan to ensure energy transition as the EU aims to become the first climate-neutral continent by 2050 [6]. To oblige with these implications, energy-saving technologies have to be integrated into different energy sectors, especially the building sector since the energy demand is 36% of the global final energy use [7]. Studies have been conducted to analyze the increased use of biomass to reduce CO_2 emission in different sectors such as transportation and building sectors [8, 9]. One way of reducing the amount of resource use is to connect several customers' heat and cold demands with the available sources [10]. District energy systems are said to promise energy security as they offer flexibility in their energy use compared to individual energy systems [11]. The heating or cooling resources can be from renewable sources of energy as well as non-renewable sources.

The cooling energy demand for buildings varies depending on countries and their outdoor temperatures. Buildings have various cooling demands due to the differences in the construction material, size, occupant behavior, the purpose of the building, etc. However, it should be pointed that even identical buildings have different cooling demands depending on the kind of activities within the building. Due to the recent changes in climate and its implications on the energy performance of the buildings and indoor thermal conditions, different space cooling technologies have gained more attention. It is likely to predict the growth of cooling demand in Europe due to rising ambient temperatures (including heat waves), heat island effects, higher thermal insulation levels, increased comfort desires/requirements, and the fact that saturation of cooling demand is significantly lower than in the USA and Asia. Estimated cooling saturation for commercial and residential buildings in the USA was 80 and 65%, respectively, and Japan had 100 and 85%, respectively, in the year 2005. Corresponding cooling saturation numbers for Europe were 27 and 5%, respectively [12]. The cooling saturation for EU27 has passed 40% for the service sector and is around 7% for residential buildings [12]. It has been estimated that 10% of all building areas in EU28 were cooled and covered around 16% of the total cooling demand in the year 2014 [13]. In Europe district cooling was introduced in the 1990s; however, it is still a rather uncommon cooling solution with a market share of only around 1% of the cooling market in 2014 [12].

The desired indoor conditions can be met using individual cooling devices such as air conditioners, central air conditioning systems, or district cooling system (DCS). The district cooling system supplies chilled water for cooling and dehumidification to a group of buildings in a district (city, neighborhood, or campus). The coolant (usually water) is typically generated at a central chiller plant and circulates through a distribution network between a central cooling plant and the buildings in the district [14, 15]. **Figure 1** depicts a DCS using a natural source such as a lake/sea to cool the buildings. It is generally referred to as free cooling.

Water in the district cooling network gets cold from nearby natural cold sources, such as a river/sea, and if needed from the cooling machines, that is, when the temperature of the cold source (the river) is high. The combination of free-cooling and cooling machines demands less electricity compared to separate heat pumps or cooling machine installations in every building.

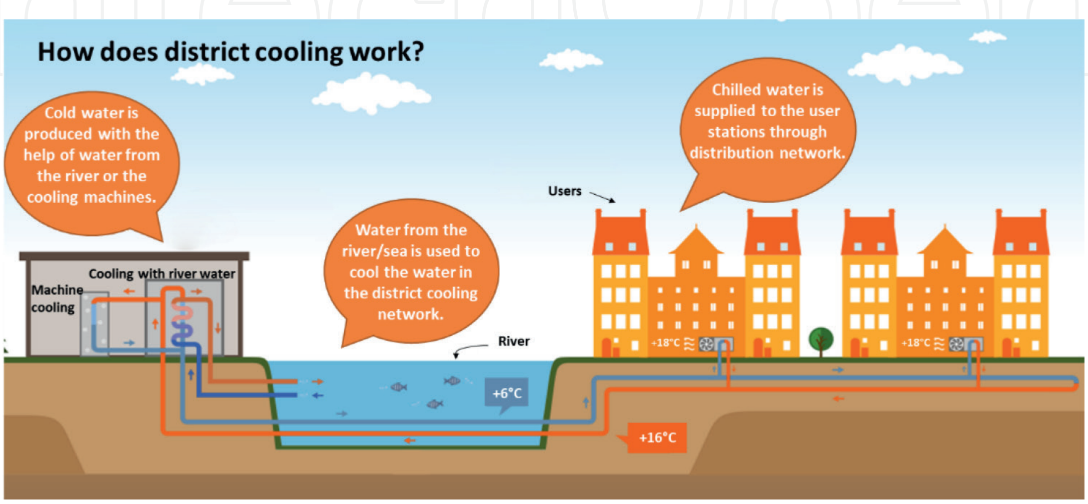

Figure 1.
Schematic of a district cooling system (DCS). Reprint with permission from Gävle Energi AB [16].

Water from the river/sea is used to cool the water in the district cooling network. When the district cooling water is cooled to 6°C, it is pumped to the connected building/consumers through the distribution network that comprises supply and return pipe. The cold and heat carriers in the district network are generally in the form of pressurized water and to be economical, the dense urban areas appear to be a fulfilling choice as the distribution pipes should be short [10].

Cold is delivered to the consumers (offices, buildings, industries, server halls, etc.) through the district cooling network with the help of the heat exchangers at user buildings [17]. Cold can be delivered to the cooling coils (to cool the supply air in the air handling units) or via chilled beams installed in the building zones.

