CONVENTIONAL AND ADVANCED DISTRICT ENERGY SYSTEMS

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ABSTRACT

District energy systems have the potential to decrease the CO_2 emissions linked to energy services (heating, hot water, cooling and electricity), thanks to the implementation of large polygeneration energy conversion technologies, connected to a group of buildings over a network. To transfer the energy from the large polygeneration energy conversion technologies to the users, conventional district energy systems use water as energy transfer medium with often two independent supply and return piping systems for heat and cold. However, sharing energy or interacting with decentralized heat pump units often results in relatively large heat transfer exergy losses due to the large temperature differences that are economically required from the water network. Using refrigerants as a district heating or cooling fluid at an intermediate temperature could alleviate some of these drawbacks. Because of the environmental concerns about conventional refrigerants, CO_2, which is a natural refrigerant, used under its critical point, could be an interesting candidate. Pipe sizing of a multiservices superstructure, based on a two pipe CO_2 network at 18°C is compared with a standard 4 pipes water network for heating and cooling.

Keywords: District energy system, CO_2, piping.

1 INTRODUCTION

The reduction of CO_2 emissions is a challenge for the coming decade, especially with the implementation of the Kyoto protocol. Beside transportation, heating (and in the future most probably also cooling) is responsible for a large share of the total greenhouse gas emissions. For example in Switzerland, more than 40% of the total distributed energy is dedicated to heating purposes [1]. Considering the fact that the generation of electricity in Switzerland is almost free of CO_2 emissions (nuclear and hydro-power), and that another 32% of the total distributed energy is dedicated to transports (fuels), one can assume that the CO_2 emissions due to heating are above 50% of the total emissions, making it a priority candidate among energy services when considering ways to decrease the overall emissions of Switzerland.

To decrease the emissions generated by energy services (heating, hot water, cooling or electricity), one way is to increase the efficiency of the different energy conversion technologies that provide these services, by combining them in a polygeneration energy system. A polygeneration energy system is a system that generates more than just one single energy service. In the case of heating for instance, polygeneration systems could save over 60% of the energy resources and emissions compared to conventional solutions [8]. Sharing energy between services and buildings, leveling load requirements, ensuring minimum storage solutions and reducing management requirements represent positive arguments for district heating and cooling systems. Heat pump based district heating and, to a lesser extend, cooling systems, have been proposed or installed in significant number from the eighties in Europe [2], Asia [9] or America [3]. However, when considering the large variety of building energy and temperature level requirements due to the age or the level of

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retrofitting of the building stock, novel systems integrating centralized and decentralized energy conversion units offer good prospects for exergy efficiency improvements.

District heating systems with both centralized and decentralized heat pumps using two pipe water systems have been proposed [7] or optimized in simple network configurations [4]. Configurations including a three pipe system, circulating a refrigerant to take advantage of the latent heat, have been analysed [5]. However the best fluid candidates analysed at the time, like HFCs or ammonia, present major feasibility drawbacks. Hence the choice of CO_2, as a natural and non toxic fluid, is being considered for district energy networks. CO_2 as a refrigerant is gaining in importance at least for automotive air-conditioning and domestic water heating systems. Besides it could be envisaged both as the network fluid and as the working fluid for the heat pump units.

2 DISTRICT ENERGY SYSTEMS OPERATING WITH WATER

Most district energy systems reported in the literature use water to transport the energy from the heating/cooling plant to the user. Water has the advantage of being non toxic, non flammable, easily available, stable, and with good thermodynamic properties. Steam systems are still being used but most systems rely on pressurized water with either renovated networks (60-90°C) or higher temperature networks (90-120°C) like in Scandinavia [10] and in Switzerland [6]. Higher temperature networks induce fairly high exergy losses in all buildings but particularly in new or retrofitted buildings. Besides they are problematic when it comes to using heat pumps, seasonal heat storage, or solar and geothermal heat. Unfortunately existing contractual arrangements guarantying a high temperature level to building owners are often seen as a major obstacle for reducing the average temperature levels. Alternatives to improve the exergy efficiency of such high temperature networks are the introduction of local ORC (Organic Rankine Cycle) cogeneration units exploiting the exergy difference between the supply temperature and the temperature required by the building heating network, the use of decentralized heat pumps using the return pipe as a heat source, and the use of absorption heating and cooling units. In all these cases steam would be a better choice as the temperature glide of liquid water cooling or heating is unfavorable when interacting with no or very low glide Rankine cycle fluids.

