

Review

The Innovative Concept of Cold District Heating Networks: A Literature Review

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Abstract: The development of sustainable and innovative solutions for the production and supply of energy at district level is nowadays one of the main technical challenges. In the past, district heating and cooling networks aimed to achieve greater energy efficiency through the centralization of the energy production process but with relevant losses related to heat transport. Moving towards a higher share of renewables and lower demand of primary energy requires redesign of the energy district networks. The novel concept of cold district heating networks aims to combine the advantages of a centralized energy distribution system with low heat losses in energy supply. This combined effect is achieved through the centralized supply of water at relatively low temperatures (in the range 10–25 °C), which is then heated up by decentralized heat pumps. Moreover, cold district heating networks are also very suitable for cooling delivery, since cold water supplying can be directly used for cooling purposes (i.e., free cooling) or to feed decentralized chillers with very high energy efficiency ratio. This paper provides a preliminary literature review of existing cold district heating networks and then qualitatively analyses benefits and drawbacks in comparison with the alternatives currently used to produce heat and cold at district level, including the evaluation of major barriers to its further development.

Keywords: cold district heating; district heating and cooling; free cooling; drawback-benefit analysis

1. Introduction

The integration and implementation of renewable energy systems at district scale is described in a number of recent reports and studies, including [1–6]. District heating and cooling networks play an important role in the task of increasing renewable energy exploitation and the development of novel design approaches, while business models are crucial to meet future demands for a higher level of efficiency and lower environmental impact of energy production, supply and use at district level. The idea of district heating was developed to provide greater efficiency and better environmental impact than localized boilers through the centralized production of heat and its distribution to final users (usually both residential and commercial) by a network of pipes [7]. The pipeline network can be designed in different ways, including ring networks, branched networks and looped networks [8]. The so called 1st generation of district heating networks was introduced in the late 19th century in the US, using steam as a heat carrier. These systems were replaced by 2nd generation networks, which use pressurized hot water with supply temperatures over 100 °C as a heat carrier. Since space heating in traditional residential buildings has generally been ensured by heat transfer from radiators at about 80 °C supply temperature, district heating networks with lower supply temperatures were therefore established in the market starting from the 1970s, i.e., the so called 3rd generation of district heating systems, which are currently and widely applied [9]: the total number of systems has been estimated at 80,000 systems worldwide, of which about 6000 systems (7.5%) in Europe. Third generation district

heating systems are characterized by using pressurized hot water as a heat carrier but with lower temperatures (below 100 °C) than 2nd generation systems.

The higher efficiency in energy production due to centralization in comparison with decentralized systems has a drawback in distribution losses, which are usually in the range of 10–30% [10,11] and in the costs related to distribution pipeline insulation [12,13]. Furthermore, high temperature-sustaining materials (i.e., steel) must be used for the network [14], including heat exchangers, valves and instrumentations. Moreover, integration in the network is suitable only for high temperature sources, thus limiting the possibility of renewables exploitation [15,16]. Finally, in the last few years the improvement in building energy performance and in the retrofitting of building stock contributes to a generalized decrease in heating demand [17,18]. This fact produces an increase of the relative distribution losses and a decrease of the overall cost effectiveness of existing district heating networks.

A further reduction of heat supply temperatures has been identified as one of the possible solutions. This so-called 4th generation of district heating networks is a novel and quite recent district heating concept developed in Denmark [19] and characterized by lower temperatures. The temperature decrease in the network can lead to (i) an increase of efficiency of district heating systems due to reduction of heat losses and (ii) can allow easier integration of cost-efficient renewable energy technologies (like solar energy or geothermal heat pumps) which are not linked to combustion processes. A further division of 4th generation systems can be made between so-called low temperature district heating (LTDH) and ultra-low temperature district heating (ULTDH). LTDH networks are usually characterized by supply temperatures in the range 50–70 °C, while ULTDH networks have supply temperatures below 50 °C, without a common definition of lower limit [20]. In ULTDH networks, decentralized micro-heat power stations should be used to boost the domestic hot water (DHW) temperature as needed [21]. Another advantage of 4th generation systems is the possibility of using cheaper materials like plastic for pipes and other network components, including also a relevant decrease of insulator thickness and related costs.

Although the idea has only recently been developed, a considerable amount of literature can be found on 4th generation or low temperature district heating. Qualitative benefits and drawback analysis have been assessed [22–24], including the evaluation of how 4th district heating systems can be integrated into the smart city concept. Further specific analysis has been carried out to identify how technical [25–27], legislative [28,29] and economic [30,31] barriers can be overcome. Case studies from different countries have also been reported [20,32–34]. Nevertheless, the development of 4th generation systems of district heating is characterized by two strong limitations: the first is that the demand side of a district heating network consists of buildings built at different times. This means that they have different thermal loads and, in particular, they use different indoor space heating distribution systems, which require diverse inlet temperature set points. However, heating terminals of existing buildings are usually oversized compared to real needs. Therefore, lower distribution temperatures may be acceptable in some cases and can cover a fraction of the seasonal thermal load [35,36]. The application of 4th generation district heating is thus mainly suitable in new and/or renovated buildings. Secondly, 4th generation as well as traditional district heating systems have low compatibility with district cooling networks. Some authors suggested creating a bidirectional low temperature network [37]. The warmer pipe has temperatures between 12 °C and 20 °C, while the cold pipe has 8–16 °C. In the case of a heating demand, the circulation pump of the building withdraws water from the warm line, uses it in a heat pump to reach temperatures suitable for space heating and then discharges the cooled water to the cold line. In the case of a cooling demand, the system works in the other direction. The system requires a complex regulation of both the energy supply network and the end-users' substations and does not solve the problem of requiring two pipelines (one for heating and one for cooling). Finally, a great challenge in district heating networks is the hygienic preparation of DHW [38] if supply temperatures fall within a certain range (25–55 °C): to avoid the origin and the proliferation of legionella in a centralized DHW system, minimum temperatures must be guaranteed.