Overall, as seen in **Figure 1**, four major parts could be introduced in a district heating or cooling system: the main supply unit, distribution networks, user stations, and finally the heating or cooling system inside the building's zones. Cold can be supplied for industrial purposes too, such as food preparation, although it is beyond the scope of this chapter.

It is possible to incorporate either a single or multiple cooling technologies in the DCS central chiller plant depending on the available energy sources (thermal or electrical), environmental and economic considerations as well as the demand profile. Absorption chillers are among the available options for chiller plants. Absorption chillers use heat and not electricity as their primary source of energy [18]. They possess a lower COP (coefficient of performance); however, the electricity consumption and primary energy use are reduced in these chillers and the mechanical compressor of a compression chiller is substituted by a thermal compressor [19]. Renewable thermal energy such as biomass waste or solar energy could be utilized using heat-driven chillers or thermal power plants. In such plants, the heat could be transferred to electrical or mechanical energy to drive the vapor compression chillers. The triple-effect lithium bromide absorption chillers could be exploited for DCS as they could be driven by higher-grade sustainable heat sources [20].

Free cooling is another option for a central plant. The available natural cold sources are involved in cooling the building; the heat will naturally flow out without the need of the compressor and the vapor-compression refrigeration system [15, 21–23]. Rivers, lakes, the sea, and outdoor air are among the natural cold sources. By using seawater air conditioning, deepwater conditioning could be employed as in this situation, and the water temperature is well below the ambient temperature (generally around 5°C). For such DCS, it is possible to utilize 100% free cooling. However, given the lack of natural cold sources, free cooling could be combined with other cooling technologies such as absorption chillers to compensate for the lack of available cold from the lake/sea, especially on a seasonal basis. An approach to using naturally cold water is cold district heating and cooling [24]. In this context, the cold water from the lake, sea, etc., is used for direct or active cooling in the system and serves as the cooling fluid. With the help of the decentralized chillers or pumps, the water is chilled or heated for the district system. A research project introduced seawater district cooling and analyzed the system through a case study in Diego Garcia [25]. It was concluded that the system was economically efficient and reduced maintenance and electricity usage.

This book chapter aims to investigate the implementation of district cooling systems by exploring research studies reported in the literature. The topics addressed include typologies and design parameters, benefits and limitations, applications of the system, and the technology readiness level.

2. Review method

To provide an overview of the available district cooling systems and their performance for different applications in various climate conditions, a literature review was performed.

Different databases have been used to identify available books and academic literature, including ScienceDirect, Google Scholar, and Scopus.

Keywords such as district energy, district cooling system, free cooling, absorption chillers, the resilient building were used. No limitation was applied on the publication period, though recently published works were prioritized.

3. Typologies (classifications) and design parameters

In this section, three different classification groups are proposed. The primary proposed classification is based on the system: Centralized and decentralized DCS. The former category is suitable for large-scale regions where the energy is distributed among several buildings in an area. The latter category is more suitable for small capacities where the energy conversion takes place in the units outside the buildings and then is transferred to the buildings [2, 26–28].

The second proposed category is based on the central plant: free cooling systems or the use of heat pumps and chillers [29–31].

The third category is based on the occupant behavior as well as the building typology, which is design parameters that can affect the energy use in the buildings. Occupant behavior mainly consists of interactions with operable windows, lighting, blinds, thermostats, and plug-in appliances. Building types are such as villa, retail, public office.

4. Benefits and limitations

Literature covers the benefits and limitations (disadvantages) of DCS. These benefits and limitations are categorized from three perspectives; environmental, operational, and economical.

Environmental advantages:

- District heating and cooling (DHC) possesses the ability to be integrated with renewable resources, consequently reducing greenhouse gas (GHG) emissions, and saves energy. The central water-cooled chiller plants on the large scale use a lower amount of energy and appear more efficient compared to the on-site small capacity systems [20, 32–34]. Therefore, DCS appears more successful in dense areas in a city or municipality since nearby these areas, there are generally some natural cooling or waste energy sources available [35]. However, these two criteria can be found in many areas and cities.

- A DHC system aims at saving primary energy, electricity, space, inhibiting air pollution, and reducing environmentally harmful refrigerants [36].

- A DHC system aims at saving energy and space, and inhibiting air pollution, and helps to eliminate environmentally harmful refrigerants [36, 37].

- District cooling can greatly reduce the electricity use and peak power demand, and thus reduce energy use, during the cooling season [35].

Environmental disadvantages:

- Depending on the central plants, DCSs may not totally be environmentally friendly as long-term use of the free cooling sources such as sea or lake might affect the temperature of the sources and limit the cooling capacity if no anticipating measures are considered. It also could affect the ecosystem of the sources [38].

- A free cooling system uses a vast amount of water, which is a problem in areas lacking water [30].

Operational advantages:

- Prevention of intensive use of chillers and machinery space in the user stations [39].

- Noise and structure load reduction [39].

- Saves space by removing the cooling tower and chiller plant from the buildings or roofs [39].

- A wide range of production methods and always the latest type of equipment are integrated with DCS due to mitigation measures against global warming [30, 40].