Beside the high exergy losses of conventional district heating systems, the other major drawback of water networks is the required space for the pipes when considering also cooling requirements. There are basically two solutions to add the cooling services to already exisiting district heating sytems:

1. Implement the cooling supply and return pipes parallel to the heating supply and return pipes (see figure 1). In the figure, the supply and return temperatures of the cooling network have been chosen based on [10], but they usually vary from place to place.

2. Implement a cooling supply pipe parallel to the heating supply and return pipes, and let the cooling water flow into the already existing waste water pipes, after it has been used for the air-conditioning.

Solution 1 requires four pipes altogether, which isn't a problem when there is a lot of space available, but can become problematic when space in existing underground channels is limited. An example of the implementation of solution 1 is done for instance in Turko, in Finland, where it is considered a logical, symmetric solution to the already existing heating network [10]. In the case of Turko, the district cooling network only meets cooling requirements for the air-conditioning and no refrigeration requirements are met. However this would be possible if a local heat-pump is implemented as represented on the figure. Solution 2 can be an interesting option for districts located near a lake or a river, and for which the cooling requirements can be met simply by pumping water from the lake or from the river. This solution has the advantage of requiring less space, and saving a return pipe by valorizing what is already existing.

To alleviate the main drawbacks of water systems mentioned above (namely exergy losses and space), a new CO_2 system is proposed.

3 CO_2 DISTRICT HEATING AND COOLING NETWORK

CO_2 is a non toxic, non flammable natural refrigerant, which in refrigeration units, results in the