District cooling has been a more recent development compared to district heating: this fact is justified by the greater technologic and non-technologic barriers involved in district cooling in comparison with district heating [39,40]. District cooling systems are therefore neither as common nor as extensive as district heating systems. On the other hand, energy demand for space cooling has grown rapidly since the 90's: this is confirmed by the number of central air-conditioners and room air-conditioners installed which increased by more than 50 times from 1990 to 2010 in the European Union [41]. Other parameters which underline this trend are heating degree days and cooling degree days, which have, respectively, decreased and increased in the last 15 years in Europe [42]. Similar trends can be observed in other Countries. So, the combined effect of the decrease in heat demand and the increase in cooling request is making the creation of district heating networks alone, i.e., without cooling, less profitable and reliable. Centralized energy production offers the possibility to combine heat and cold plants, i.e., cogenerative units that electrically feed compressor chillers and/or thermally feed absorption chillers [43]. On the other hand, from an infrastructural point of view the integration between district heating and cooling networks has some techno-economic obstacles. In fact, it is difficult to use only one pipeline for both heating and cooling purposes since the demand for production of DHW may be simultaneous to cooling demand. As a result, the network cost is more or less doubled if compared with district heating alone. A possible alternative is the use of decentralized absorption chillers for the production of cold, the supplying pipeline being a hot network [44,45]: however, in this case, the application of 4th generation district heating networks would be not favoured, since hot water temperatures lower than 85–90 °C produce lower (if any) cooling effect in the absorption chillers.

A possible solution to favour a high degree of integration between district heating and cooling networks, without compromising energy efficiency production and also to reduce thermal losses in the supply network, is the creation of a so-called “cold” district heating (CDH) network. The CDH network concept is based on the circulation of cold water, coming from different sources (surface and deeper aquifers, seawater, wastewater, aqueducts), which is sent to secondary stations where it can be used as condensing and/or evaporating fluid in a heat pump/chiller to produce, respectively, hot water for space heating and/or DHW production and cold water for space cooling. In some cases, the centralized cold water may be used directly as the cooling fluid, thus greatly increasing the system's efficiency. A CDH network thus always includes the possibility to also deliver cooling energy to the end-users.

The first objective of this paper is to map and analyse the existing CDH networks. Furthermore, the paper aims to qualitatively evaluate, from a techno-economic perspective, the benefits and drawbacks of the innovative CDH model in comparison with the alternatives currently applied to produce and deliver heat and cold at district level, including the evaluation of relevant barriers to its further development. Economic aspects related to energy prices are not directly evaluated in the paper since both electric energy and thermal energy production are affected by local frameworks.

2. Cold District Heating Networks

The concept of CDH, even though it can be found in the literature, has not been defined and generally analysed. So, the first aim of this paper is to give a definition of a CDH network (Figure 1), which can be defined as a system for distributing cold water in a temperature range between 10 °C and 25 °C to end-users' substations where it is used to produce, also simultaneously, hot and cold water at different temperatures and for different purposes (space heating, cooling, DHW production) via heat pumps and chillers. Figure 1 shows two optional configurations: the first concerns the creation of a primary and secondary circuit, thus avoiding a direct energy exchange between the water source(s) and the users' substations. A second option is the pre-heating of the water flowing through the cold ring (see Section 2.2): this option may be needed when the water source temperature in wintertime is too low. Users can act in three different ways: they can return water to the network which is heated up (user #1 in Figure 1), cooled down (user #2 in Figure 1) or has no temperature variation (user #3

in Figure 1). The last case occurs when the user has an equal energy use for space heating or DHW production and cooling.