- District cooling has less requirement for technical staff on building level [34].

Operational disadvantages:

- Heat loss within the plant itself as well as the building serviced by the DHC due to distribution losses in pipes and heat exchangers is inevitable [41, 42].

Economic advantages:

- The transparency of costs and future proof investment due to easy payment of utility bills [30].

- The DCS is relatively flexible as different central plants could be utilized based on the fuel cost, therefore reducing the cooling cost [20, 35, 43].

- Owned by the municipality, a district cooling system can capture cash flows that were previously paid for imported natural gas or electricity [35].

- DCS can provide more job opportunities as it provides more reliable and flexible services by a specialized professional team [39].

Economic disadvantages:

- Selection of a system that shows large environmental benefits may, in fact, end up not being economical as both the environmental and economic aspects have to be considered together [32].

- In purpose to utilize cogeneration of district system and electricity, larger DHC is required [44].

- High initial investment costs and lack of negotiable prices and tariffs from the customer's side as DCS are often owned by few local energy companies, and there is a risk of monopoly for the cooling prices and tariffs [10].

5. Application, technology readiness level, and performance with a focus on resilience

In this section, DC cooling technologies, energy sources, operational aspects, and the applications of DC systems are reviewed based on implemented DC technologies through published DC design and analysis research. Before heading to the applications of the DC systems, the concept of resilience is introduced.

The resilience of the building is its ability to withstand extreme weather conditions and recover from the possible incurred damages efficiently and quickly [45]. Chen et al. [46] investigated the resilient cooling strategies and Hay [47] investigated resilience as a developing planning tool for communities. District energy was recommended as the technology that can balance the relationship between the communities and the region [47]. Sharifi et al. advocated for developing district energy systems, net-zero buildings, and neighborhoods as criteria for assessing urban energy resilience [48].

Based on a report from International District Energy Association (IDEA) [49], in 2019, 303 buildings and Ca 10.8 million ft^2 were added to the district systems, beyond North America, which is a strong growth in the district systems employment. The number of buildings and the area that was used for the system in 2018 correspond to 156 buildings and Ca 50 million ft^2. Based on the statistics in [50], 70% of residential end users in high-population areas in Europe were powered by fossil fuel in 2015. Hence, DHC networks show great potentials that can help in decarbonization and improvement of indoor air quality as these systems help to reduce the primary energy use by utilizing renewable sources of energy and reducing the thermal losses [51].

A few studies are introduced to show the performance of DCS through simulation and real data collection in different climate conditions and their effects on building's cooling loads. The studies that were dedicated to Asian countries are presented to show the diversity of DHC systems as Asian countries are developing more DHC systems to reduce air pollution, primary energy use, etc. Later in this section, research projects dedicated to DHS in Europe are introduced.

A study was conducted on the performance of DCS vs. individual cooling systems (ICS) in Hong Kong considering different chilled water pump schemes [52, 53] for commercial buildings. Based on the simulation results, DCS consumes around 15% less energy compared to ICS. The annual operation cost of DCS also is 10% lower than ICS under the electrical tariffs of Hong Kong.

Energy modeling of DCS was conducted in [14] in the South East Kowloon Development Project in Hong Kong for residential and commercial buildings. Based on the simulation results, chilled water, eutectic salt, and ice storage could respectively result in a 38, 38, and 22% reduction in installed cooling capacity. An et al. [54], Yan et al. [55], and Nagota et al. [56] analyzed the performance of DCS in districts in China and Japan and concluded the energy-saving effect of DCS. Studies were conducted with absorption chillers as the cooling technology in other parts of Asia such as Thailand [57], Turkey [58], Iran [59] and concluded the energy and carbon emission-saving effect of DCS. As it could be seen from the mentioned studies so far, the positive economic implication of the DHC system is generally observed from the conducted studies.

The Scandinavian market is taking the lead with 49 operating DCS, followed by Germany (28 operating DCS) and Italy (14 operating DCS) [30].

A detailed study on the market of DCS in Sweden is done by [60]. Major district cooling systems appear in Stockholm, Gothenburg, Linköping, Solna-Sundbyberg, Lund, and Uppsala. Based on the statistics reported by Energiförtagen [61], deliveries for 2018 totaled 1156 GWh. It was a record year for Swedish district cooling and an increase of 26 percent compared to 2017, due to an exceptionally hot summer. The total length of district cooling pipelines increased to 627 km, while in 2019, deliveries totaled 991GWh. **Figure 2** shows deliveries and network length from 1996 to 2019 [61].

From **Figure 2**, and the economic and environmental benefits provided through the expansion of DC capacity, a continued growth in DCS is expected.