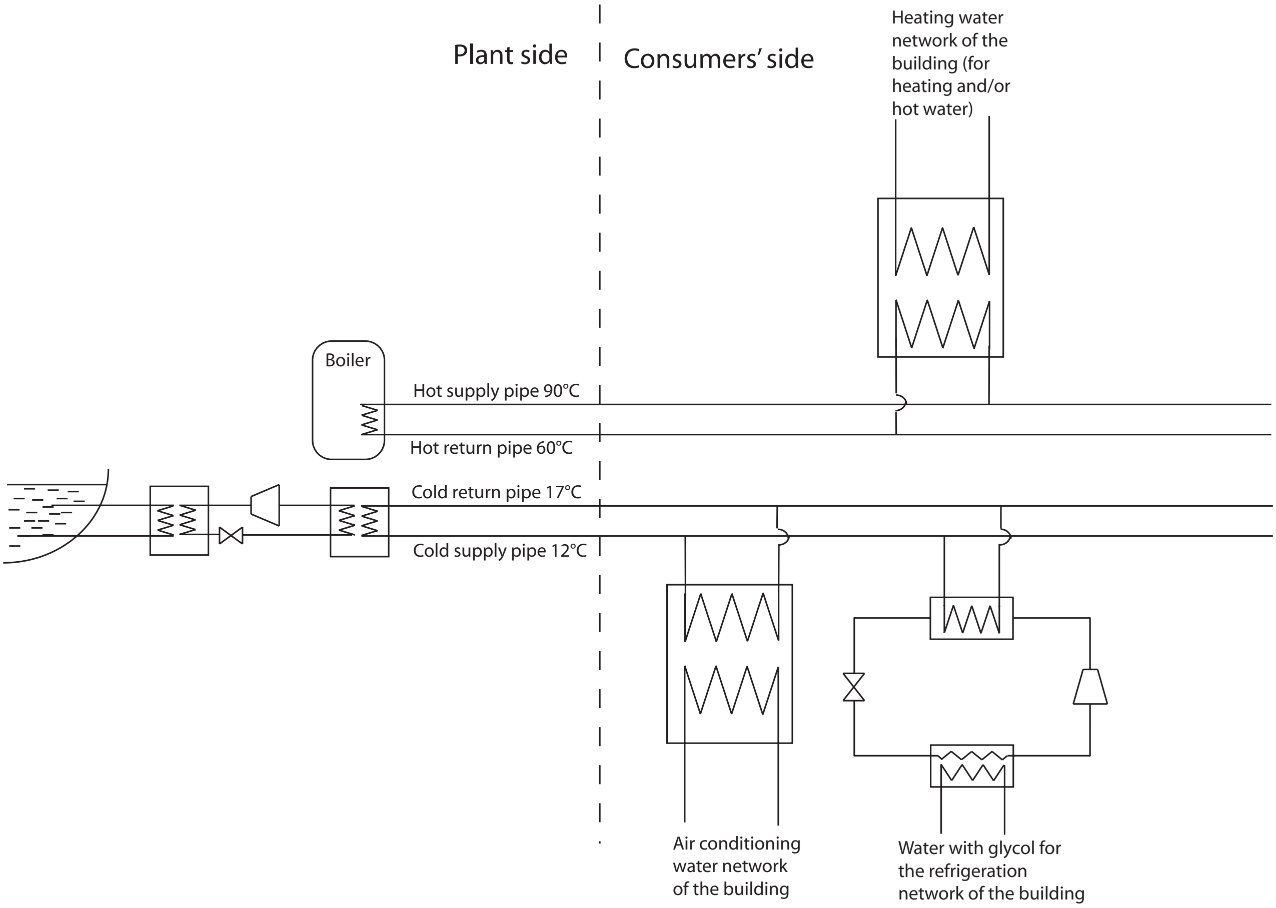

Figure 1: Connection between the network and the users in a district energy system using water as energy transfer medium

same reversed Rankine cycle as common refrigerants. However in heat pumping, supercritical cycles are to be used with a large glide instead of the plateau of condensation of most conventional refrigerants. This implies that CO_2 is well suited for large temperature glide applications like hot domestic water but less adapted to conventional heating networks, which have only a temperature glide of 5 to 15°C. Moreover CO_2 critical pressure is high (7.4 MPa) for a temperature of only 31°C. In the following a 2-pipe (a liquid and a vapor pipe) CO_2 network and the way it meets heating, hot water, air-conditioning and refrigeration requirements, is explained.

Considering that the cold composite curve of most buildings is rather flat with a low temperature glide of the heating heat exchanger, which is dominant in heat rate, one concept is to distribute CO_2 in a district heating network at an intermediate temperature below the critical pressure. CO_2 then still presents a condensing plateau and can be a cold source for a decentralized heat pump working with a conventional refrigerant with zero glide, like HFC134a, or a small glide, like HFC407C. In this case the CO_2 condensing and HFC evaporating temperature profiles are similar, which allows a very small pinch and therefore small exergy losses. The advantage of such a solution is that the decentralized heat pump temperature lift can be tailored to the real heating needs of the building considered. For domestic water preparation a decentralized dedicated CO_2 compressor can be directly used in an open cycle. The system can also take advantage of a small pressure difference between both pipes (the liquid pressure being higher than the gas pressure), to allow for air-conditioning without any powered equipment (pump or compressor). Such considerations guide the choice of the average pressure to be in the range of a saturation temperature of 18°C. Besides, in the event of having a high temperature heat source in its vicinity, the CO_2 system can be used as heat sink for an ORC. Finally, whenever a heat source or heat sink is available at some place on the network, CO_2 can be evaporated or liquefied according to the needs of the whole network. It is also interesting to note that CO_2 has a very low viscosity , leading to potentially small pressure drops in the pipes [10].

Based on the above, a superstructure of a network is proposed. Like any district energy system, the CO_2 system studied comprises a heating/cooling central plant, a distribution network and the connections from the network to the different users, or the different suppliers (in case of CO_2 evaporation or liquefaction). The superstructure of the system is represented in figure 2 and the different possible modes explained hereunder.