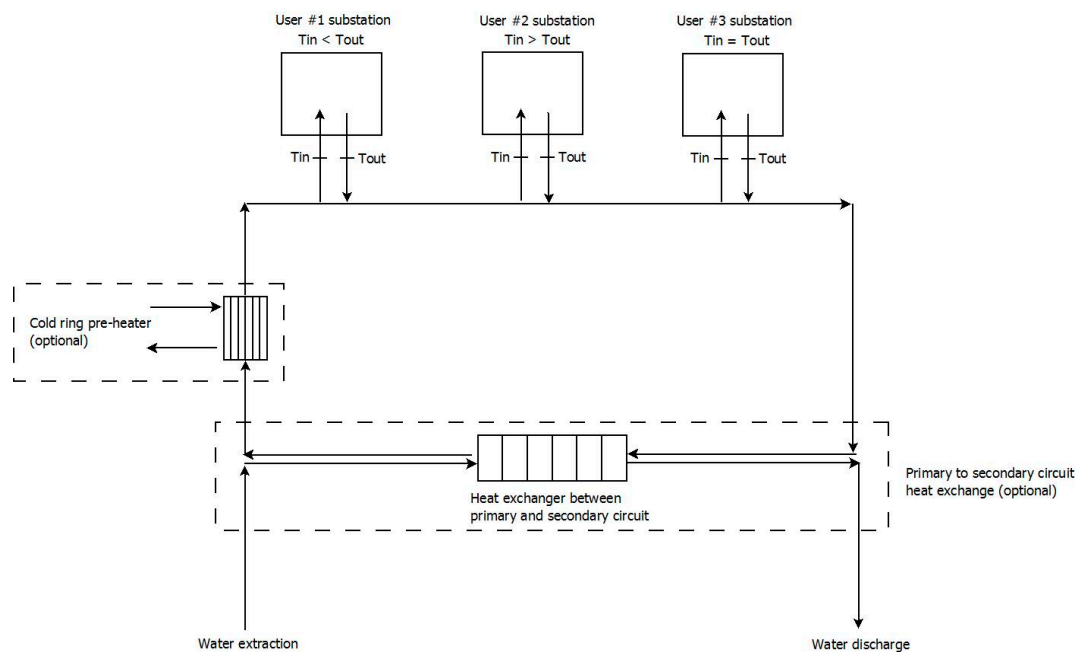


Figure 1. Cold district heating and cooling network. The scheme includes the primary-secondary circuit option, as well as the possibility to pre-heat the water flowing through the cold ring.

A CDH network can be seen as a water-loop heat pump (WLHP) system developed at district level: in fact, a WLHP uses a loop composed of small water-air heat exchangers and through a ring of circulating water in the temperature range 16–32 °C it can simultaneously provide heating and cooling for different areas of one building. The WLHP has been successfully applied in many countries and has shown a high rate of energy saving potential and interesting payback time [46,47]. On the other hand, WLHP system effectiveness is strictly related to the possibility of perfectly balancing heating and cooling demand. When a balance is not possible, it is necessary to integrate the loop with a heat rejecter (i.e., cooling tower or geothermal heat exchanger), heat adder (i.e., boiler or geothermal heat exchanger) or energy storage. In the following paragraphs the main system blocks of a CDH network are analysed to determine how the system can be adapted to different frameworks.

2.1. Cold Water Sources

The cold network can be fed by different water sources. A first distinction can be made between natural and artificial water sources. The first includes superficial and shallow (up to 100 m depth) aquifers and can be further distinguished in fresh water (river, lake) and salt water (sea and lagoon). The second includes cold water coming from infrastructures like aqueduct networks, sewer and wastewater systems.

The use of fresh water from the underground has involved several research activities as well as pilot schemes. In particular, in the case of groundwater exploitation energy storage can also be achieved through aquifer thermal energy storage (ATES) [48]. In fact, the concept of ATES is that in summer, groundwater is extracted to provide cooling. The heated groundwater is injected back into the aquifer to create a heat storage. In winter, the flow direction in the system is reversed such that the heated groundwater is extracted to provide heating and create a cold storage. There may be limits to groundwater exploitation due to the specific characteristics of the aquifer [49]: in particular, water flowrate extraction capacity (which can be determined through pumping test realized accordingly to ISO 22282-4 standard).

Compared with groundwater, the exploitation of water coming from superficial sources should have fewer issues regarding flowrate ranges. On the other hand, while groundwater has a stable temperature over the year, temperatures of superficial water are highly influenced by ambient temperature [50,51]. So, under certain environmental conditions, it may be necessary to heat the water beyond a certain limit (i.e., 10 °C) before being pumped into the cold water network (see Figure 1). In this case, the integration of a cogeneration plant can be an interesting option. Furthermore, in the case of salt water use, it is necessary to protect heat pumps and chillers, heat exchangers, water pumps and pipelines against salt corrosion and galvanic currents. A possible solution to limit these issues is the use of a secondary circuit (see Figure 1) to supply cold water to the users, thus limiting the circulation of salt water in a smaller pipeline [52].

In residential and/or industrial areas it is possible to recover or reject heat also through artificial water flows. At building level, a large part of the drinking water provided is heated, used as DHW and then discharged in the sewage system. So, on a large scale the wasted heat can be recovered directly from the sewer. For example, in Oslo about 8% of the thermal energy required by district heating is obtained by recovering heat from the sewage system [53]. A similar system was installed near the Olympic village in Vancouver [54]. Heat recovery can also be achieved downstream of water treatments, where it is possible to find large flows and stable temperatures in comparison with sewers [55]. Heat recovery from wastewater is a fairly common system in Switzerland: for example, in the Bremgarten quarter in Berne about 60% of the heat demand is provided by heat pumps that extract thermal energy from treated water [54]. Limitations to the use of water coming from sewers and wastewater in a CDH network include (i) the relatively high temperatures (usually over 25 °C) that are not suitable for free cooling and require chillers and (ii) physical-chemical characteristics, which may have some implications on network operation and maintenance costs (clogging potential, corrosion risk). The drinking water that constantly flows throughout the distribution network [56] can represent another water source. An interesting aspect of aqueduct exploitation as an energy source is that the aqueducts themselves can be considered as the cold water distribution network of CDH, thus potentially being implemented at urban level with relatively low costs, also in existing buildings.