Fahlén et al. [62] presented a study based on the DHC system of Gothenburg. Combined heat and power (CHP) plants and excess heat from industries supply about 80% of the heat. The study assesses the potential of absorption cooling technology

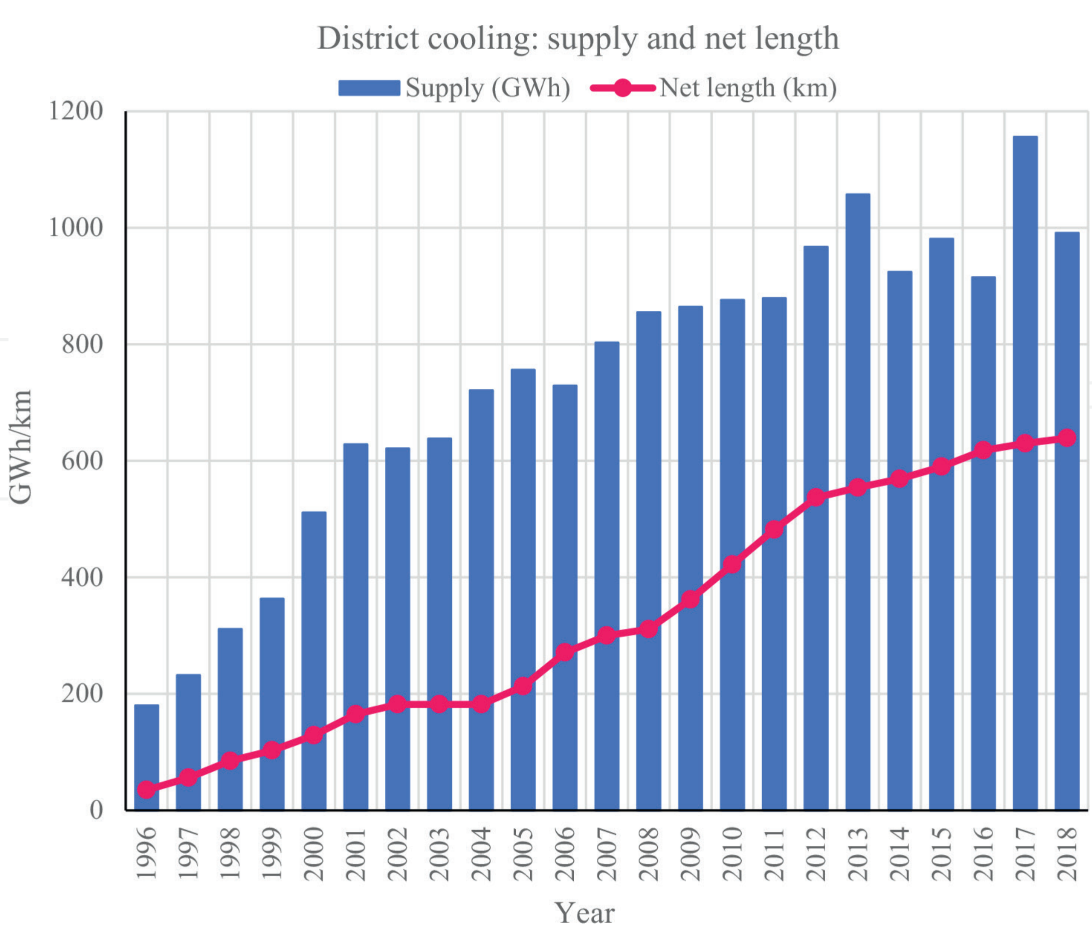

Figure 2.
District cooling deliveries (GWh) and network length (km) in Sweden [61].

to improve the economic and environmental performance of the DHC system. The results show potentials for cost-effective CO_2 emission reduction.

The use of absorption chillers in a DCS in Sweden was studied in [63, 64] and the energy performance of the system appeared to improve. A DCS was initiated in 1995, in the city center in Södermalm, Stockholm. Later, it was expanded and another area was added to the system. Both the districts are connected by pipes located in lake Mälaren [65]. In the Södermalm DCS, existing heat pumps in Hammarbyverket were used.

DCS design has evolved over the years from for example constant to variable flow in the distribution loop. These evolutions and updates in design practices have continuously been upgraded and employed in the system. A long-term security of supply is a driving factor in the heating/cooling systems especially in DHC since the heat/cold is generally supplied by local units. Therefore, it is important to upgrade the design in such a way as to achieve this aim. To be able to express a general reliability level, a definition has been anticipated as the system reliability rate for a DH system [10]. The rate is regarded as the ratio between the numbers of supplied available district heating to the customers during a year by total hours in a year [10]. Many factors are responsible for low system reliability rates such as the fuel supply, pipe failures in the distribution networks, water leakages caused by corrosion or pressure surges, and power outages. The latter mentioned factor also influences the short-term reliability of the system. All the mentioned incidents affect the resilience of the system. To compensate for the power outage, a backup electricity generation is generally anticipated for the main distribution pump. To measure the technology readiness level also, the U.S. Department of Energy has introduced a method to calculate the readiness level [66].