3.1 Heating/cooling plant

The two pipes of the network consist of liquid CO_2 for the first pipe and vapor CO_2 for the second pipe. At the district heating/cooling plant the pipes are connected to a heat-exchanger working either as evaporator in heating mode (winter) or as condenser in cooling mode (summer). A set of valves at the central plant couple the evaporator with an expansion valve and a compressor in the heating mode, and the condenser with a pump in the cooling mode. When dealing with a district located near a lake, a river, or a waste water treatment facility, the available water can serve as heat source (heating mode) or heat sink (cooling mode). However, any other heat source such as solar energy, geothermal energy, seasonal heat storage, waste incineration... could also be used, directly in the heating mode, or over an absorption chiller in the cooling mode. To compensate pressure losses in the pipes and avoid parasitic boiling, intermediate circulation pumps could be implemented along the network if requested. Unlike conventional district heating/cooling systems having dedicated supply and return pipes, with the system described here the direction of the flow in the pipes depends on the ratio of the heating (and/or hot water) and cooling (and/or freezing) requirements. If the total heating (and/or hot water) requirements in the district exceed the total cooling (and/or freezing) requirements, the vapor pipe is the supply pipe and the liquid pipe the return pipe. In this case, the CO_2 is evaporated at the central plant and pumped to the customers. On the other hand, if the total cooling (and/or freezing) requirements in the district exceed the total heating (and/or hot water) requirements, the liquid pipe becomes the supply pipe and the vapor pipe the return pipe. In this case, the CO_2 is condensed at the central plant before being pumped to the customers.

3.2 Energy conversion technologies at the user's place

As already mentioned, at the user's place, following processes can take place: heating, hot water preparation, air-conditioning and refrigeration. Besides, assuming that another heat source is available at some place along the network (heat from a chemical industry for instance), the CO_2 network can operate as a heat sink for an ORC. In case geothermal collectors are available or possible (under green areas for example), CO_2 vapor could be generated in winter by means of a heat pump, and CO_2 liquification could take place in summer, when the air-conditioning requirements are predominant. Finally, if unglazed solar roofs are installed, CO_2 could be circulated through the solar pannels in winter for instance, if the sun is shining, in order to generate additional CO_2 vapor to meet the heating and hot water requirements. In summer, at night, CO_2 could be liquified if the atmospheric temperature is below 18°C. In order to compare this CO_2 system with the conventional district energy systems operating with water, the heating, hot water and cooling processes are explained hereunder (the ”Liquid” and ”Vapor” pipes in the figure always refer to the pipes connecting the user with the heating/cooling plant):

1. HEATING AND HOT WATER (OPEN CO_2 HEAT PUMP)

   In the heating mode, the CO_2 vapor is compressed according to the specific needs (temperature level) of the building. It then passes through the heat-exchanger where it releases its energy to the building heating network, before being circulated through an expansion turbine (if any mechanical energy can be recovered), an expansion valve and a separator. The liquid phase is sent to the liquid CO_2 pipe. The vapor phase is directly recirculated to the compressor. If the heating requirements decrease, thus diminishing the needs for CO_2 in the vapor phase, the CO_2 vapor can be circulated directly