2.2. The “Cold Ring”

The cold water distribution network, also named “cold ring,” is the infrastructural element which supplies the energy vector to the end-users. The water from this energy which is finally extracted or discharged can directly flow into the cold ring, or a secondary circuit can be created to separate the ring from the cold water sources. The cold ring is at the same time both a heater and a sink: this is a crucial aspect from the environmental point of view. In fact, while in traditional district heating and cooling networks heat and cold are discharged to the environment, in CDH networks the cold ring works as a heat and cold recycling unit. For example, the heat that is normally rejected by buildings (i.e., through a common split unit) will be fed into the cold ring by reversible heat pumps (which work as chillers) and then recycled by the heat pumps that produce DHW. As a consequence, it is possible to use the cold ring as an energy distributor which pumps heat and cold from one user to the other, depending on each user’s specific request. So, the higher the number of simultaneous requests for heat and cold the greater the possibility to limit the temperature variation of cold ring water. Finally, if CDH is analysed through a wider perspective, it is possible to state that, especially at urban level, the creation of different cold rings, fed by cold water coming from different sources, should be considered.

2.3. Substation Configuration: Multipurpose Heat Pumps

The use of electrically-driven reversible heat pumps has become a recognized valuable solution to improve district heating and cooling efficiency since it embodies the opportunity to simplify the management of electric grids in conditions characterized by a high share of renewable energy, especially if coupled with energy storage. The so-called “multipurpose heat pump system” (Figure 2) can operate in four different working conditions, depending on the combination of open-close position

of the solenoid valves from V1 to V5. The first working condition is hot water production for heating purposes (heat pump): in this configuration V1 and V5 are open, while V2, V3 and V4 are closed. The heat exchanger S1 on the user side works as the condenser, while the heat exchanger S3 on the cold ring side acts as the evaporator. The expansion valve LV1 is closed, while LV2 is open. The second working condition is cold water production (chiller): V1, V2 and V5 are closed, while V3 and V4 are open. The heat exchanger S1 is now the evaporator, while S3 is the condenser, with LV1 open and LV2 closed. A third configuration can be used in in-between seasons for the production of DHW (heat pump for DHW production): V2 and V5 are open, while V1, V3 and V4 are closed. The working condition is similar to the first one, except for the condenser that is the heat exchanger S2 instead of S1. Finally, the fourth configuration is the one that allows cold water production with total condensation heat recovery (chiller plus DHW production): V2 and V4 are open, while V1, V3 and V5 are closed. The machine works as a chiller (LV1 open, LV2 closed) but the condensation is achieved in the heat exchanger S2 instead of heat exchanger S3. So, in this last configuration, there is no heat delivery to the cold ring. Non-return valves (NRV) are also present in the machine.

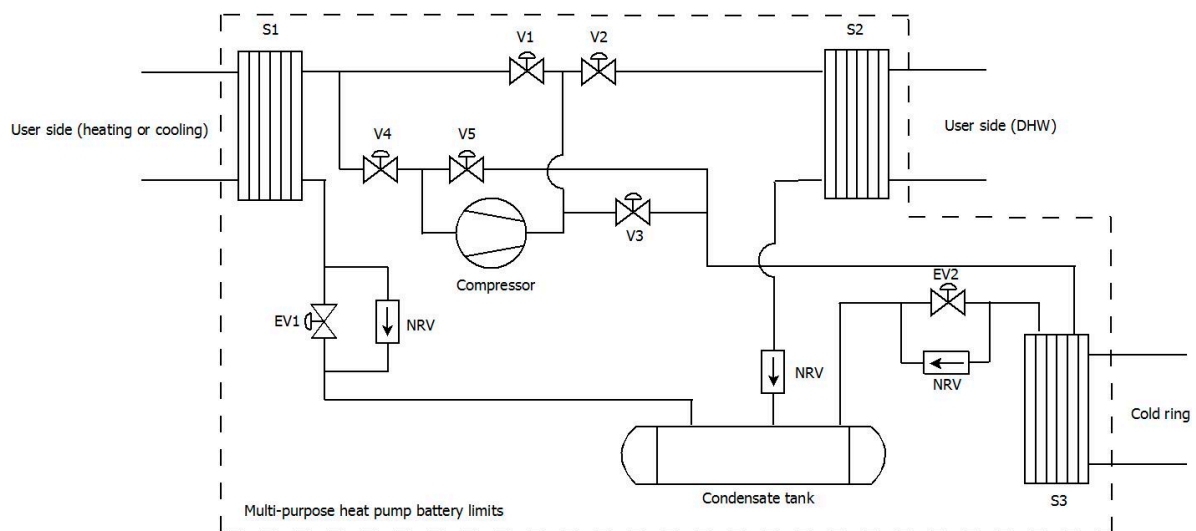


Figure 2. Piping and Instrumentation Diagram (P&ID) of a multi-purpose heat pump system: in particular, heat exchangers (S1, S2, S3), solenoid valves (V1, V2, V3, V4, V5), expansion valves (EV1, EV2) and non-return valves (NRV) are shown.