Another problem associated with DHC systems that affect the resilience of the system is the high delta-T syndrome. Due to several reasons, degradations occur over time, which deteriorates the standard temperature difference between the supply and return water that in turn affects the performance of the system. A research project was conducted on the low delta-T problem of the DCS in Gothenburg, Sweden [67]. The problem was analyzed by collecting operational data from the Gothenburg district cooling system along with chilled water systems from 37 of the connected buildings. The results depicted several solutions in the district cooling system to overcome a low delta-T and increase the return temperature. For instance, it was recommended to comply with the building design guidelines as well as limit the flow on the primary side of the heat exchanger, and this helps to restrict the operation in the saturation zone of the heat exchanger. A similar study was carried out by Henze et al. [68] on two university campuses in Massachusetts and Colorado and proposed a solution that provided additional cooling load to the campuses with the same central plant system. The mentioned issues raise the importance of maintenance of the system since the system has to be able to retain its ability to withstand future shocks such as those mentioned above, as well to extend its technical lifetime to remain resilient.

6. Energy efficiency and life cycle analysis

To quantify the energy efficiency of the DCS, three energy efficiency factors were proposed [55]. These factors are presented using Eqs. (1)-(3) and each is explained in this section.

"Coefficient of performance" of the chiller plant is represented by COP_{Plant} (Eq. (1)) where Q is the total cooling supply of the chiller plant. W_{plant} is the energy use of the DCS plant.

$$COP_{\text{plant}} = \frac{Q}{W_{\text{plant}}} \tag{1}$$

WTF_{distri} represents the "water transport factor" of the cooling distribution network system (Eq. (2)) where W_{distri} is the energy use of the cooling distribution system which is the total energy use of all secondary water pumps for chilled water.

$$WTF_{\text{distri}} = \frac{Q}{W_{\text{distri}}} \tag{2}$$

SCOP represents the "system coefficient of performance," which is the overall energy efficiency of the chiller plant and the distribution system (Eq. (3)). Based on the previous studies, 80% of the energy consumed by the chilled water pumps leads to cooling loss, which is due to the chilled water distribution; therefore, it must be accounted for in the calculation process.

$$SCOP = \frac{\left(Q - 0.8WTF_{\text{distri}}\right)}{W_{\text{plant}} + W_{\text{distri}}} \tag{3}$$

Keeping the efficiency of the system aside, the feasibility of a DHC system could be investigated by taking into account the cost analysis. To provide an effective evaluation of the energy system and the cost-effective alternatives, life cycle cost analysis (LCCA) could be considered. The energy performance and cost analysis of DCS have been evaluated in several studies [69–71].

LCCA takes into account the costs involving the construction, operation, and demolition phases [72]. The life cycle cost (LCC) is as below [71]:

$$LCC = C_{IC} + \sum_{1}^{n} PWF(i,n) \times \left(C_{\text{fuel}} + C_{OM}\right) - PWF(i,n) \times C_{\text{Dispose}} \tag{4}$$

$$PWF(i,n) = (1+i)^{-n} \tag{5}$$

where $PWF(i,n)$ is present worth factor; C_{IC} is initial capital cost; C_{fuel} is natural gas cost; C_{OM} is operational and management cost; C_{Dispose} is abandoned equipment cost; n is life cycle period and i is interest rate.

The dynamic payback period (PP) of investment, considering the time value of the capital, is calculated using Eq. (6):

$$PP = \frac{\ln\left[\left(1 - \frac{i \times C_{IC}}{C_{\text{power}} + C_{\text{cool}} + C_{\text{heat}} + C_{\text{hotwater}} - C_{\text{fuel}} - C_{OM}}\right)^{-1}\right]}{\ln(1+i)} \tag{6}$$

where C represents cost and the subscripts represent the respective parameters.

7. Conclusions

With the increase in energy demand, especially cooling energy due to climate changes and the rise in comfort requirements in buildings, meeting the future energy demand has gained more attention. Resilient, economic, and environmentally friendly solutions are required to meet the future energy demand. To fulfill the growing cooling demand and the community's growing concern about carbon footprint reduction and energy resilience, DC systems are becoming increasingly attractive to communities. District energy is a flexible system in terms of the sources as they can accommodate both cooling and heating. The main focus of the chapter was the district cooling systems and it was aimed to outline the possibilities and benefits of using a district energy system specifically the DCS. Three classification groups based on the system, central plant, and occupant behavior were proposed.

DCS can reduce electricity use and peak demands and be integrated with renewable resources, and, therefore, contributes to reducing greenhouse gas emissions and air pollution. Several sources can be used—free cooling together with electricity or thermally driven chillers. These systems are more efficient in more populated districts. Since the coolant is produced in the central chiller plant, not only the use of space in the building is minimized, but the noise pollution also is reduced. District cooling systems have been reported as economic and environmentally friendly solutions to meet the cooling demand of buildings. The investigated studies in this chapter reported a decrease in energy use when DCS was implemented.

Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

Funding of the study by the Swedish Energy Agency, Termo program, is greatly acknowledged (District cooling vs. local solutions for space cooling, project number 48296-1, Dnr: 2019-003410).