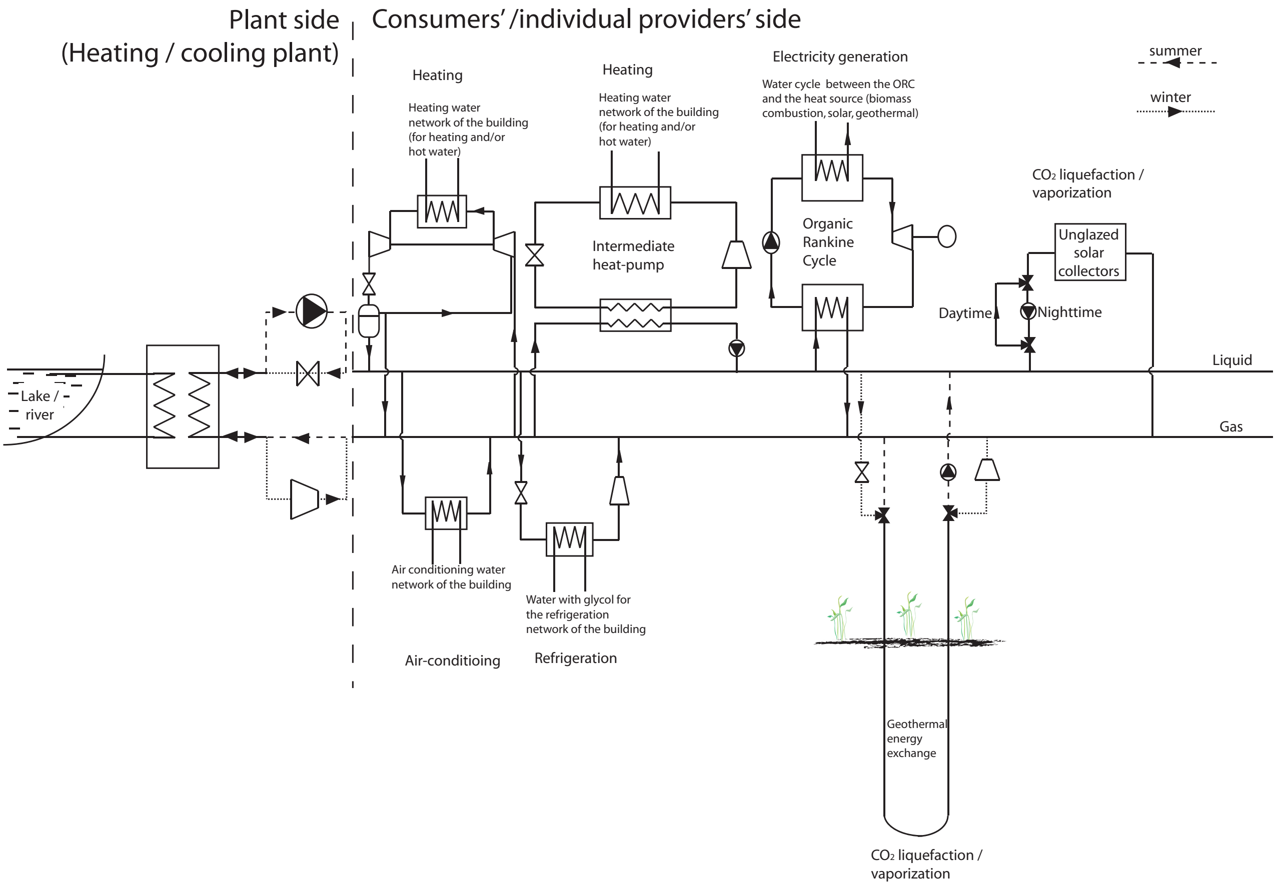

Figure 2: Schematic representation of the CO_2 based district energy system

from the separator back to the vapor CO_2 pipe. This mode is specially advantageous for the hot water preparation.

2. HEATING AND HOT WATER WITH A CLOSED LOOP HEAT PUMP

   A conventional heat pump can be used as superposed cycle in particular when the heating temperature glide is small and disadvantageous for a supercritical CO_2 cycle.

3. AIR CONDITIONING

   In the air conditioning mode, liquid CO_2 is circulated from the liquid pipe, via the heat-exchanger where it is evaporated with the heat coming from the building, to the vapor pipe. Due to the slight over-pressure in the liquid pipe compared to the vapor pipe, no pump is required in the cooling mode.

4. REFRIGERATION

   In the refrigeration mode, liquid CO_2 is circulated over an expansion valve to the heat-exchanger where it serves as heat-sink to the refrigeration network of the building (for industrial refrigeration for instance). The expansion valve can be regulated so as to meet the exact refrigeration temperature required by the building. After the heat-exchanger, the CO_2 is compressed and sent back to the vapor line.

5. ELECTRICITY GENERATION

   If a heat-source with a high enough temperature is available somewhere along the CO_2 network, the network can operate as a heat-sink for an ORC and thereby generate some electricity.