The user substation (Figure 3) can thus consist, for example, of a multipurpose heat pump, a storage unit for heating hot water or cool water, a storage unit for DHW production and circulating water pumps. Energy back-up and integration units can also be installed. In the case of a simultaneous need for hot and cold water for heating and cooling, two different tanks should be considered. Moreover, if the cold ring temperature is low enough, the water can be directly sent to the user side (thus bypassing the multi-purpose heat pump) for free cooling. Finally, the possibility to directly exchange heat/cold with local energy sources can be included: in Figure 3, for example, it is possible to heat or cool the return water to the cold ring. The presence of local energy storage as well as hot and cold integration units is a similar solution to the ones adopted in WLHP systems to balance heat and cold demand.

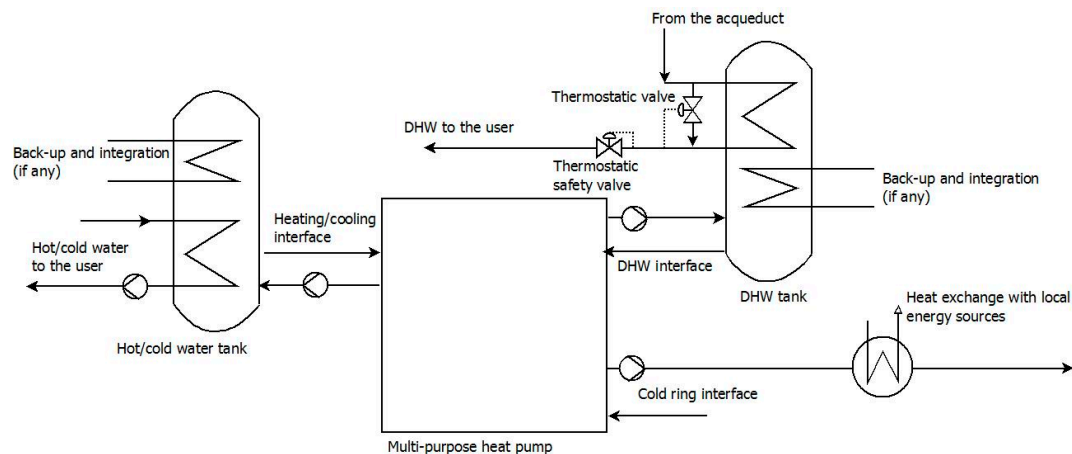


Figure 3. P&ID of an example of a substation for a cold district heating (CDH) network. DHW: domestic hot water.

2.4. Intelligent Control and Metering of the Network Performance

The design of a decentralized intelligent metering system is crucial to assure the closest possible link between energy demand coming from users and the energy delivery of the network [22,57,58], also including the continuous measurement of energy consumption for an efficient payment system. Wireless meter readings over a short time interval is the way to make the whole system work properly from both users' and producers' perspectives: in fact, the use of wireless sensors simplifies the installation of new sensors (especially in existing premises) [59,60], while continuous monitoring and mining of data make it possible to optimize the matching of energy demand and production not only at substation level but also at district level [61,62]. The system should also include the possibility to measure (and economically compute) the surplus heat or cooling production from a single user to the network, thus favouring the implementation of a smart and bidirectional energy grid [22,63].

3. Cold District Heating and Cooling Network State of the Art

A list of existing cold district heating networks, based on a literature review, is presented as follows, divided by Country. It should be noted that all the applications are limited to small size plants outside urban settings.

3.1. Switzerland

The first examples of cold district heating can be found in Switzerland [64]. The Furka railway tunnel has a drained water outflow of 5400 L/min at about 16 °C, which is piped to the nearby village of Oberwald (about 200 inhabitants), where since 1991 the water feeds individual heat pumps, tailored to supply various types of buildings. A total of 177 apartments and a sports centre are heated, with an installed capacity of 960 kW thermal (kW_{th}). Other examples, even if smaller in size compared to the Oberwald case study, can be found in the villages of Kaltbrunn, Minusio and Trimbach.

3.2. Germany

Within the national funded project EnVisaGe, a small district mainly with single-family homes was built in the 6800 inhabitants town of Wüstenrot [65]. The district is characterized by the presence of a cold water grid which supplies low temperature heat from a near-surface geothermal system to decentralized heat pumps located in the connected buildings. The system includes hot water storage.

In the town of Aurich (40,000 inhabitants), up to approximately 1200 m³ of wastewater in the range 25–35 °C are generated each day during the local production process of cheese and other dairy products. There is an approximately 2 km long ring from which users, with their heat pumps, can tap

from the dairy's wastewater heat up to 80% of the total heating energy peak demand, cooling down the wastewater by about 10 °C.