Abbreviations

CHP	combined heat and power plant
CO_2	carbon dioxide
COP	coefficient of performance
COP_{plant}	coefficient of performance of a chiller plant
DC	district cooling
DCS	district cooling system
delta-T	temperature rise of the cooling water
DH	district heating
DHC	district heating and cooling
GHG	greenhouse gases
ICS	individual cooling system
SCOP	system coefficient of performance

Q	cooling supply of a chiller plant
W_{distri}	energy use of a cooling distribution system
W_{plant}	energy use of a chiller plant
WTF_{distri}	water transport factor
$PWF(i, n)$	present worth factor
C_{IC}	initial capital cost
C_{fuel}	natural gas cost
C_{OM}	operational and management cost
C_{Dispose}	abandoned equipment cost
C_{cool}	cooling cost
C_{heat}	heating cost
C_{hotwater}	hot water cost
n	life cycle period
i	interest rate

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References

[1] Zhou X, Yan D, Feng X, Deng G, Jian Y, Jiang Y. Influence of household air-conditioning use modes on the energy performance of residential district cooling systems. Building Simulation. 2016;**9**:429-441. Available from: https://link.springer.com/article/10.1007/s12273-016-0280-9

[2] Inayat A, Raza M. District cooling system via renewable energy sources: A review. Renewable and Sustainable Energy Reviews. 2019;**107**:360-373. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032119301649

[3] Sayegh MA, Jadwiszczak P, Axcell BP, Niemierka E, Bryś K, Jouhara H. Heat pump placement, connection and operational modes in European district heating. Energy and Buildings. 2018;**166**:122-144

[4] Angrisani G, Entchev E, Roselli C, Sasso M, Tariello F, Yaïci W. Dynamic simulation of a solar heating and cooling system for an office building located in Southern Italy. Applied Thermal Engineering. 2016;**103**:377-390

[5] Ampofo F, Maidment GG, Missenden JF. Review of groundwater cooling systems in London. Applied Thermal Engineering. 2006;**26**:2055-2062

[6] European Commission. EU Climate Action and the European Green Deal | Climate Action [Internet]. 2021. Available from: https://ec.europa.eu/clima/policies/eu-climate-action_en

[7] Jangsten M, Filipsson P, Lindholm T, Dalenbäck J-O. High temperature district cooling: Challenges and possibilities based on an existing district cooling system and its connected buildings. Energy. 2020;**199**:117407. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360544220305144

[8] Joelsson JM, Gustavsson L. Reduction of CO2 emission and oil dependency with biomass-based polygeneration. Biomass and Bioenergy. 2010;**34**:967-984. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0961953410000607

[9] Gustavsson L, Holmberg J, Dornburg V, Sathre R, Eggers T, Mahapatra K, et al. Using biomass for climate change mitigation and oil use reduction. Energy Policy. 2007;**35**:5671-5691

[10] Frederiksen S, Werner SE. District Heating and Cooling. 1st ed. Studentlitteratur AB: Lund, Sweden; 2013. Available from: https://search.ebscohost.com/login.aspx?direct=true&AuthType=shib&db=cat02894a&AN=hig.14219756&lang=sv&site=eds-live&custid=s3912055

[11] Spurr M. The role of district energy in future energy systems. Cogeneration and Competitive Power Journal. 2001;**16**:22-47

[12] RESCUE Project. EU District Cooling Market and Trends [Internet]. Capital Cooling; 2014. Available from: https://www.euroheat.org/our-projects/

[13] Persson U, Werner S. Quantifying the Heating and Cooling Demand in Europe – WP 2 – Background Report 4. Halmstad University: Halmstad. Sweden; 2015. Available from: https://heatroadmap.eu/

[14] Chow TT, Fong KF, Chan ALS, Yau R, Au WH, Cheng V. Energy modelling of

district cooling system for new urban development. Energy and Buildings. 2004;**36**:1153-1162. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0378778804001410

[15] ASHRAE Handbook Fundamentals 2017; American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHAE): Atlanta, GA, 2017

[16] Gävle Energi. Gävle Energi AB [Internet]. 2021. Available from: https://www.gavleenergi.se/

[17] Čož TD, Kitanovski A, Poredoš A. Exergoeconomic optimization of a district cooling network. Energy. 2017;**135**:342-351. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360544217311246

[18] Amiri S. Economic and Environmental Benefits of CHP-based District Heating Systems in Sweden. Linköping: Linköping University Electronic Press. Press; 2013

[19] Olbricht M, Lonardi F, Luke A. Performance improvement of absorption chillers by means of additives—A numerical study. Solar Energy. 2018;**166**:138-145. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0038092X18302809

[20] Eveloy, V, and DS Ayou. Sustainable district cooling systems: Status, challenges, and future opportunities, with emphasis on cooling-dominated regions. *Energies*. 2019;**12**(2):235-299. DOI: https://doi.org/10.3390/en12020235

[21] Pawlish M, Varde AS. Free cooling: A paradigm shift in data centers. 2010 Fifth Int Conf Inf Autom Sustain [Internet]. IEEE: Colombo, Sri Lanka; 2010. p. 347-352. Available from: http://ieeexplore.ieee.org/document/5715685/

[22] Eicker U, Vorschulze C. Potential of geothermal heat exchangers for office building climatisation. Renewable Energy. 2009;**34**:1126-1133

[23] Oropeza-Perez I, Østergaard PA. Active and passive cooling methods for dwellings: A review. Renewable and Sustainable Energy Reviews. 2018;**82**:531-544. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032117313084