6. GEOTHERMY In cities and districts with big green parks, geothermal probes can be dug into the soil. In winter, geothermal heat could be used to evaporate liquid CO_2 using a heat-pump, and therefore help providing the required CO_2 for heating and hot water purposes. On the other hand, in summer, vapor CO_2 can be liquified (mainly in the nighttime) in order to have enough liquid CO_2 for the air-

conditioning during the day. Geothermal energy can also be gained by means of geothermal structures implemented in the foundations of large multi-storey car parks.

7. UNGLAZED SOLAR COLLECTORS Unglazed solar collectors mounted on the roof of buildings can help generate vapor CO_2. During the nighttime, especially in summer, if the atmospheric temperature is below 18°C, the existing heat-exchanger can be used to liquefy vapor CO_2 for the daytime air-conditioning.

8. COMBINATION
   The operating modes described above can also be combined. For instance the heating and air-conditioning modes can be combined at the customer's place. When both heating and air-conditioning are required in the same building, this system directly transfers the energy from the evaporator (air-conditioning) to the heat-exchanger (heating and/or hot water) or vice-versa via the CO_2. When one of the two energy requirements exceeds the other, the CO_2 that cannot be reused internally at the customer's place is circulated via the heating/cooling plant. In the heating mode, the CO_2 vapor is compressed according to the specific needs (temperature level) of the building, as described above (point 1). After having passed through the heat-exchanger, expansion turbine, expansion valve and separator, the liquid can be circulated directly to the evaporator together with any additional liquid CO_2 from the pipe of the network, if cooling is required in the building. The vapor on the other hand either flows back to the compressor, or, if the heating (and/or hot water) requirements decrease, to the vapor pipe. Likewise, the CO_2 evaporated in the evaporator (cooling mode) can be circulated to the compressor for heating (and/or hot water) requirements, via a separator to insure the vapor quality, or back to the vapor pipe.

4 COMPARISION BETWEEN THE CONVENTIONAL WATER SYSTEM AND THE PROPOSED CO_2 SYSTEM

To compare conventional district energy systems with the CO_2 system presented in this paper, it is interesting to analyse how both systems perform in terms of annual costs (including investment and operation costs), and in terms of annual CO_2 emissions. Besides, since the space available for the pipes can be an issue at some places, as already mentioned, dimensional aspects are also of interest. For the annual costs and emissions, a software is presently under development [11]. To analyse the dimensional aspects, a very simple Y-shaped network with three users has been used (see figure 4). For dimensioning, only the two peak periods have been considered for the consumption profile: a winter period and a summer period. The assumed peak consumption of each user is given in table 1 below.

User	Season	Cooling requirements [kW]	Heating requirements [kW]
1	Winter	2500	25000
	Summer	10000	2500
2	Winter	1000	10000
	Summer	8000	1000
3	Winter	1500	15000
	Summer	7000	1500

Table 1: Heating and cooling consumptions of the three different users

For the water system, the network considered is characterized by the temperatures given in table 2. The temperatures of the heating network have been chosen according to the actual best practice for an existing district heating network in Switzerland. For the cooling temperatures, following considerations have been taken into account:

1. Since all major cities in Switzerland are located at lake or river sides, advantage has to be taken to use directly the available water in the cooling network (instead of implementing energy conversion technologies to cool down some water).

2. The supply temperature of the water is not chosen too low, in order to avoid condensation.

Following assumptions have been made to compute the diameters:

1. The velocity of the fluid in the pipes has been set to 4 m/s for the water and the liquid CO_2, and to 15 m/s for the gas CO_2.