Starting from 2014, a cold district heating network has also been functioning at Troisdorf (73,000 inhabitants). Groundwater is circulated into a 5 km pipeline to two new residential development areas where individual reversible heat pumps in the connected houses (about 100 units) use the circuit as a heat source and sink [66].

Finally, in Hamburg the cold district heating concept has been applied to the newly built district "Jenfelder Au", with roughly 700 accommodation units for approximately 2000 residents [67]. The CDH network operates at a temperature level of 10 °C.

3.3. Italy

In the town of Berlingo (2700 inhabitants), a geothermal power plant serving the heating and cooling demand of a new school building was constructed in 2013 [68]. The water is pumped from the aquifer at 11–15 °C and then sent through one pipeline to heat pumps and chillers that use it to simultaneously produce hot and cold water for space heating/cooling and DHW production. On the basis of this pilot plant, a similar plant is being constructed in the town of Sale Marosino: in this case, the cold water source will be Lake Iseo, while the users will be two school buildings and a sports centre, with an estimated peak heating power of about 300 kW th.

A small heating and cooling district plant is under construction near Bologna [69]: the plant will exchange energy with the groundwater and will distribute it to two different buildings for the simultaneous production of heat and cold.

3.4. The Netherlands

The city of The Hague (500,000 inhabitants) has developed a district heating concept consisting of a seawater central supply unit with a heat exchanger and heat pump unit that uses the nearby sea as a source of heating and cooling [70]. In summer, when the temperature of the seawater is more than 11 °C, only the heat exchanger is used. The heat exchanger feeds heated water to the local district heating system, drawing enough heat from the seawater to cover residents' needs (750 houses). In the winter, when the water temperature is less than 4 °C (but above 0 °C), an ammonia heat pump is used to warm the water to approximately 11 °C, which is then fed into the local grid. On reaching each household, both in winter and summertime, the water is further heated by each home's own heat pump for space heating (only in wintertime) and DHW production.

4. Drawback-Benefit Analysis

4.1. Cold Water Sources: Flowrate and Temperature Limitations

A common characteristic of natural water exploitation is the presence of technical and legislative barriers that limit their exploitation. A first parameter to be carefully controlled is the discharge temperature. In fact, since temperature is a key driver of hydrogeochemical and biological processes, anthropogenically-induced temperature changes can be presumed to influence natural water systems. In particular, in ATEs systems the reinjection of heated groundwater can lead to carbonate precipitation, increased dissolution of silicate minerals, the mobilization of organic compounds from sediments, a decrease in groundwater oxygen saturation and effects on aquifer bacteria and fauna [71]. As consequence, legislative limits (order of magnitude ± 5 °C, varying by Country) are usually set for aquifer temperature increase/decrease before rejection. Similar problems may occur in the case of superficial water, both fresh and salt, especially for heated up water. Since the discharge water body (river, lake, sea) is usually also the source of the cooling water, a local temperature increase can be generated after mixing with the receiving water and temperature dissipating downstream through radiant transfer or evaporating into atmosphere. Typical discharge temperatures from power plant cooling systems are about 8–12 °C above intake temperatures, with some systems raising temperatures

as much as 15 °C [72]. The energy exploitation of surface water is thus generally favoured if compared with underground water, since the first allows a higher temperature variation between inlet and outlet flows, with a consequent reduction of water flowrate at constant heat exchange (thus reducing pipeline diameter, heat exchanger size, etc.).

Physical-chemical characteristics of the water (i.e., hardness, salt content, contaminants concentration, etc.) are a key factor in the design of the cold ring. High levels of hardness and/or contaminant concentration may result in a high risk of clogging and/or damage to the pipeline components, like valves or heat exchangers. Depending on the particular application, a filtration-separation system may be added to the plant, or a secondary cold ring circuit could be introduced to separate the water from the users' substations. In the case of salt water, further attention should be paid to the choice of materials to avoid both corrosion and galvanic currents.

In the case of drinkable water distribution network exploitation, temperature flowrate and water quality are kept quite constant by the system itself. Moreover, drinkable water temperatures can be interesting also for free cooling. On the other hand, drinkable fresh water has stringent limits regarding temperature and physical-chemical properties: the heat exchange potential could thus be limited, also from a legislative perspective, through a limitation of temperature variation. Contamination potential has also to be considered as a barrier to system development. The use of certified components (i.e., sanitary use) may be required, with relevant cost increasing.

Finally, a combination of ATES and remediation is considered a promising new concept to achieve both energy savings and improvement of the groundwater quality [73]: however, the presence of soil and/or groundwater contaminants in many urban environments may limit applicability of ATES and hampers redevelopment of these sites.