[24] Pellegrini M, Bianchini A. The innovative concept of cold district heating networks: A literature review. Energies. 2018;**11**:236. Available from: http://www.mdpi.com/1996-1073/11/1/236

[25] Looney CM, Oney SK. Seawater district cooling and lake source district cooling. Energy Engineering: Journal of the Association of Energy Engineers. 2007;**104**:34-45. Available from: https://www.tandfonline.com/doi/abs/10.1080/01998590709509510

[26] Sameti M, Haghighat F. Optimization approaches in district heating and cooling thermal network. Energy and Buildings. 2017;**140**:121-130

[27] Udomsri S, Bales C, Martin AR, Martin V. Decentralised cooling in district heating network: Monitoring results and calibration of simulation model. Energy and Buildings. 2011;**43**:3311-3321

[28] Buragohain B, Mahanta P, Moholkar VS. Biomass gasification for decentralized power generation: The Indian perspective. Renewable and Sustainable Energy Reviews. 2010;**14**:73-92

[29] Tredinnick S, Phetteplace G. District cooling, current status and future trends [Internet]. Wiltshire R, editor. Adv. Dist.

Heat. Cool. Syst. Cambridge, United Kingdom: Elsevier Science & Technology; 2016. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9781782423744000082

[30] Carreras Bertran A. Energy System and Economic Analysis of District cooling in the city hall of Gävle [Internet]. University of Gävle: Gävle, Sweden; 2013. Available from: https://www.diva-portal.org/smash/get/diva2:653274/FULLTEXT01.pdf

[31] Pezzola L, Danti P, Magnani S. Performance comparison among gas heat pump, electric heat pump and conventional thermal devices in tertiary sector applications. Energy Procedia. 2016;**101**:416-423. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1876610216312620

[32] Lake A, Rezaie B, Beyerlein S. Review of district heating and cooling systems for a sustainable future. Renew. Sustain. Energy Rev. Elsevier Ltd; 2017;**67**:417-25. DOI: 10.1016/j.rser.2016.09.061

[33] Rezaie B, Rosen MA. District heating and cooling: Review of technology and potential enhancements. Applied Energy. 2012;**93**:2-10. Available from: https://linkinghub.elsevier.com/retrieve/pii/S030626191100242X

[34] Weber C, Maréchal F, Favrat D. Design and optimization of district energy systems. Computer Aided Chemical Engineering. 2007;**24**:1127-1132. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1570794607802124

[35] Felsmann C, Grajcar M. Cool conclusions—How to implement district cooling in Europe. 2015. Available from: https://www.euroheat.org/our-projects/rescue-renewable-smart-cooling-urban-europe/

[36] Sakawa M, Kato K, Ushiro S. Operational planning of district heating and cooling plants through genetic algorithms for mixed 0-1 linear programming. European Journal of Operational Research. 2002;**137**:677-687. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0377221701000959

[37] Difs K, Danestig M, Trygg L. Increased use of district heating in industrial processes—Impacts on heat load duration. Applied Energy. 2009;**86**:2327-2334. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261909000853

[38] Monleón A, David J, Roca V. Study of Temperature Raise in Gavleån River Related to District Cooling [Internet]. University of Gävle: Gävle, Sweden; 2010. Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-7129

[39] Shu H, Duanmu L, Zhang C, Zhu Y. Study on the decision-making of district cooling and heating systems by means of value engineering. Renewable Energy. 2010;**35**:1929-1939. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0960148110000388

[40] Shimoda Y, Nagota T, Isayama N, Mizuno M. Verification of energy efficiency of district heating and cooling system by simulation considering design and operation parameters. Building and Environment. 2008;**43**:569-577. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360132306003301

[41] Wiltshire R. Low temperature district energy systems. In: Proceedings 17th "Building Services, Mechanical and Building Industry Days", Urban Energy Conference. Debrecen, Hungary; 2011

[42] Best RE, Rezazadeh Kalehbasti P, Lepech MD. A novel approach to district

heating and cooling network design based on life cycle cost optimization. Energy. 2020;**194**:116837. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360544219325320

[43] Lazzarin R, Noro M. Local or district heating by natural gas: Which is better from energetic, environmental and economic point of views? Applied Thermal Engineering. 2006;**26**:244-250. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1359431105001572

[44] Truong N Le, Gustavsson L. Cost and primary energy efficiency of small-scale district heating systems. Applied Energy. 2014;**130**:419-427. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261914005261

[45] Mallawarachchi H, Silva L, Rameezdeen R. Green buildings, resilience ability and the challenge of disaster risk. International Conference on Building Resilience. Ahungalla, Sri Lanka; 2013

[46] Zhang C, Kazanci OB, Levinson R, Heiselberg P, Olesen BW, Chiesa G, et al. Resilient cooling strategies – A critical review and qualitative assessment. Energy and Buildings. 2021;**251**:111312. Available from: http://creativecommons.org/licenses/by/4.0/

[47] Hay AH. Briefing: Resilience: A developing planning tool. Infrastructure Asset Management. 2015;**1**:130-134. DOI: 101680/iasma1400021. Available from: https://www.icevirtuallibrary.com/doi/abs/10.1680/iasma.14.00021