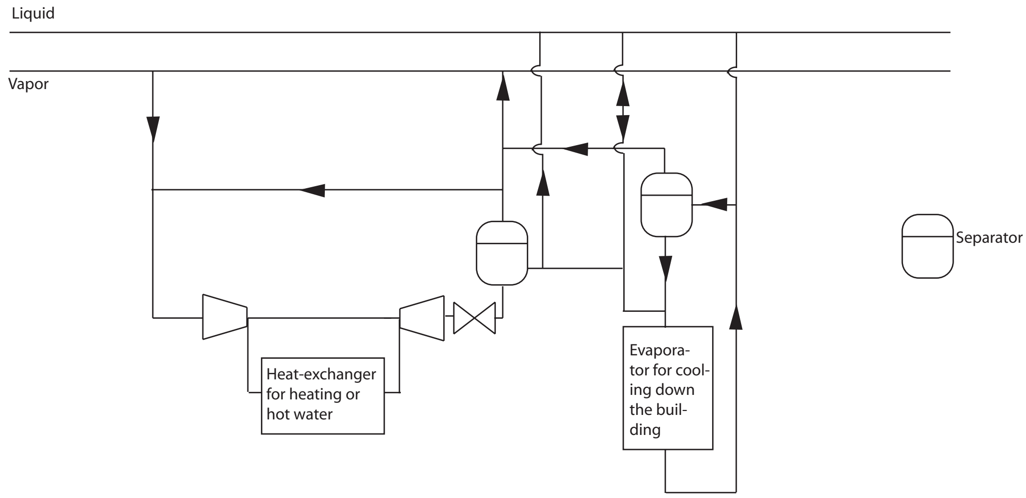

Figure 3: Combined heating and cooling mode

District energy system	Energy service	Supply pipe	Return pipe
	[°C]	[°C]	
4-pipe	Heating	90	60
	Cooling	17	12
3-pipe	Heating	90	60
	Cooling	18	Waste water

Table 2: District energy systems operating with water

2. For the CO_2 system, the compressor at the user's place compresses the CO_2 to reach a temperature of 80°C, and the CO_2 is cooled down to 40°C in the heat-exchanger.

The diameters of the pipes are given in table 3. (For the water system, the diameters are of course the same for the supply and return pipes, since all the water that flows to the user has to be pumped back to the heating/cooling plant. If the return cooling water directly flows into the waste water pipe, then only a supply pipe needs to be considered). If the order of magnitude of the diameters are the same for conventional systems and the presented system, it is important to recall that with the presented system only two pipes are needed.

5 CONCLUSION AND FUTURE WORK

A new CO_2 district heating, cooling and refrigerating network is presented and pipe size comparison are made with conventional water systems. The sys-

Fluid type	Fluid state	Pipe number	Pipe diameter [mm]
Water	Hot	1	317
		2	224
		3	224
		4	173
Water	Cold	1	317
		2	200
		3	245
		4	168
CO_2	Gas	1	390
		2	276
		3	276
		4	213
CO_2	Liquid	1	218
		2	133
		3	173
		4	114

Table 3: Diameters of the pipes for both district energy systems

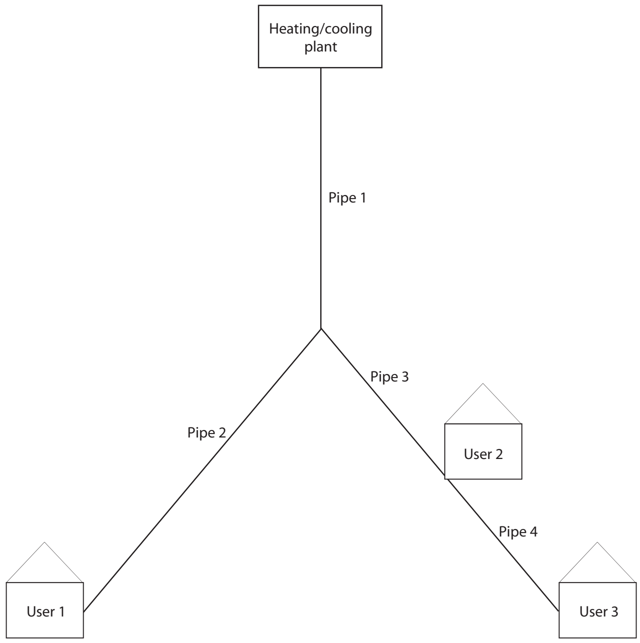

Figure 4: Simplified Y-shaped network

tem heavily relies on decentralized heat pump and refrigeration units. It is shown that piping can be reduced by half in terms of size and cost compared to an equivalent 4-pipe water system. Calculations of energy and emissions gain are under way.

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