4.2. Low Thermal Losses in the Distribution Network

A common advantage of cold ring distribution systems is the consistent reduction in thermal losses. It is estimated that a low-temperature distribution network with 50 °C of supply water temperature and 20 °C of return water temperature should cut the current 3rd generation distribution temperature difference between average water temperature and ground by a factor 2 [20]. A further temperature reduction in the circulating water as in the CDH network can increase energy saving. In the case of the Hamburg CDH plant, the estimated thermal losses of the CDH network working with water at 10 °C are 2% of the energy supplied, while if the same amount of energy is delivered through the district heating network at 60 °C or 90 °C the estimated thermal losses are, respectively, 19% and 25% [67].

Furthermore, thermal losses can be prevented through the application of a lower insulator thickness compared to traditional district heating networks. Depending on cold ring water temperature (i.e., if the temperature is near ground temperature), thermal insulation can be avoided. So, a relevant cost reduction can be expected.

4.3. Primary Energy Saving

Primary energy can be saved through the application of a CDH network in comparison with 3rd and 4th generation district heating [69]. The amount of energy saving depends on working conditions, in particular cold ring water temperature and temperature to the end-users, which influence the coefficient of performance (COP) and energy efficiency ratio (EER) of reversible heat pumps. An additional benefit is produced by the lower thermal losses and if renewable energy is introduced in the network further advantages can be achieved. In the case of the Hamburg CDH plant [67], the primary energy consumption is estimated at 757 MWh per year, while if the same amount of energy is delivered to the end-users through a 60 °C (produced via a centralized heat pump) or 90 °C (produced by a centralized gas boiler) network, the primary energy consumption is, respectively, 838 MWh/year (+11%) and 1.607 MWh/year (+112%).

4.4. Pipeline Design

Proper network design in district heating and cooling should generally balance the initial investment and the heat/cold distribution cost. The design is often based on a recommended value for specific pressure loss in the main lines, which is substantially determined by the volumetric flow rate in the network [74,75]. The pipeline diameter of the cold ring is thus determined by total peak flowrate, which is computed in turn on the basis of total peak thermal/cooling demand and available temperature decrease/increase. A comparison can be made between the 3rd district heating network and the proposed CDH network to evaluate under which working conditions CDH thermal carrier flowrate is higher than the traditional system one. The comparison is made taking into consideration a demand of 1 kW th. The traditional district heating network is designed with a 20 °C temperature drop and a thermal loss in the network of about 15% can be estimated as a mean value. A flowrate of about 50.6 L/h is thus needed in the distributing network to deliver 1 kW th to the user. In the case of the CDH network, several parameters have to be taken into account to estimate the water flowrate needed in the cold ring. First of all, depending on the cold water source, different temperature drops may be available. Secondly, the flowrate is also influenced by the COP of the substation heat pump. The COP may vary over a wide range, depending on both the temperature of the cold water in the ring as well as the temperature needed by the user [76], since these parameters respectively influence the evaporator and condenser temperature. Figure 4 shows how the flowrate of CDH varies in comparison with the one required by the traditional district heating network as a function of heat pump COP in the user substation and of available temperature drop in the cold ring (i.e., difference between inlet and outlet cold water temperatures). Thermal losses in a CDH network are negligible. The traditional district heating flowrate of 60.6 L/h computed before is equal to 1 (or 100%) in the y-axis in Figure 4.

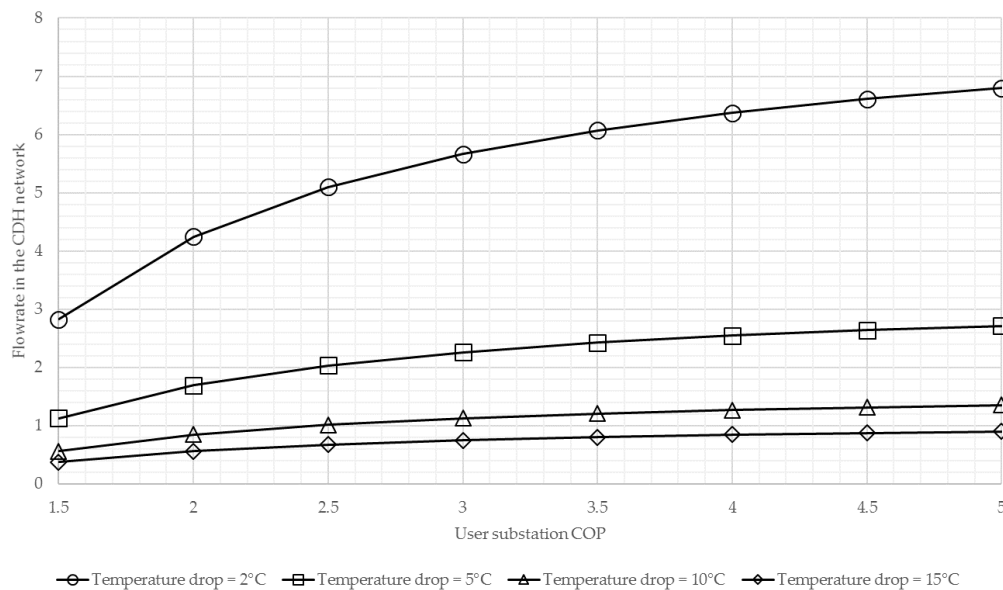


Figure 4. Flowrate network comparison between traditional district heating (equal to 1) and CDH as a function of available temperature drop in the CDH network and of heat pump coefficient of performance (COP) of the user substation.