[48] Sharifi A, Yamagata Y. Principles and criteria for assessing urban energy resilience: A literature review. Renewable and Sustainable Energy Reviews. 2016;**60**:1654-1677. Available from: http://creativecommons.org/licenses/by/4.0/

[49] International District Energy Association. District Energy Space 2019. International District Energy Association: Westborough, USA; 2019. p. 19. Available from: http://www.districtenergy.org/district-energy-space

[50] Bertelsen N, Mathiesen BV. EU-28 residential heat supply and consumption: Historical development and status. Energies. 2020;**13**:1894. Available from: https://www.mdpi.com/1996-1073/13/8/1894/htm

[51] Saletti C, Morini M, Gambarotta A. The status of research and innovation on heating and cooling networks as smart energy systems within horizon 2020. Energies. 2020;**13**:2835. Available from: www.mdpi.com/journal/energies

[52] Gang W, Wang S, Gao D, Xiao F. Performance assessment of district cooling systems for a new development district at planning stage. Applied Energy. 2015;**140**:33-43. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261914011635

[53] Wang S. Dynamic simulation of a building central chilling system and evaluation of EMCS on-line control strategies. Building and Environment. 1998;**33**:1-20. Available from: https://linkinghub.elsevier.com/retrieve/pii/S036013239700019X

[54] An J, Yan D, Hong T, Sun K. A novel stochastic modeling method to simulate cooling loads in residential districts. Applied Energy. 2017;**206**:134-149. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261917310516

[55] Yan C, Gang W, Niu X, Peng X, Wang S. Quantitative evaluation of the impact of building load characteristics on energy performance of district cooling systems. Applied Energy. 2017;**205**:635-643

[56] Nagota T, Shimoda Y, Mizuno M. Verification of the energy-saving effect of the district heating and cooling system—Simulation of an electric-driven heat pump system. Energy and Buildings. 2008;**40**:732-741. Available from: https://linkinghub.elsevier.com/retrieve/pii/S037877880700165X

[57] Udomsri S, Martin AR, Martin V. Thermally driven cooling coupled with municipal solid waste-fired power plant: Application of combined heat, cooling and power in tropical urban areas. Applied Energy. 2011;**88**:1532-1542

[58] Erdem HH, Akkaya AV, Dagdas A, Sevilgen SH, Cetin B, Sahin B, et al. Renovating thermal power plant to trigeneration system for district heating/cooling: Evaluation of performance variation. Applied Thermal Engineering. 2015;**86**:35-42

[59] Ameri M, Besharati Z. Optimal design and operation of district heating and cooling networks with CCHP systems in a residential complex. Energy and Buildings. 2016;**110**:135-148

[60] Werner S. District heating and cooling in Sweden. Energy. Elsevier. 2017;**126**:419-29. DOI: 10.1016/j.energy.2017.03.052

[61] District Cooling—Energy Companies Sweden [Internet]. 2020. Available from: https://www.energiforetagen.se/statistik

[62] Fahlén E, Trygg L, Ahlgren EO. Assessment of absorption cooling as a district heating system strategy—A case study. Energy Conversion and Management. 2012;**60**:115-124. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0196890412000647

[63] Svensson IL, Moshfegh B. System analysis in a European perspective of new industrial cooling supply in a CHP system. Applied Energy. 2011;**88**:5164-5172

[64] Karlsson V, Nilsson L. Co-production of pyrolysis oil and district cooling in biomass-based CHP plants: Utilizing sequential vapour condensation heat as driving force in an absorption cooling machine. Applied Thermal Engineering. 2015;**79**:9-16

[65] Frohm H, Tvärne A, Koski K. Best practice examples of District Cooling Systems [Internet]. 2015. Available from: https://www.euroheat.org/our-projects/rescue-renewable-smart-cooling-urban-europe/

[66] U.S. Department of Energy. U.S. Department of Energy Technology Readiness Assessment [Internet]. U.S Department of Energy: Washington, D.C.; 2009. Available from: https://www.directives.doe.gov

[67] Jangsten M, Lindholm T, Dalenbäck JO. Analysis of operational data from a district cooling system and its connected buildings. Energy. 2020;**203**:117844

[68] Henze GP, Henry W, Thuillard M. Improving campus chilled water systems with intelligent control valves: A field study [Internet]. In: AEI 2013. Building Solutions for Architectural Engineering: State College, Pennsylvania, United States; 2021. pp. 103-112. Available from: https://doi.org/10.1061/9780784412909.011

[69] Gang W, Wang S, Xiao F, Gao D. Performance assessment of district cooling system coupled with different energy technologies in subtropical area. Energy Procedia. 2015;**75**:1235-1241

[70] Alajmi A, Zedan M. Energy, cost, and environmental analysis of individuals and district cooling systems

for a new residential city. Sustainable Cities and Society. 2020;**54**:101976

[71] 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. Applied Energy. 2008;**86**:1395-1404

[72] Lake A, Rezaie B, Beyerlein S. Review of district heating and cooling systems for a sustainable future. Renewable and Sustainable Energy Reviews. 2017;**67**:417-425. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032116305585