Figure 4 shows that a CDH network requires a higher flowrate in comparison with traditional district heating if the allowable temperature drop in the cold ring is under 10 °C: in this case, the pipeline diameter of a CDH network is higher than the diameter of a traditional district heating network. On the other hand, if the temperature drop is over 15 °C a reduction in the requested flowrate can be observed and so the diameter can be potentially reduced. Nevertheless, it should be considered that a CDH network can simultaneously supply users requiring heat and cold. So, the greater the

balance between heat and cold demand, the lower the flowrate required by the cold ring, thus also allowing the use of a water source with more stringent limits on temperature variation. Moreover, heat production can be integrated at substation level, meaning that the energy produced by the cold ring does not have to be equal to the maximum required peak.

4.5. Substation Design

The substations of traditional district heating networks usually include two heat exchangers, one for the production of DHW and one for the production of hot water for heating purposes. An additional heat exchanger for cool water production can be added if the user is also connected to a district cooling network [9,77]. Traditional district heating and cooling substations are therefore compact and do not require large areas for the installation.

A CDH network requires user substations with a higher level of complexity. Larger machines should be installed (multi-purpose heat pumps), including tanks for the storage of hot and/or cold water. Energy back-up and integration units may also be present. As a result, the installation of the substation may need a large area: this can become an important issue, especially in the case of connection of existing buildings to a CDH network.

4.6. Ability to Utilize Renewable Energy and Create a Smart Energy System

A smart energy grid can be defined as an energy system in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them to achieve an optimal solution for each individual sector as well as for the overall energy system [78]. Traditional district heating and cooling networks are not suitable for this kind of smart integration, since the relatively high temperature of the water delivered in the network makes the system quite rigid and does not allow easy integration with renewables. Moreover, the energy flux is mono-directional, from the central plant to the users and cannot be reversed.

Conversely, the construction of a CDH network with energy integrated substations can be a way of creating a smart energy system. In fact, the substation (see Figure 3) is open to integration coming from different potential sources. First of all, it is possible to integrate DHW production with solar thermal or hybrid photovoltaic-thermal (PV/T) panels, which are an interesting alternative to produce both electric and thermal energy when limited area for panel installation is available [79]. Depending on the characteristics of each user's heating terminal (i.e., floor heating or radiators) the hot water delivery temperature may be at different level. So, if relatively low temperatures are required for heating purposes, thermal solar and/or PV/T panels can be considered also for the integration on the heating side. When higher temperatures are required, it may be interesting to evaluate other renewables, like biomass boilers.

A CDH network also gives the user the possibility of returning heat and/or cold to the cold ring: the cold ring thus performs a bidirectional energy exchange between the network and the users. This can be a revolutionary aspect, since up to now the district heating and cooling business model has been defined as an energy sell to customers wherein energy price is the key driver. In a CDH network, the user can create a mutual exchange of energy with the network. In fact, under certain conditions, the network may require heat or cold from users who can deliver energy to the cold ring: for example, in wintertime heat can be sent to the network to reduce the temperature decrease of the cold ring, thus allowing water discharge limits (if any) to be respected. Nevertheless, to be really effective the bidirectional system [80,81] needs a sophisticated smart metering network and an efficient control and regulation system, including novel business models [82–84]. Two relevant issues can thus be identified: the first one is the cost of the metering and control infrastructure, while the second one is the reliability of the smart meters.

Finally, a CDH network can create a smart energy system: the presence of both substation thermal storage (hot and cold) and/or widespread thermal storage (i.e., ATEs system) and the possibility to integrate the network with energy produced locally by renewables is the first step in creating a

smart thermal energy network. Nevertheless, the heat pumps installed in the substation need electric energy: the electric grid is thus also involved in the development of CDH network. The diffusion of small size electric energy consumers that can be remotely controlled can lead to the implementation of an effective integrated community energy system [85]. The creation of electrically driven substation can thus be a way to connect a thermal grid with the electric grid. The multi-purpose heat pump can consume electric energy when the energy is produced at lower costs, or when peak production coming from renewable plants is present, thus also favouring electric grid conservation [86,87] and it can produce heat or cold to be stored and consumed later by the users or by the network (cold ring). A methane grid can also be included in the network [88,89], since a methane boiler can be installed as a back-up or integration unit of the multi-purpose heat pump, especially in substations connected to users requiring hot water at high temperatures (i.e., over 65 °C). In this case too, the presence of thermal storage can allow the real-time use of the cheapest form of energy.

5. Conclusions

The purpose of the paper was to define the concept of cold district heating (CDH), including the description of which water source can be used for the application and how the network as well as the substation should be set up. The paper described the state of the art of existing examples of CDH. Finally, the paper identified drawbacks and benefits of CDH networks in comparison with traditional district heating and cooling networks, thus identifying the future challenges that a CDH network has to meet to reach full implementation. Further investigations are needed to identify in which working and environmental conditions the CDH network can be a reliable and sustainable alternative to current district heating and cooling network applications.

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